TUNNEL SHIELDS AND THE USE OF COMPRESSED AIR IN SUBAQUEOUS WORKS

JAMES HENRY GREATHEAD.

B. 1844. *D.* 1896.

TUNNEL SHIELDS AND THE USE OF COMPRESSED AIR IN SUBAQUEOUS WORKS

BY

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WITH 260 ILLUSTRATIONS AND DIAGRAMS

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PREFACE

ALTHOUGH the employment of a shield, with or without the aid of compressed air, in tunnelling operations is of English origin, and the length of tunnels so constructed in this country is many times greater than the total amount of similar work elsewhere, the subject is nowhere dealt with in Engineering text books written in English, except in Simms' *Practical Tunnelling* and Prelini and Hills' *Tunnelling,* which, however, touch only slightly on it as a part of the general history of tunnelling.

Except for a few pages in these works, no account in English of shield-work exists save in the form of papers printed in the *Proceedings of the Institution of Civil Engineers* and some description of current works which have from time to time appeared in the technical journals.

In French two books only on the subject have appeared: the very complete work by M. Legouëz, *L'Emploi du Bouclier dans la Construction des Souterrains,* and M. Philippe's *Le Bouclier,* which gives some interesting information on recent French tunnel works.

The Author hopes, therefore, that a history of recent developments in shield-work may be found of some use to his professional brethren, if only by collecting in one volume a mass of information hitherto scattered through many publications, and consequently difficult and troublesome of access.

He has treated as briefly as possible the early records of the shields, and of compressed air working, holding, indeed, that only with Mr. Greathead and his Tower subway shield the history of practical tunnelling by shield really commences, but of the developments witnessed since he has endeavoured to present as clear a record as the limits of one volume will permit.

Of the Greathead shield work, the "assisted shield" method of tunnelling, and the various subaqueous tunnels recently built in and around London, he may claim to write from personal knowledge, supplemented by information generously placed at his disposal by the Engineers engaged in the various undertakings described.

Of the tunnels constructed abroad, in France and in the United States, his information is for the most part obtained from original sources or the writings of those who were themselves actors in the operations they describe.

The obligations he is under to his professional colleagues in each case are indicated in treating of the various undertakings; he would acknowledge here, however, his special indebtedness to the Council of the Institution of Civil Engineers for permission to use the material contained in the Minutes of Proceedings of that body, and to the Editors of the English, American and French Engineering journals by whose courtesy he has been able to reproduce many illustrations of interest.

The descriptions in this book of each undertaking are limited by considerations of space to those portions constructed by shield or in which compressed air was employed, and only such further details as are necessary for the understanding of the conditions governing the execution of such portions are included.

LONDON,
October, 1905.

CONTENTS

CONTENTS

CONTENTS

CONTENTS

PAGES

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS

Chapter I

THE SHIELD: ITS EARLY HISTORY, 1818 to 1880

Brunel's Patent—The Thames Tunnel Shield—The Shield as Described in Brunel's Patent—Dunn's Patent, 1849—Guibal's Shaft-Sinking Machine—Rziha's Removable Centres—Barlow's Patent, 1864—Greathead's Tower Subway Shield, 1869—Beach's Shield with Hydraulic Rams, 1869—Shields at Cincinnati and Cleveland—Woolwich Shield, 1874—Woolwich Erector—Antwerp Tunnel, 1879—Greathead, and the Introduction of Shield Work in Recent Years

THE first mention in tunnelling operations of a "casing or cell intended to be forced forward before the timbering which is generally employed to secure the work" is found in the Specification of Patent No. 4204 of 1818 of Marc Isambard Brunel, which specification, it is hardly too much to say, covers every subsequent development in the construction and working of tunnel shields.

The progress of mechanical science, and particularly the improvements of hydraulic, electrical and pneumatic machinery (Mr. Colladon is said however to have suggested this last to Mr. Brunel in 1828) have placed in the hands of the tunnel engineer sources of power unknown to the inventor of 1818; yet allowing for these advantages the most elaborate shield of to-day is worked on the lines proposed in Brunel's patent, and this not only as regards the shield itself, but also in the use with it of cast iron as a tunnel lining which for the first time is recommended in this specification and is figured in the plans attached to it.

The date of this patent of Mr. Brunel's forms therefore the starting point at which the history of tunnelling by means of a shield commences, and precedes by twelve years only the equally famous patent of Sir Thomas Cochrane, styled Lord Cochrane, which first described the application of compressed air to shaft sinking and tunnelling in water-bearing strata; which method, used in conjunction with the shield, has made possible the great tunnel enterprises of the last twenty years.

More fortunate than Lord Cochrane, Mr. Brunel was able to test his invention himself and to bring the Thames Tunnel, the first constructed by means of a shield, to a successful conclusion; but, on the other hand, while this tunnel remained for thirty years the only one so constructed, the method of Lord Cochrane was, in a much shorter time, in general use, not indeed in tunnels, but in shaft sinking and in caisson work in the foundations of bridge piers and similar structures.

The shields used by Brunel in the Thames Tunnel between 1825 and 1828 substituted for the ordinary timber work of a tunnel a movable frame or curtain capable of sustaining the working face and holding up the roof of the excavation during the carrying out of mining operations, and at the same time affording space within its shelter for the construction of the permanent lining of the tunnel.

That tunnel, now used by the East London Railway, crosses the Thames at Rotherhithe, and was originally intended to serve as a vehicular tunnel, or

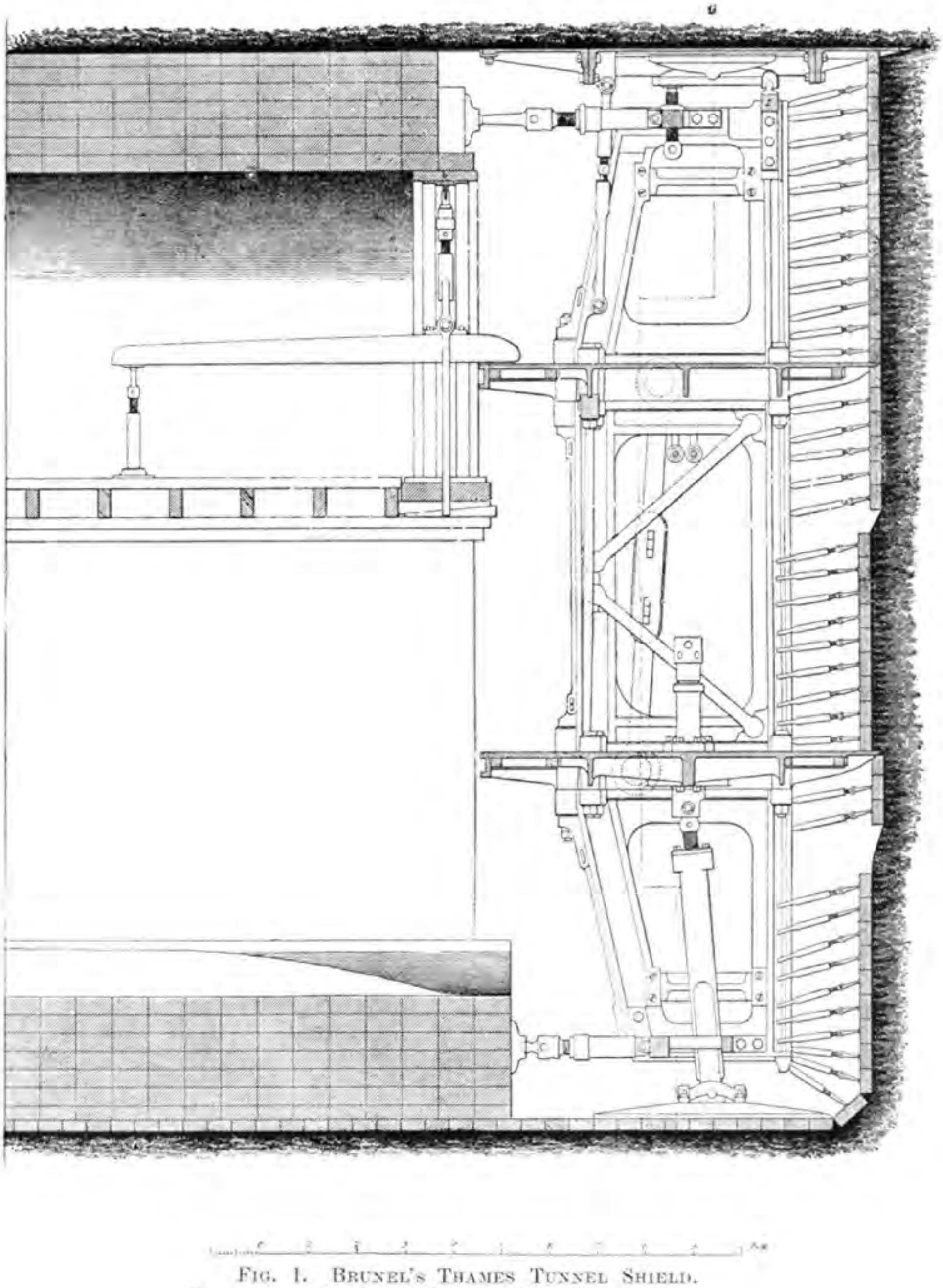


FIG. 1. BRUNEL'S THAMES TUNNEL SHIELD.
Section on line A, A (Fig. 2).

rather tunnels, for it consists of two brick tunnels side by side having a common pier in the centre.

The cross section of the masonry was a rectangle, the actual area of which was greater than that of any tunnel constructed since.

The shield originally designed under the erroneous idea that the materia to be met with in making the tunnel was mainly of a clayey nature, was found defective when employed in loose waterbearing material—as might well be expected in an entirely novel machine — and although it continued in operation during the first period of the tunnel works, from 1825 to 1828, was removed on the resumption of the works in 1835, and an improved shield substituted which continued in use until the completion of the tunnel in 1843.

This second shield, which is the one figured in detail in Mr. Henry Law's article on the Thames Tunnel, published in Weale's *Quarterly of Engineering*, vol. v. 1846, was of the same general type as the first one, but with improvements in details.

It is this second shield which is always figured and described in engineering text-books (see Figs. 1 and 2).

The dimensions of the shield over all were: width, 37 feet 6 inches; depth, 22 feet 3 inches; and length, not including tail plates, 9 feet.

It consisted of twelve frames of cast iron, each about 3 feet 3 inches wide, capable of independent movement, and each comprised of three sections, upper, middle and lower, which could also be propelled separately.

The top section in each frame was provided with roof plates or staves, which sustained the ground above, and being chisel-shaped in front, served the same purpose as the cutting edge (which indeed was suggested by them) of a modern shield. Each of the two lower sections had also roof plates which served as floor plates to the section

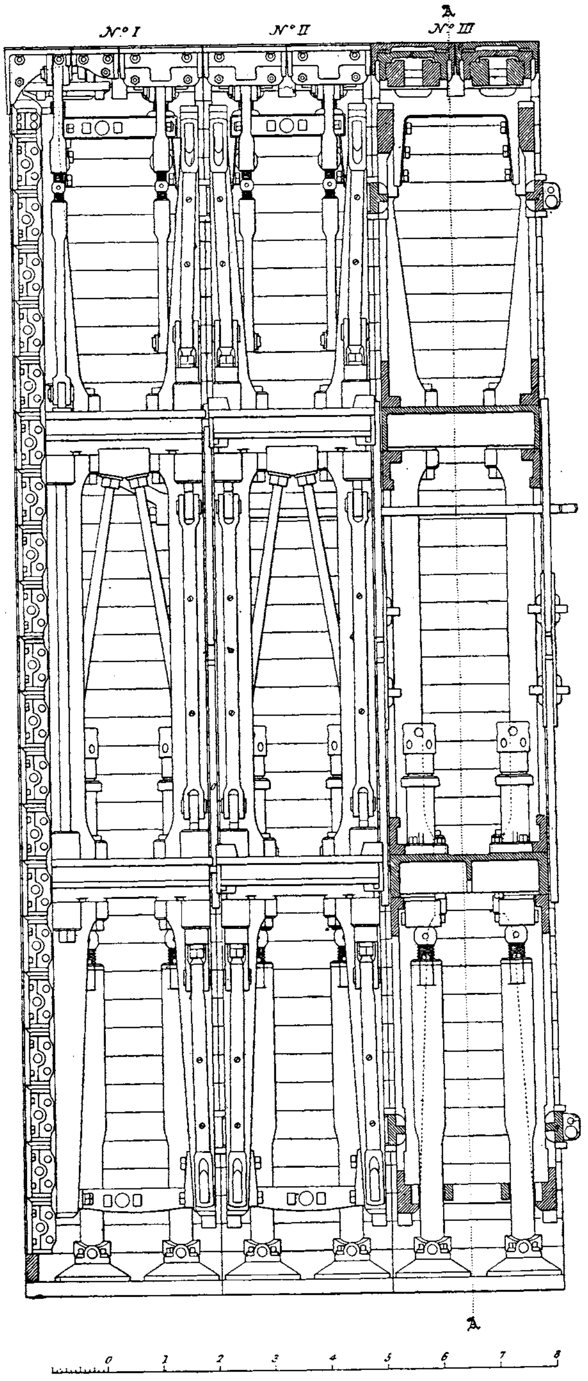


Fig. 2. Brunel's Thames Tunnel Shield, showing Three of the Lower Frames Composing the Shield.

Section on line *B*, *B* (Fig. 1).

Showing three of the twelve frames composing the shield.

above, while the lowest of the three sections rested on a foot or base, which in turn rested on planks, introduced one at a time as the shield moved forward. Those planks subsequently formed a platform on which the brickwork of the tunnel was laid.

Each section was provided in front with fourteen or fifteen poling boards, held up by screw stretchers, each poling having independent screws, and so enabling the face to be excavated and immediately supported in front of each poling separately. By an ingenious arrangement, it was possible, when the polings in front of any section had been advanced the required distance, to support each poling from the adjacent sections, and so allow the section, the polings of which had so advanced, to be moved forward, when the polings in front were again stretched to it.

By a somewhat similar disposition of vertical jacks, the roof plates of each section could be sustained from the floors of the adjoining sections so as to admit of each section being moved forward, free from pressure from above.

The whole shield was held up against the face by screw jacks which bore on the finished masonry of the tunnel.

To prevent the falling in of the roof between the tail of the shield and the finished tunnel when the shield was moved forward, iron plates long enough to bear in front on the roof plates of the shield, and behind on the top of the masonry, were provided.

The working of the shield was based on the general idea that, while it was impossible to excavate over a face of such large area, and to push forward the shield to support the new face sufficiently rapidly to avoid the material falling in, it was possible to advance piecemeal, by one frame, or rather by one section of a frame at a time, the remainder of the face of the excavation being supported by the other frames (where no excavation was going on,) which were at the same time supporting the polings in front, and themselves sustained by jacks behind bearing against the finished tunnel.

In actual work, it was the practice to move forward at one time alternate frames of the twelve into which the shield was divided ; the advance made being not more than 6 inches at a time. At best the rate of progress was not rapid, 14 feet being the greatest length built in one week.

Although Mr. Brunel, as the result of almost unexampled courage and skill, managed to complete the tunnel, and connect the two banks of the river by a subaqueous passage, the great cost of the work, and the consequent disappointing financial results, undoubtedly checked for a long period any further enterprises in similar situations.

For twenty-six years he found no imitator, but when in 1869 the Tower Subway was built by Mr. Greathead, who must be regarded as the pioneer in all modern work of this class, the shield used embodied the main features of the earlier machine.

Indeed the shield of 1869 bore in its general appearance more resemblance to the first of the two shields figured in the Brunel patent of 1818 than to the actual shield, or rather shields, used in the Thames Tunnel.

If in Figs. 3 and 4, which are reproduced from the drawing attached to Mr. Brunel's patent, we imagine the separate cells to be bolted together instead of sliding freely, the one on the other, and the outside plates to be joined up and so made into one cylindrical skin, we should have a machine very much resembling the Barlow, or the Beach, or the later shields figured in Chapter IV.

The manner in which the shield of 1818 was intended to work may be given in Mr. Brunel's own words (extract from patent Specification) :—

I shall premise by observing that the chief difficulties to be overcome in the execution of tunnels under the beds of great rivers lie in the insufficiency of the means of forming the excavation. The great desideratum, therefore, consists in finding efficacious means of opening the ground in such a manner that no more earth shall be displaced than is to be filled by the shell or body of the tunnel, and that the work shall be effected with certainty.

The first method I shall describe for obtaining this desirable result is applicable to a tunnel of large dimensions as well as to a simple drift or a driftway. In the formation of a drift under the bed of a river, too much attention cannot be paid to the mode of securing the excavation against the breaking down of the earth. It is on that account that I propose to resort to the use of a casing or a cell, intended to be forced forward before the timbering which is generally applied to secure the work. This cell may be similar to one of those represented in Fig. 1, see letter *C*. The workman thus inclosed and sheltered may work with ease and in perfect security. It is obvious that the smaller the opening of a drift, the easier and the more secure the operation of making the excavation must be. A drift on dimensions not exceeding 3 feet in breadth by 6 feet in height, forms an opening of 18 feet area ; whereas the body of a tunnel on dimensions sufficiently capacious to admit of a free passage for two carriages abreast cannot be less than 22 feet diameter, consequently about twenty times as large as the opening of a small drift. One of the modes which I propose to follow for the purpose of forming excavations suitable to tunnels of large dimensions consists in rendering the operation nearly similar to that of forming a small drift, as being the most easy and the most secure way of proceeding. The apparatus represented in the Fig. 1, 2, 3 and 4, is one of the nature above described, and whereby a large excavation suitable to the dimensions of the proposed tunnel may be made. This apparatus is intended to precede the body or shell of the tunnel, and it is represented as if the work had already been commenced with a part of the tunnel *a, a, a, a*, Figs. 2 and 4, formed behind it. Fig. 1 represents a transversal view of an apparatus composed of small cells *A, B, C, D, E, F, G, H, J, K*, lying alongside of and parallel with each other. Each cell may be forced forward independently of the contiguous one, so that each workman is supposed to operate in a small drift indepen-

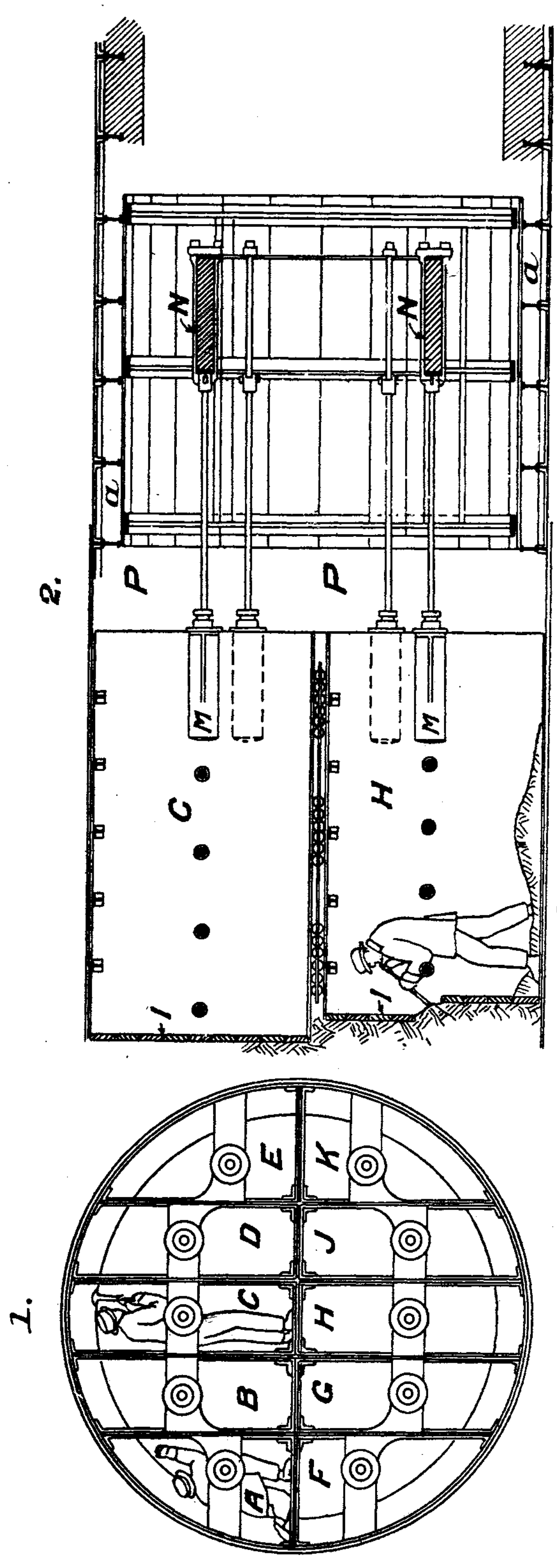
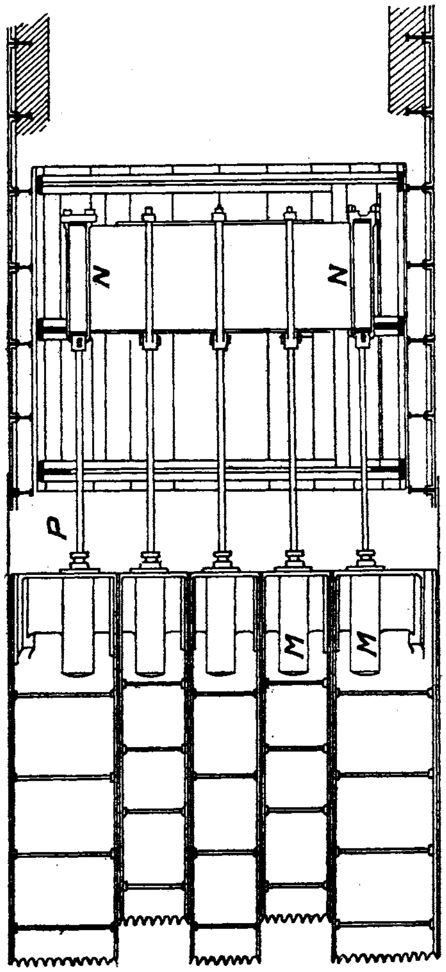


FIG. 3. BRUNEL'S SHIELD.
From drawing attached to Specification of Patent No. 4204 of 1818.

4.



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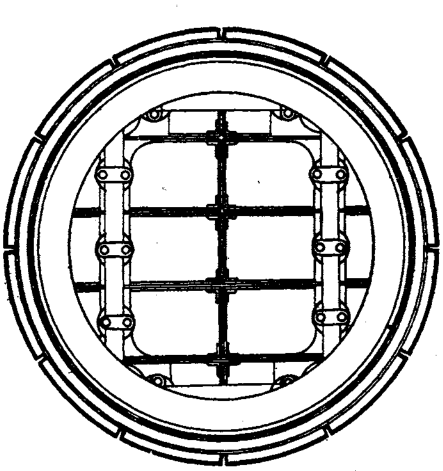


Fig. 4. Brunel's Shield.
From drawing attached to Specification of Patent No. 4204 of 1818.

dently of the adjacent one. The front of the work is protected by small boards *I, I, I, I,* which the workman applies as he finds most convenient. Several men may work at the same time with perfect security, and without being liable to any obstruction from each other.

Fig. 2 represents a longitudinal section of the apparatus, wherein a workman is seen at work. Each cell is to be moved or forced forward by any mechanical aid suitable to the purpose, but I give the preference to hydraulic presses *M, M,* Fig. 2, which are made to abut against a strong framing *N, N, N,* fixed within the body or shell of the tunnel. When the ground has been removed and the several cells have been forced forward to a sufficient distance, then a space *P, P,* corresponding with that distance, is left between the ends of the cell and the shell of the tunnel *a, a, a, a.* But in order to prevent the breaking down of the earth, or the eruption of a large body of water to each of the cells, and on that side of each which is exposed to the pressure of the earth, I apply strong iron plates extending beyond the cell, so as to overlap the shell of the tunnel previously made, thus protecting the space already cleared. The body or shell of the tunnel may be made of brick or masonry, but I prefer to make it of cast iron, which I propose to line afterwards with brickwork or masonry.

Fig. 3 represents a transverse sectional view of the tunnel showing the framing which is to form the abatement for the hydraulic presses.

Fig. 4 is a plan exhibiting the internal arrangements of the cells, the hydraulic presses *M, M, M, M,* and the framework *N, N, N,* forming the abatement of those presses. Each cell in the longitudinal direction thereof is formed into a prismatic figure such as adapts itself to the situation which it respectively occupies in the area which is intended to be excavated. In order to facilitate the progressive movement of the cells, I introduce friction rollers between the opposite sides of all the cells, one row of which, for the sake of exemplification, is represented at *P,* Fig. 2. As the construction of the hydraulic presses is well understood by mechanics in general, and as the application and use of the said presses and framework forming the abatement to the same must be sufficiently apparent from the preceding description thereof and the various figures in the annexed drawings, they require no further explanation; I have only to add, that after so much of the earth, as before described, has been removed by the workman, and after the cells have been forced forward by the aid of the presses into the position as represented in Figs. 2 and 4, and also after another portion of the shells of the tunnel has been added so as to occupy or fill up the space *p, p,* it then becomes necessary that the framework or abatement *N, N, N,* should be moved forward through a space equal to that through which the cells had previously been moved. The said frame having been so moved, it must again be firmly fixed in its new situation.

The above extract describes the essential features of all the shields which have been constructed since 1869, and perhaps the comprehensive character of Mr. Brunel's invention can best be described by saying that while it covered in its main features the comparatively simple machine designed by Mr. Greathead for tunnelling in the London Clay, which in its own sphere also remains to-day the best and indeed the only apparatus in use for that work; the more complicated apparatus used in the St. Clair and Blackwall tunnels also derive their essential features from the same original.

It is of course easy to criticise the details both of the shield as patented by Brunel and of that actually used. Their complication of parts, and the division and subdivision of the working face are defects, but on the other hand, as M. Legouez has well pointed out, many of those features of the shield are due to the insufficiency of the mechanical appliances at Brunel's disposal, and one may well add that many of Brunel's details have reappeared in the more powerful shields of later times. The same writer points out, for example, that the skin of the shield, the rams which advance it, the polings dividing up the working face into small sections, and even the use of clay in front of the cutting edge, are all in existence, in a rudimentary form sometimes it is true, in Brunel's shield.[1]

The author may remark here that in 1900, when engaged in preparing for Sir A. Binnie the plans for a tunnel about 11 feet in diameter under the River Lea in connexion with the main drainage system of London, he had brought under his notice a model of a shield practically similar in design to the one in Figs. 1 and 2, except that the outside skin was comprised of "needles" or metal strips about 9 inches wide.[2] This was invented by a miner in the employ of the London County Council, and was actually tried a year later in the construction of a sewer about 7 feet in external diameter in the Isle of Dogs. The results were unsatisfactory, but perhaps had the Thames Tunnel been circular in section, instead of rectangular, the system of working in independent compartments might have equally failed there. On this point Mr. Greathead (*Proc. Inst. C.E.*, vol. cxxiii. p. 55) says: "In the Thames Tunnel, Brunel adopted a rectangular section, probably as being more suitable for his form of shield." Mr. Law, in the paper referred to above, says that the rectangular form was adopted on account of the better resistance it offered to constantly varying pressures due to the rise and fall of the tides.

The second type of shield described and figured in the specification of 1818 is the one suggested, as described by Brunel himself, by the screwlike action of the Teredo Navalis, a marine worm which can pierce the hardest woods. The shield was never practically tested, and it is one of fame's little ironies that Brunel is popularly supposed to have derived his great invention from his observation of a natural excavating machine, whereas in fact the actual shield used by him borrowed nothing from any previously known natural or other mechanism.

The next tunnel constructed by means of a shield was the Tower Subway under the Thames constructed in 1869, but prior to this date several inventions were put forward on similar lines to Brunel's.

In 1849 a Mr. Samuel Dunn, of Doncaster, took out a patent (No. 12,634 of 1849) for a tunnelling machine, for working in soft sand and mud, which, however, was never tested by actual work.

[1] Legouez, *Emploi du Bouchier*, p. 43.

[2] Patent 7374 of 1890.

It consisted of a cylindrical or elliptical shield, having its front, which was entirely closed, formed somewhat like a ploughshare.

The rear portion contained in the cylindrical skin, which was sufficiently long to overlap the tunnel already constructed, formed an hydraulic or atmospheric ram, the piston of which had a head the full size of the shield, and when a bearing was taken on the tunnel already constructed, forced the whole shield forward.

The making of a piston of such dimensions properly watertight would offer some difficulties, and perhaps with some idea of this, the inventor suggested as an alternative construction that a smaller hydraulic ram should be fixed in the centre of the plough, in the axis of the tunnel, and that its piston should bear with radial arms in the tunnel lining already built.

The general design, as shown in the drawings accompanying the specification of the patent, is very crude, and the main feature, the plough front, quite unworkable ; but the inventor puts forward for the first time the suggestion that the machine should move in one piece, which is a characteristic of all modern shields.

In 1857, a Mons. Guibal devised for sinking shafts in running sand, and similar material, a shield, which, except that its movement was vertical, instead of horizontal, was in all respects an adaptation of Mr. Brunel's machine.[1]

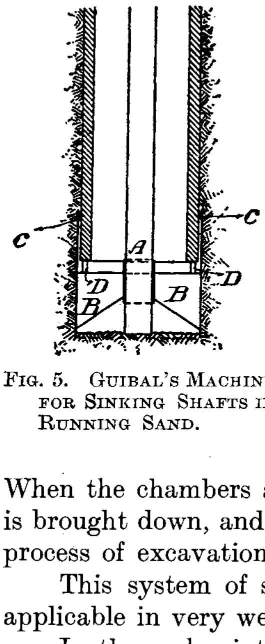


Fig. 5. Guibal's Machine for Sinking Shafts in Running Sand.

In Fig. 5 a shaft is shown partly constructed, in the centre of which is hung a pipe *A*. At the lower end of this pipe are fitted to it segmental frames or chambers *B*, *B*, capable of separate movements. The chambers together cover the area of the bottom of the shaft. The plates forming their outside skins are extended upwards so as to surround the lower end of the shaft already built, and are provided with leather flaps *C*, *C*, making a more or less watertight joint. The chambers are supported from the shaft above by means of hydraulic jacks *D*, *D*.

By means of a spoon bore the material below the chambers is removed through the tube *A*, and the chambers are successively forced down by the jacks *D*, *D*. When the chambers are all sunk a convenient distance, the lining of the shaft is brought down, and that done, the pipe in the centre is again lowered, and the process of excavation recommenced.

This system of shaft sinking has not been extensively used, as it is only applicable in very wet sand, and even then the rate of progress is not rapid.[2]

In the early sixties, a M. Rziha introduced a system of tunnelling with iron removable centres which had some success, but which since the reintroduction of the shield system has been little used.[3]

In 1864 Mr. P. W. Barlow took out a patent (No. 2207) for an improved method of constructing and working railways and in constructing railway tunnels.

In the specification he describes his invention as follows :—

> In constructing tunnels for railways, particularly where the tunnels are to pass under rivers or under towns and places where the upper surface cannot without serious

[1] Drinker's *Tunnelling*, p. 742.

[2] In sinking an 18 foot shaft through wet sand near the Kennington Road for the Baker Street and Waterloo Railway, London, Mr. Dalrymple Hay has recently (May 1905) employed a rudimentary shield with very satisfactory results.

[3] Drinker's *Tunnelling*, p. 677.

injury be broken up or interfered with, a cylinder of somewhat larger internal diameter than the external diameter of the intended tunnel is employed, such cylinder being by preference of wrought iron or steel. The forward edge of this cylinder is made comparatively thin. Within this cylinder and near the forward end thereof, are upright plates parallel to each other, also formed with cutting forward edges in order to cut freely through the soil in front when the cylinder is forced forward. The earth is continuously removed from within this cylinder, and the cylinder is from time to time forced forward a short distance to admit of a ring of iron being put together within the inner end of the cylinder, such iron rings being of a strength suitable for forming a permanent lining to the tunnel. It is desirable that the thickness of the iron of the cylinder should be as little as may be, in order that the space between the outer surfaces of the rings and the earth which surrounds them may not produce any subsidence in the surface of the land above.

* * * * * *

The cylinder is from time to time forced forward by screws, and the rings of the iron tunnel are then put together, whilst the surrounding earth is upheld by the cylinder. If the soil is weak, provision may be made for using poling boards as is well understood. The space, as it is left between the earth and the exterior of the tunnel, may be filled by injecting or running in fluid cement.

Fig. 6 is prepared from the drawing filed with the specification, and shows a shield moving forward in one piece, but in all other respects resembling the Brunel Patent of 1818.

The suggestion that the space left void behind the cylindrical skin of the shield when the latter is moved forward should be filled with cement is put forward for the first time.

As is well known the apparatus devised by Mr. Greathead for injecting grout behind the tunnel lining is everywhere used in this class of work, and perhaps has done more than any other invention except the shield itself, to render tunnelling under shield in the London Clay practicable.[1]

In the Tower Subway the filling with grout was done by means of a hand syringe and was not satisfactory; the grout having to be put in in too fluid a condition for setting well, and the syringe not having enough pressure to force the grout into the smaller interstices in the clay.[2]

In 1866 a Mr. R. Morton, of Stockton-on-Tees, took out provisional protection for a shield described as under[3]:—

A tubular shield of cast or wrought iron, or of any suitable metal, circular or elliptical in form, and somewhat larger than the proposed tunnel. The front of this shield is sharp or pointed like a wedge. Inside of the shield I fix hydraulic presses (one or more); the pumps of these presses are worked by steam power in the usual way. I fix a strong table of cast iron or any suitable metal on the outer ends of the hydraulic rams to take the thrust or pressure. I form segmental rings of cast iron in suitable widths, with which I build the tunnel as excavated by the shield, these rings having internal flanges with which they are bolted together. They are made small enough to pass within the shield and leave a proper space all round for packing. The shield will always overlap the rings 2 feet, and in the space between I place india-rubber tubes, expanded by pumping air or water into them, thus filling the space and keeping out water or mud from the tunnel; or I use an india-rubber ring or cupped leather fixed to the after part of the shield outside. On the bottom of the segmental rings I fix longitudinal girders to suitable flanges for carrying the roadway.

This provisional patent appears to have remained entirely unknown, for in the discussions which subsequently arose as to the paternity of the modern shield no reference has ever been made to this, which at any rate appears to anticipate Mr. Beach's use of hydraulic power in his New York shield.

In 1868 Mr. Barlow provisionally protected another design of a shield, the

[1] Patent No. 5221 of 1886. [2] *Proc. Inst. C.E.*, Vol. cxxiii. p. 62.
[3] Patent No. 770 of 1866.

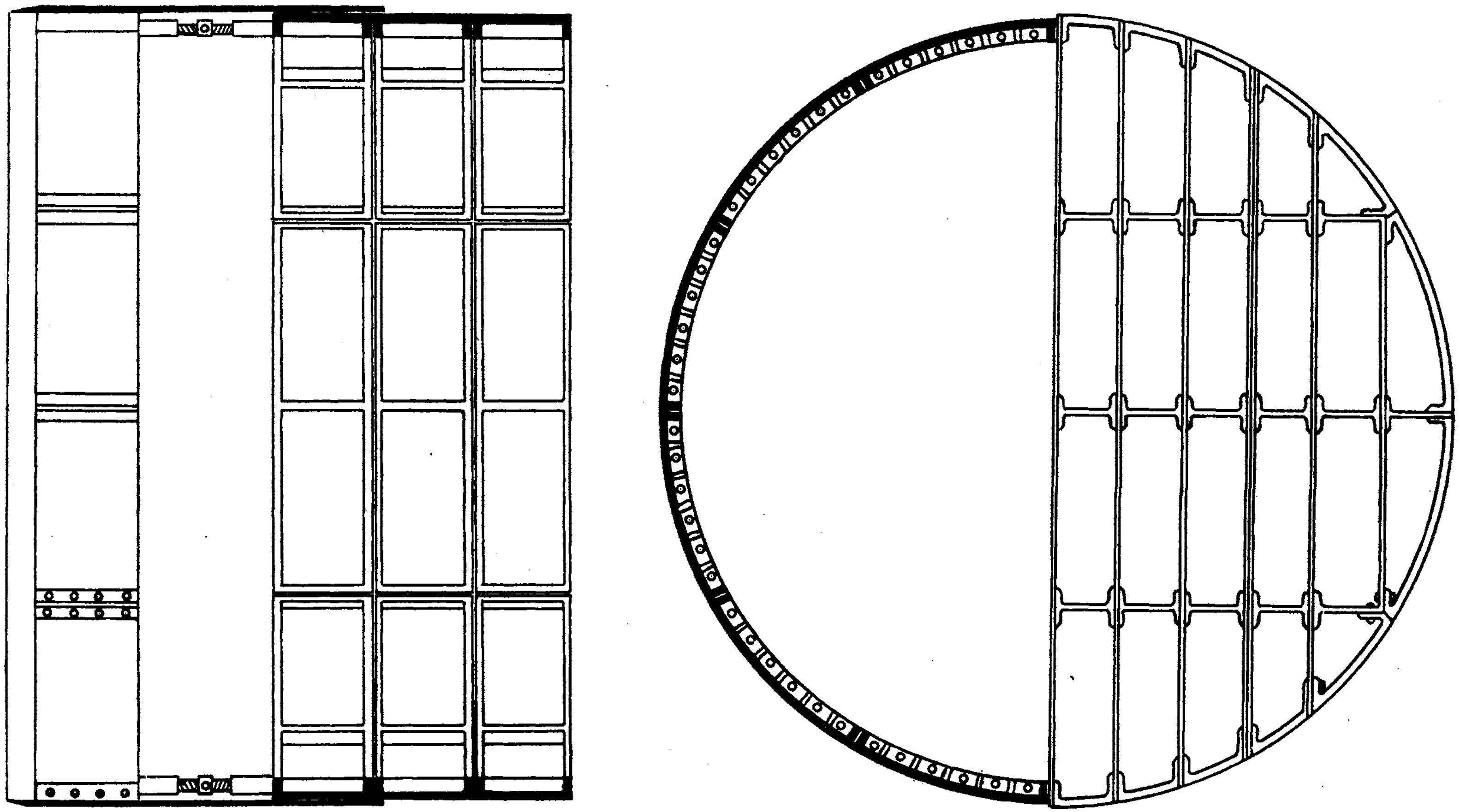


FIG. 6. BARLOW'S SHIELD.
From drawing attached to Specification of Patent No. 2207 of 1864.

main feature of which was the provision of a transverse partition or diaphragm having in its centre an opening capable of being closed at will. The object of this diaphragm which closed the tunnel above the level of the top of the door was to insure that in the event of an inrush of water, the air in the upper portion of the tunnel would be unable to escape, and an air chamber be formed in which the miners could remain until rescued (see Fig. 7).

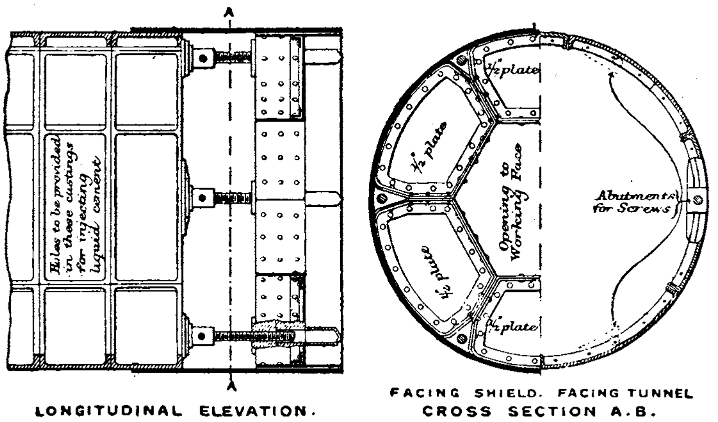


FIG. 7. BARLOW'S SHIELD.
From Provisional Patent taken out in 1868.

The main features of the two patents—namely (1) the cast-iron lining to the tunnel and grouting outside of it, (2) the cylindrical overlapping skin of the shield, (3) the use of screws or presses to move the shield forward, and (4) the transverse diaphragm of the 1868 invention, or the open rectangular frame of the earlier—have been reproduced in all shields used since, and in a sense Mr. Barlow's design must be considered as the type from which the Greathead and Beach shield are modelled. It is true that it was itself derived from the earlier invention of Brunel, but some of its arrangements, notably the transverse diaphragm, the movement in one piece, and the grout filling, are modifications of such importance as almost to constitute a new invention.

The Tower Subway

Mr. Barlow's designs, in the forms set forth in his patents, were never put into practical shape by him, and even the Tower Subway under the Thames, of which he was the original promoter, was built with a shield, of similar character indeed to his 1868 patent, but designed by Mr. Greathead.

This Subway is interesting historically, as being the first tunnel built of cast iron, with grout filling behind, and also as the first tunnel of any kind constructed with a shield movable in one piece. It is, in fact, the model on which all similar work carried out since has been designed.

Its successful construction was due entirely to Mr. Greathead, who took the contract for the entire scheme from the Company which had obtained powers from Parliament to construct it, devised himself the plant and equipment for the work, and personally superintended its execution.

It is constructed in its entire length in the London Clay, with a minimum cover under the river of 22 feet, and no difficulty was met with in carrying out the work, either in the tunnel itself or in the shafts, from water, nor from loose material.

The cast iron tunnel lining is shown in Fig. 8. Its external diameter is 7 feet 1¾ inches, and the thickness of the casting over all is 3 inches except at the horizontal flanges, which are 4 inches deep.

Each ring is 18 inches wide, and consists of three equal segments and a key piece.

The weight per yard forward is about 1 ton 6 cwt.

The shield (see Fig. 9) [1] consisted of a cylinder of iron plates ½ inch thick, and about 4 feet 9 inches long. It was made with a slight taper; that is, it was not a

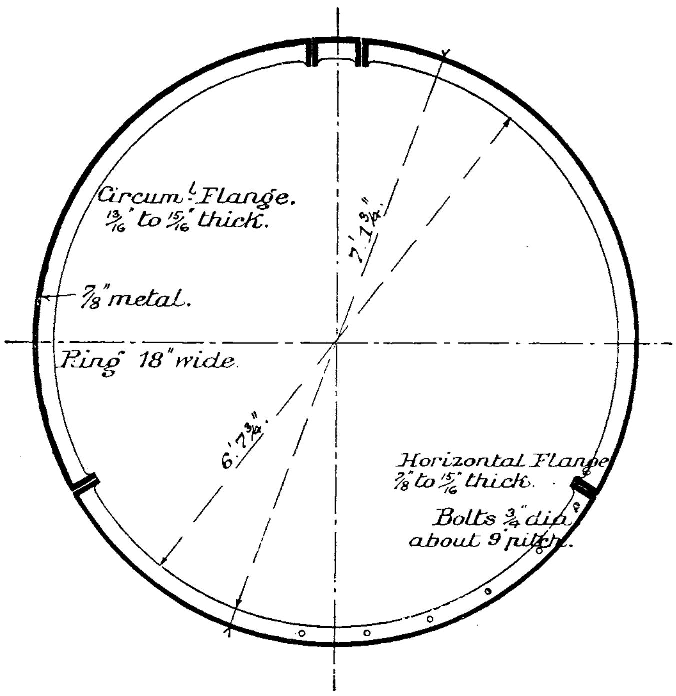


FIG. 8. TOWER SUBWAY UNDER THE THAMES.
Cast Iron Lining.

true cylinder, the diameter in front being slightly larger than at the back, with an idea of reducing the skin friction of the surrounding clay when the shield was in movement.

The front of this cylinder was stiffened by a cast-iron ring, bolted to it and made with a rounded edge forward, instead of the now usual acute, or cutting edge.

Behind this cast-iron ring was fixed a bulkhead, or diaphragm, of ¾ inch plates. having in it a doorway or opening, reaching nearly to the top of the shield, through which the miners could pass to the face. This doorway could be closed if necessary by dropping across it 3-inch planks, the ends of which could be held by the vertical channel irons forming the jambs.

[1] No detailed drawing of this, the earliest of the modern shields, exists. The figure is obtained from a sketch prepared in Mr. Greathead's office in 1895.

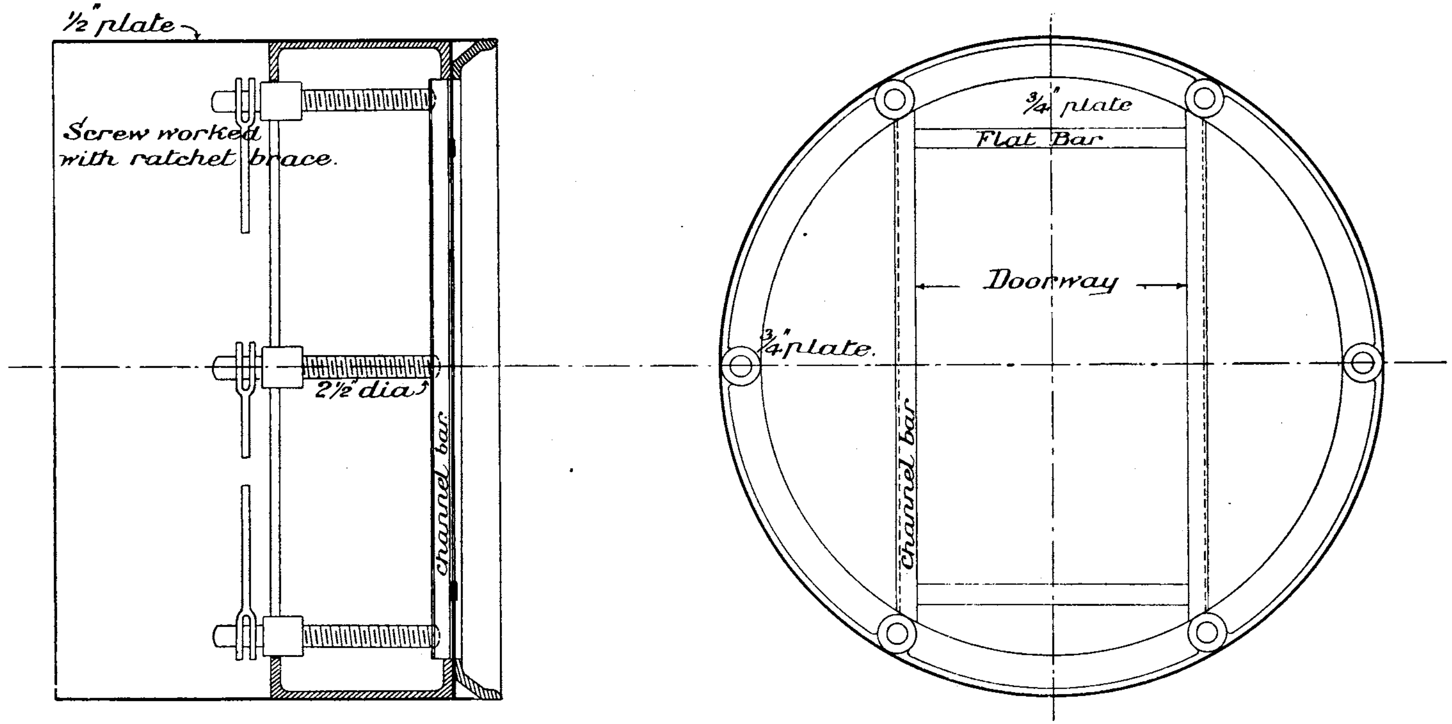


FIG. 9. THE TOWER SUBWAY UNDER THE THAMES.
Greathead Shield employed in its Construction.

Behind the diaphragm again were segmental castings forming a cast-iron internal stiffening ring, which gave solidity to the skin or envelope of the shield, and at the same time carried the screw jacks which propelled the shield.

These screw jacks were worked by ratchet braces, and bore on the last ring of the cast iron lining already built.

With this machine a maximum speed of 9 feet per day of twenty-four hours was attained.

The substitution of an opening reaching nearly to the top of the shield in place of the central opening proposed by Barlow in his patent of 1868 can hardly be regarded as an improvement. No doubt access to the face was easier, but on the other hand, the raising of the top of the doorway did away with the safety diaphragm above. With this shield, an inrush of water would at once have filled the tunnel to the soffit of the roof.

Subsequent works in the London Clay, however, have proved that there is practically no risk involved, this material being of so homogeneous a nature that little or no danger is to be apprehended from faults and a consequent inrush of water.

The use of hand-worked screw jacks in a tunnel of such small size is probably as economical as the employment of hydraulic or other rams, in view of the obstruction caused by pressure pipes and the like, and their greater liability to break down, or get damaged, in the conditions in which tunnelling works are carried on.

Indeed Mr. Greathead, as late as 1895, gave it as his opinion that for a tunnel in clay of similar size as the Thames Subway hand-worked screws had a decided advantage over hydraulic rams on the score of simplicity.

On the other hand, it is not easy to manipulate at the same time say three adjoining screws by hand, whereas it is perfectly easy, with hydraulic rams—properly connected—to move simultaneously, several or all at a time.

As stated above, cement grout was injected behind the iron lining of the tunnel by means of a hand syringe, but owing to the necessity of making the grout sufficiently fluid to pass through the syringe, and the limited amount of pressure that could be applied, the making of a complete envelope of cement round the tunnel was not satisfactorily accomplished.

The Broadway Tunnel

At the same time that the Tower Subway was projected by Barlow in England, a Mr. Beach in the United States was preparing a shield modelled on Barlow's design of 1864, for a pneumatic subway under Broadway. This subway, 8 feet in diameter, was driven through loose sandy soil, being lined with brick in cement.

The shield used is shown on Fig. 10, which is a longitudinal section of the machine. The frame of the shield is formed of a heavy timber ring *A*, fronted with a cast-iron cutting edge *D*, and having at the rear a wrought-iron forged ring *B*, to take and distribute the thrust of the rams *C*, *C*. Instead of a rectangular framing as in Barlow's shield, the face of the excavation is supported by iron shelves *E*, *E*, bevelled off on the front edge. To the rear end of the frame *A* is attached a flexible cylinder or tail of steel *G*, which overlaps the masonry of the tunnel already constructed.

The hydraulic rams *C*, *C*, are operated by a hand pump (not shown) with which they are connected by pressure pipes passing round the shield inside the frame *A*. These rams bear on the masonry of the tunnel already constructed, and their thrust behind is distributed by bearing blocks of wood *F*.

These were the first hydraulic rams used in a shield.

The shield worked in a satisfactory manner, the *modus operandi* being to drive the shield into the face of the material to be tunnelled (the total pressure obtained by the pump being about 120 tons), to the extent of the stroke of the pumps ; the shelves in the front, while they entered the face, serving to support it.

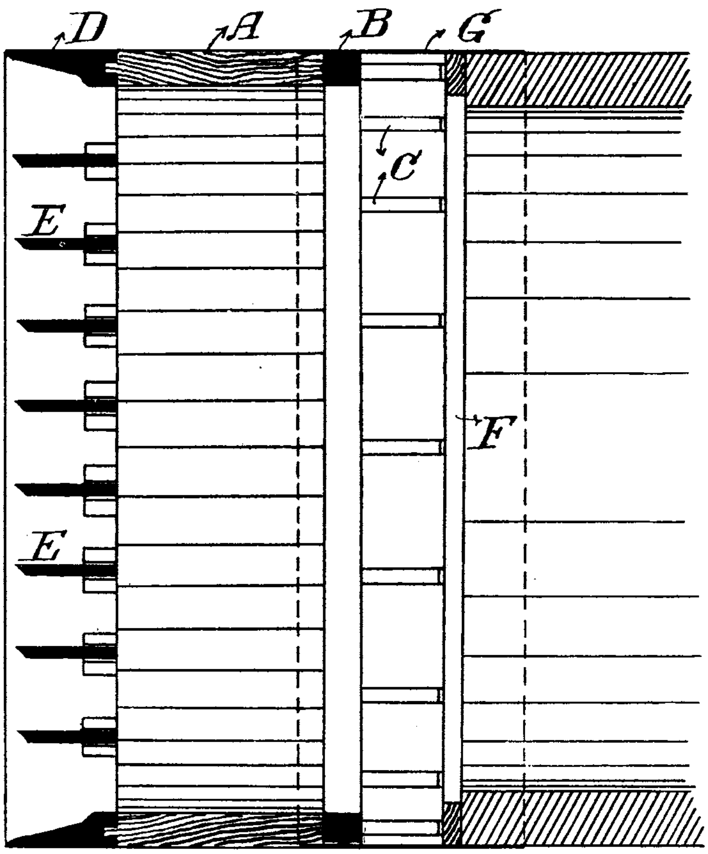


FIG. 10. BROADWAY SHIELD, NEW YORK.
Beach's Shield.

When the shield was driven forward as far as possible, the loose soil was removed from the shelves, at the same time that the permanent masonry lining was built up beneath the shelter of the tail plate of the shield.

The principal defect which the drawings of this shield show is a lack of vertical stiffening, there being no vertical plates similar to the horizontal shelves *E*, *E*. Later experience has shown that all shields unless very stiffly braced do, after a time, spread, so that the horizontal diameter increases while the vertical diminishes.

This work was carried out in 1869–70,[1] and in 1872 a similar machine was used in the construction of a subway in Cincinnati, another also in a short length of the lake tunnel at the same place, and a third at Cleveland, Ohio. The tunnel shield under the lake, however, was only used for a length of about 140 feet, where the material met with was " clay " of such fluidity that it ran in at the face faster than the permanent brickwork of the tunnel could be put in. Here, as has almost always in some degree been the case with a masonry tunnel built with a shield, the brickwork cracked owing to the advance of the shield allowing no time for setting. These cracks were made good by fixing cast iron rings or " tubbing " in segments round the inside of the brickwork where they occurred.

With the completion of these tunnels in England and America, the use of shields in similar work might have been expected to become general, but no further work was carried out in this manner until the City and South London Railway, with Mr. Greathead as engineer, was commenced in 1886, nor with one exception was similar work even projected before that year, and then by the same engineer.

The Woolwich Shield, 1876

In the year 1874 [2] the late Mr. Greathead designed and constructed for a proposed circular iron tunnel under the Thames at Woolwich a shield combining in one machine the water or fountain trap, more recently so successfully used, and the ordinary airlock.

For reasons unconnected with the engineering features of the tunnel, the shield though built was never used, and, an abortive attempt having been made to carry out the work in the usual manner and without compressed air, the whole project was abandoned.

The shield, although never put to the actual test of working, is interesting as being the first one built with a water seal, and also the first in which it was proposed to work by means of compressed air, thus anticipating by five years its actual use at Antwerp and at the Hudson River tunnel.

Fig. 11 gives a diagrammatic section of this shield.

The cutting edge is shown of considerable length, probably to afford as much protection as possible to the miners when the character of the ground might permit of work being carried on in front of the diaphragm. This latter *A*, extended over the upper half of the shield only, but behind this front diaphragm was placed another, *B*, which closed the shield completely, an airtight door *C* opening forwards being fixed in its upper half. Behind this diaphragm, which formed the front of it, was placed an airlock, having its outer door *D* also in the upper half of the shield.

Behind this airlock the skin of the shield extended sufficiently far to accommodate the hydraulic rams *E*, *E*, and to overlap the tunnel already completed.

The proposed method of working was apparently to keep the air in the space in front of the diaphragm *B* at the required pressure to dry the face and to allow the miners to work under cover of the projecting cutting edge, whence they could retreat under the front diaphragm in case of the face coming in. Mr. Greathead's (*Proc. Inst. C.E.*, vol. cxxiii. p. 66) design in making the water trap between the diaphragm *A* and *B* was of course to prevent the escape of any large volume of air

[1] It was opened to the public on February 26, 1870, see *Scientific American*, March 5, 1870.

[2] Mr. Greathead patented a shield for working in loose water-bearing strata, No. 173, of 1874.

in case of a "blow." As designed, however, it may be doubted whether even the smallest "blow," if sudden, would not have reduced the pressure to the normal before the trap came into action, owing to the smallness of the air chamber. It is essential for safe tunnelling in compressed air to have a large volume of air to draw upon in the event of a "blow" in the face.

If men were working between the two diaphragms with the front door of the airlock closed when a blow occurred, their chance of escape would be small, as the air pressure would almost certainly drop so rapidly that the water would rise nearly to the top of the shield and prevent the opening of the door in the diaphragm *B*.

A similar arrangement of locks was designed and made for the Blackwall shield, the idea being in that case to provide different air pressures in the different

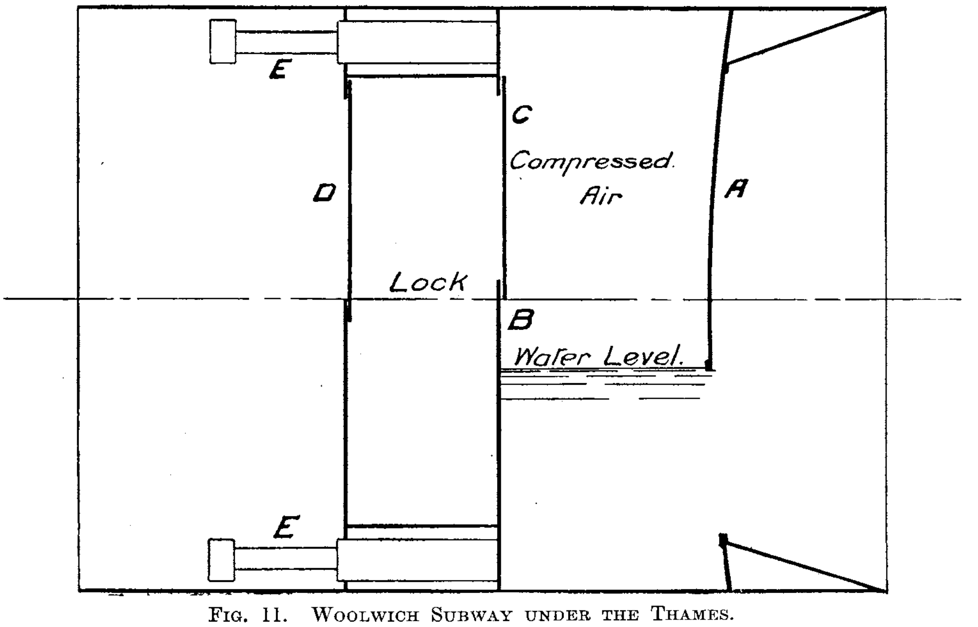


FIG. 11. WOOLWICH SUBWAY UNDER THE THAMES.
Shield designed by Greathead, but not used.

levels of the shield, but it was not used, nor so far as the author is aware have differential pressures in the same tunnel been tried anywhere.

As stated above, however, the shield, though built, was never used, and is only figured in this place as forming an interesting advance in the development of the simple Greathead shield into the more complicated machine for subaqueous work.[1]

Of equal interest is the mechanical erector designed by Mr. Greathead for this tunnel, and which has formed the model for subsequent machines (see Figs. 12 and 13).

Cast iron as a permanent tunnel lining was for the second time used at Antwerp in 1879, by Mr. Hersent, the contractor for the extensive dock works in the Scheldt. He used it in a small adit (Fig. 14) which, however, is only important because it was the first tunnel constructed under compressed air. The peculiar shape of the

[1] The first shield actually worked with a water seal or trap was that used in the tunnel under the Mersey in 1889 (see chapter vii.).

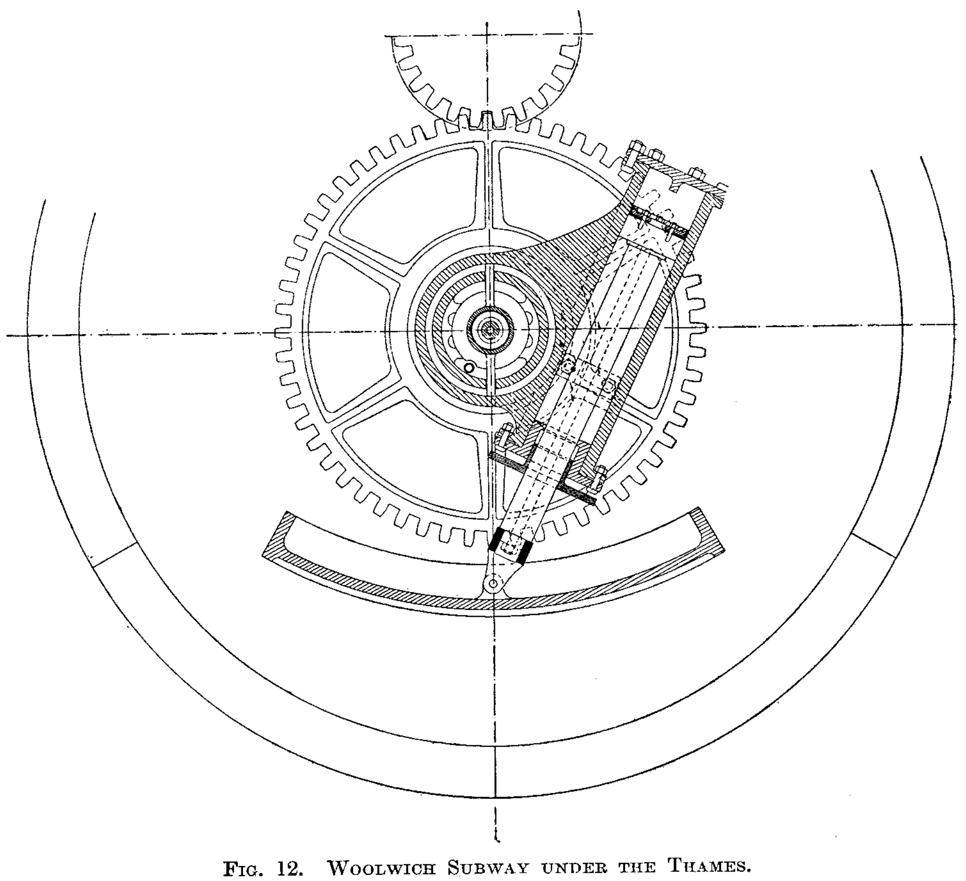


Fig. 12. Woolwich Subway under the Thames.
Mechanical Erector for putting the Cast-Iron Tunnel Segments in position. Sectional Elevation.

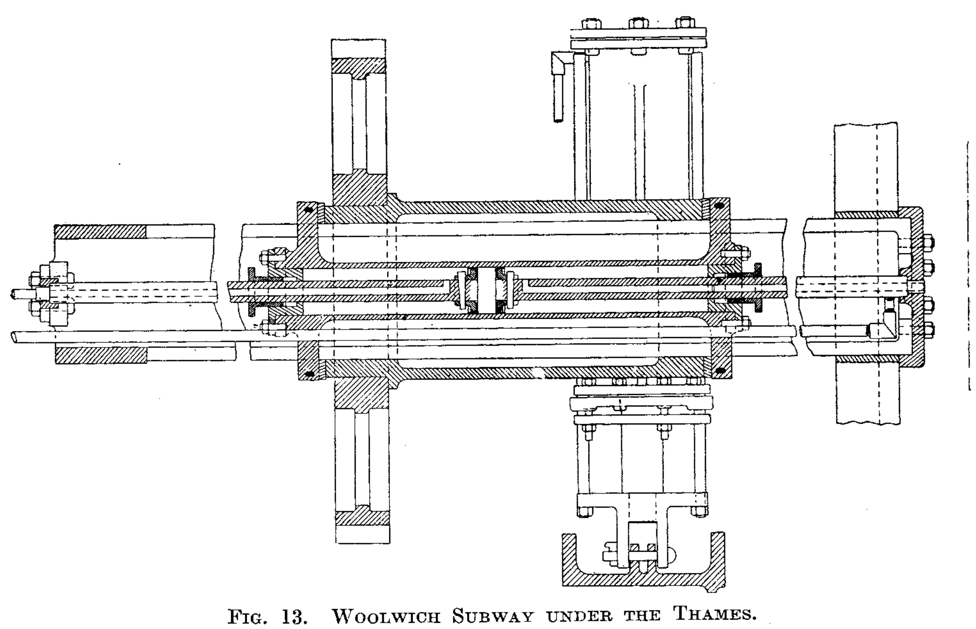


Fig. 13. Woolwich Subway under the Thames.
Mechanical Erector for putting the Cast-Iron Tunnel Segments in position. Sectional Plan.

tunnel suggests that Mr. Hersent was endeavouring to reproduce in cast metal the side trees and head trees of an ordinary miner's heading.

The joints are of a peculiar pattern, a groove being cut in the flanges of the joints, which are metal to metal, to receive a rope of tarred hemp, and this apparently formed the only caulking to the joint.

General Observations

In closing this introductory chapter, in which an outline of the first attempts at tunnelling under shield has been given, and before proceeding to describe modern shield work, which may be said to commence with the City and South London Railway, the first undertaking (for the Tower subway, like the Broadway tunnel, can be regarded as little more than an experiment) in which the new system was tried on a large scale: a few lines may be given to the consideration of the vexed question of priority of invention as among the several pioneers in modern shield work.

It is often the case that when the time is ripe for the effective use of a new idea, that idea occurs to several independent workers at the same time. The new necessity arises, a new departure is possible, and men whose professional studies have been in that direction, may, and do, arrive at very similar discoveries, in complete ignorance of others' work on the same lines.

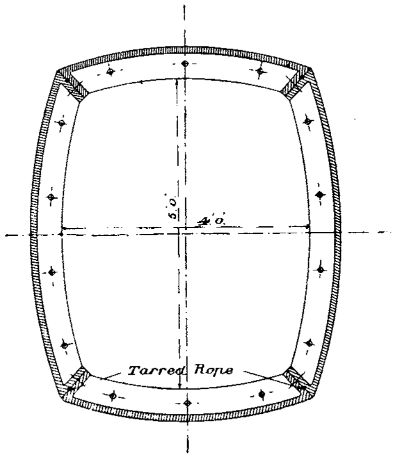


Fig. 14. Small Tunnel at Antwerp. Cross Section of Cast-Iron Lining.

It is hardly just to say that in such cases the original inventor is he whose name appears first in the lists of the Patent Office, even if his idea has not passed beyond the paper stage; still less is it fair to urge that others who subsequently have put into practice similar ideas, have necessarily borrowed from the first. Nor, when a new machine has been actually constructed and put to work, is it easy for the historian to determine how much of it is the original inventor's and how much the result of many minds working on his original idea.

There is no oblivion more complete than that which buries a patented invention [1] which for any reason remains untested by actual work, and consequently there is hardly any charge more difficult to substantiate against an inventor than that of conscious plagiarism, or, one may even say, one which in general it is more unfair to make, and this is exemplified in the case of the machines under consideration, for Greathead, though closely associated with Barlow, remained in ignorance for nearly thirty years of the latter's patent of 1868.

Three men, Barlow and Greathead in England, and Beach in America, were undoubtedly working independently at the shield problem in the late sixties (and very likely earlier).

[1] As for instance Morton's provisional patent of 1866, above quoted, which has remained unknown apparently until the author chanced upon it in search of information for purposes of this chapter.

Of these men, Barlow was certainly the first to patent, in 1864, a shield capable of motion in one piece, and surrounded by a thin cylinder of iron within which he proposed to build in successive rings a cast-iron tunnel, which tunnel he proposed to make solid by injecting grout, how he did not say, behind the cast-iron lining to fill the annular space left by the advance of the shield.

This was in 1864, and in 1868 he provisionally patented a shield having near the cutting edge a transverse partition or diaphragm.

Neither of these designs took practical form, and in 1869 Greathead in England and Beach in New York actually built and used shields having many features in common with Barlow's patents but differing from each other in details.

Speaking generally, Beach's shield resembled the Barlow patent of 1864, and Greathead's the provisional patent of 1868.

Beach states that he first designed his shield in 1865, and that he in 1868 actually constructed and tried an experimental model 3 feet in diameter. He does not appear to have been aware of the existence of Barlow's shield, though the Tower Subway shield, which was Greathead's, not Barlow's, was known to him.

That Greathead, whose shield was first used in the Tower Subway by him acting as contractor under Barlow, knew of the first Barlow patent is certain, but there is on record his own statement that until the fact was mentioned in the discussion at the Institution of Civil Engineers on his paper on the "City and South London Railway" in 1895 [1] he was unaware of the existence of Barlow's provisional patent of 1868, which his own shield most resembles.

That in the construction of the Tower Subway, a shield of the Greathead model and not the original Barlow design was employed, would indicate either that Mr. Barlow considered the Greathead shield as constructed an advance on his own, or else, as is probable was the case, that the whole direction and management of the new system of tunnelling was in the hands of Mr. Greathead.

The exact apportionment of the credit of the invention between these two men will be decided by each reader according as he may consider the original inventor of a new mechanism, or the man who applies it to practical use, the more deserving of credit.

It has been said above that the idea of the modern shield was first published by Barlow in 1864, and that the first shields actually used in tunnel work were employed practically simultaneously by Greathead in England and Beach in New York in 1869, and so far it is an arguable point to whom credit should be ascribed for initiating a new departure in tunnel work. But in the subsequent development of the shield system of tunnelling the part taken by Mr. Greathead [2] has connected

[1] *Proc. Inst. C.E.*, vol. cxxiii. p. 110.

[2] James Henry Greathead, the engineer to whose energy and perseverance the tunnelling system described in this book is mainly due, was born in South Africa in 1844, and died in London in 1896.

His successful construction of the Tower Subway, when as contractor he carried out the work for Mr. Barlow, when only in his twenty-sixth year, apparently determined the direction of his professional energies: and in the years between the completion of that work and the commencement of the City and South London Railway scheme in 1884, he designed and patented various appliances for tunnelling in water-bearing strata (Patents No. 1738 of 1874, and 5665 of 1884), and later in 1886 he patented also (No. 5221 of 1886), his system of grouting by means of compressed air, which perhaps more than any other invention has proved indispensable in all recent tunnel work. In 1874 he designed and constructed for a proposed tunnel under the Thames at Woolwich (which for reasons unconnected with the engineering features of the work was never made), a shield embodying the main features of the now well known trap his name more than that of any other man with this branch of engineering, which, next to the construction of large span bridges, is the distinctive feature of constructive engineering in the last twenty years of the nineteenth century.

or water-seal shields (see Fig. 11), and designed also an hydraulic erector which is the original of the numerous segment erectors which have been made since (see Figs. 12 and 13).

In 1884 he became associated with the City and South London Railway, or as it was then styled, the City and Southwark Subway, on which his system of shield tunnel was for the first time employed on a large scale. The satisfactory completion of this work established him in the first rank of his profession, and from that time onward to his death he was employed either as engineer or as consulting engineer in every important tunnel work.

The Hudson Tunnel, the Blackwall Tunnel, the Waterloo and City, and the Central London Railways are among the tunnels with which he was connected, while among other works with which he was connected at the time of his death was the Liverpool Overhead Railway, of which he was joint engineer with Sir Douglas Fox.

His professional qualities can be estimated from the above bare statement of the undertakings he assisted in: his personal qualities gained him the esteem of all who had dealings with him, while his unvarying kindness and consideration secured him the warm regard of those who like the author had the good fortune to work under him.

Chapter II

THE USE OF COMPRESSED AIR IN ENGINEERING WORK: ITS EARLY HISTORY: AND SOME NOTES ON CAISSON SICKNESS

COCHRANE'S PATENT, 1830—DESCRIPTION OF AN ORDINARY AIRLOCK—COMPRESSED AIR USED AT CHALONNES, FRANCE, 1839—AND AT DOUCHY, FRANCE, 1846—POTTS' VACUUM SYSTEM, 1850—ROCHESTER BRIDGE, 1851—ANTWERP TUNNEL, 1879—HUDSON RIVER TUNNEL, 1879—JAMINET'S NOTES ON ST. LOUIS BRIDGE, 1868—BROOKLYN BRIDGE, 1871—SMITH'S PROPOSAL FOR A MEDICAL LOCK, 1871—MOIR'S LOCK AT HUDSON TUNNEL, 1879—CAISSON SICKNESS—CONDITIONS OF WORK IN COMPRESSED AIR—REGULATIONS FOR CONTROLLING MEN—EFFECT OF IMPURE AIR—CLAUSES OF SPECIFICATION REGULATING WORK IN COMPRESSED AIR—EXPERIMENT IN PURIFYING AIR

Historical Notes on the Use of Compressed Air in Engineering Works [1]

THE fact that by means of diving bells it is possible for human beings to work in, and remain for some time under water in an atmosphere the pressure of which exceeded the normal by the weight of the water above it was known in the early years of the sixteenth century, and some use was made of the system; but the absence of any mechanism for renewing the air prevented any prolonged immersion, as the bell or working chamber had necessarily to be brought to the surface at short intervals on account of the vitiation of the atmosphere.

In 1664, a Dr. Henshaw, an Englishman, proposed to treat certain diseases by immersing the patient in an atmosphere artificially compressed, or exhausted, in an hermetically sealed chamber, the pressure in which could be regulated by means of bellows.

Nothing is known of any practical trial of this system until many years after, but in 1830–40 a compressed air treatment for pulmonary diseases was practised in France.[2]

These "air-baths," as they were called, were not used at high pressure; about 10 pounds per square inch above the normal being the maximum: or say two-thirds of an atmosphere.

In 1721 Dr. Halley described to the Royal Society an arrangement he had made whereby fresh air could be supplied to diving bells by means of weighted

[1] Much useful information on the medical aspects of compressed air work is contained in:—

A. H. Smith's *Compressed Air*, Detroit, U.S.A., 1886.
Jaminet's *Physical Effects of Compressed Air*, St. Louis, U.S.A., 1871.
E. H. Snell's *Compressed Air Illness*, London, 1896.
Paul Bert's *La Pression Barométrique*, Paris, 1878.
Macmorran's *Notes on Caisson Disease* (privately printed), London, 1901.

[2] *Académie des Sciences*, vol. xiii., contains Mr. Triger's "Memoirs sur un Appareil à air comprimé."

barrels, which enabled the workmen employed in them to remain under water for long periods, but it was not until 1778 that the famous Smeaton, in repairing the foundations of the bridge over the River Tyne at Hexham, used for the first time a pump for injecting fresh air into the diving bell or box employed there.

In 1820 in connexion with some submarine work at Howth, near Dublin, a Russian physician named Hamel made some observations on the effect of compressed air not only on the workmen, but on himself.

He described his sensations on going down in a diving bell, and apparently was more fortunate than most people are, for he states that "at 15 or 16 feet (deep) or about with 7 pounds pressure there was a noise in the ears like an explosion, followed by entire relief from the pain"[1] experienced in first going down. He makes the remark that one of the workmen became so accustomed to the air of the bell as to be uncomfortable under the usual atmospheric pressure.

In 1826 Dr. Colladon also published some observations on the same subject, and he is said to have recommended to Brunel, two years later, the use of compressed air in his Thames Tunnel undertaking, not only as a source of mechanical power, but also for holding up the working face.

It was in 1830, however, that the first complete scheme of mining in subaqueous or in water-bearing material by the aid of compressed air was put forward, all previous engineering applications of the system having been in open water only. In that year, Sir Thomas Cochrane, known by the courtesy title of Lord Cochrane, took out a patent (No. 6018 of 1830) for the employment of compressed air in shafts and tunnels in water-bearing material, for the purpose of expelling the water from, and holding up the face of, the excavation, and the wording of this patent covers all the essential features of compressed air work as developed since.

Up to his time, the various compressed air appliances in use do not appear to have been provided with any arrangement for easy ingress to and egress from the compressed air chamber, of workmen and material.

As the use of the airlock, as set forth in his patent, has always been a feature of later work, its main features may well be described in this place.

Since the employment of compressed air in mining work necessitates the working chamber whether that be a shaft, caisson, or tunnel, being practically airtight, except at the face where the mining work is to be done, it is impossible to have a working door giving direct access to the chamber.

The difficulty is got over by placing a small chamber or "lock," as it is called, between the pressure chamber and the open air. This lock is built into the wall closing the pressure chamber and is provided with two doors, the one opening inward into the compressed air space, the other also opening inwards, giving access to the lock from the open air.

When the working chamber is filled with compressed air by means of pumps the inner door of the lock is of course kept shut by the pressure, and access to it from outside is gained by entering the lock and, having shut the outer door, opening a valve controlling a pipe connexion of small diameter between the lock and the working chamber. This allows the air from the latter to enter the lock until the pressure in the lock is equal to that in the working chamber, which is then entered by the inner door of the lock.

The open air is reached from the working chamber by reversing this process ;

[1] Smith's *Compressed Air*, p. 3.

the outer wall of the lock being provided with a pipe by which the compressed air in the lock can, the inner door being shut, be allowed to escape into the open air, when the outer door can be opened.

In actual work the airlock takes a variety of forms, which will be noticed later, but the airlock and bulkhead shown in Figs. 15 and 16 embody the main features of all the locks used in horizontal tunnelling work, and will serve as an example to explain the general principles on which all locks are built.

In this case, a large brick sewer had been constructed by ordinary cut and cover methods to within a few feet of a water way, under which, at a depth of some

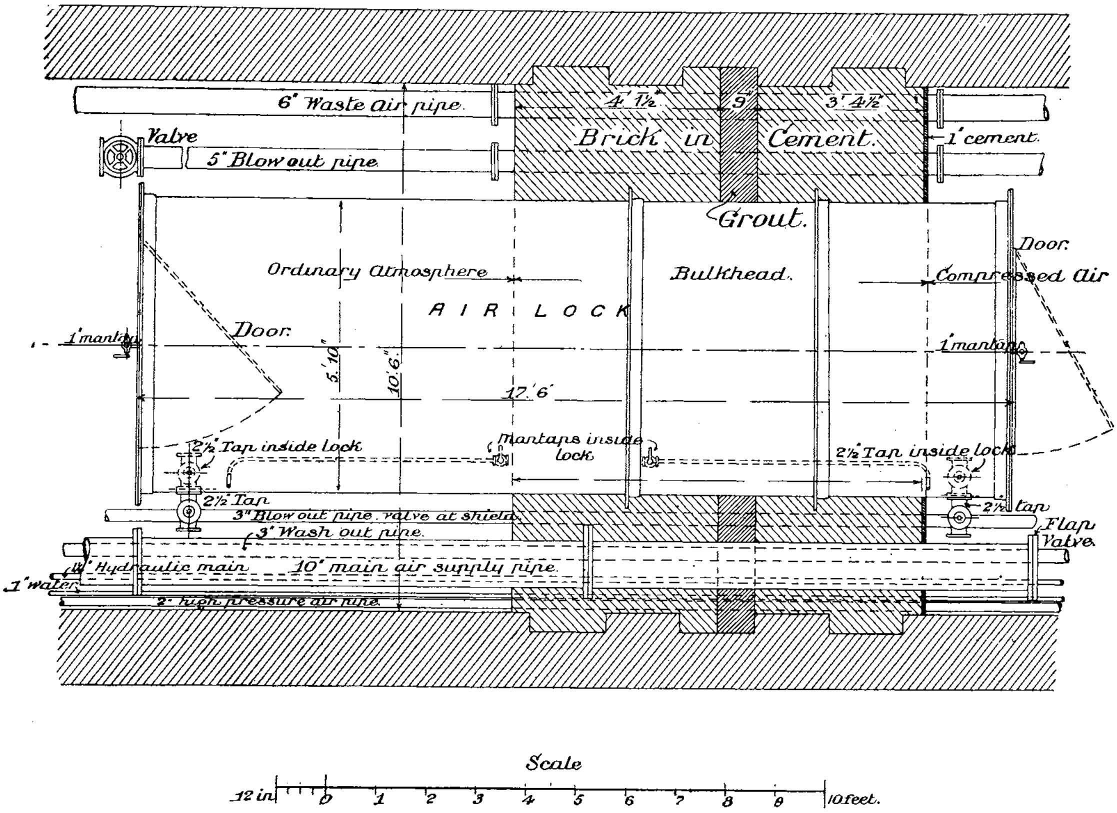


FIG 15. TYPICAL AIRLOCK FOR TUNNEL WORK.
Sectional Plan of Lock and Bulkhead used in the Lea Tunnel, London, 1901.

10 feet below the bed of the stream, it had to pass, and through material known to be water-logged.

It was resolved to carry out the work by shield and compressed air, and to do this the bulkhead shown in the figures was constructed in the sewer already built at some little distance back from the end of the completed length. The bulkhead to close up the tunnel had to be sufficiently strong to resist a possible pressure of 20 pounds to the square inch on its inner side, and of course to be absolutely airtight. It was bonded into the brick sewer already built, by cutting in the latter chases 18 inches wide into which the new brickwork was keyed. The wall was in all 8 feet 3 inches thick, a 9-inch space being left between two brick walls, into which grout was forced under pressure through the grouting pipes shown in Fig. 16. A rendering of neat cement 1 inch thick on the inside wall of the bulkhead assisted in making it airtight.

Into this bulkhead was built a cylindrical airlock of steel plates ½ inch thick, 17 feet 6 inches long, and 5 feet 10 inches in diameter, so placed that its excess length over and above the thickness of the wall projected from the latter on the outside, or ordinary atmosphere side. The reason of this was, that the position

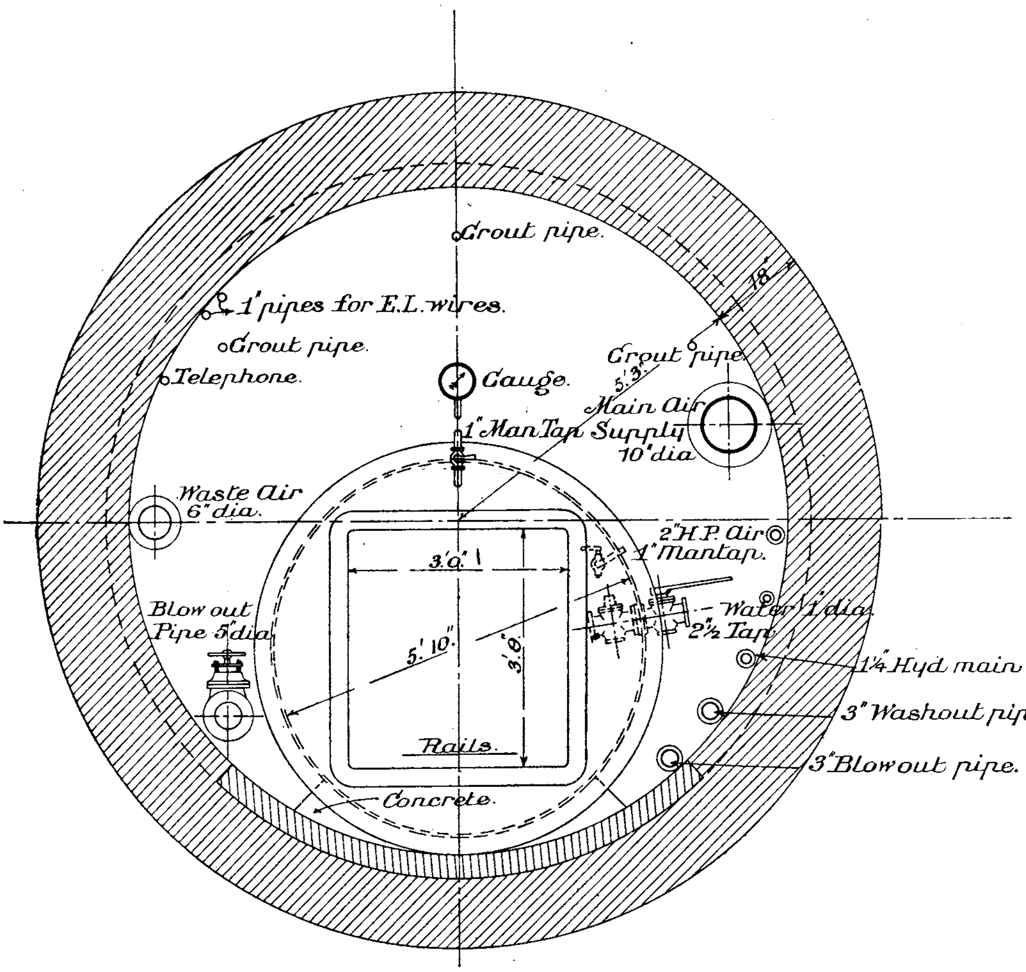


FIG. 16. TYPICAL AIRLOCK FOR TUNNEL WORK.
End Elevation of Airlock and Bulkhead used in the Lea Tunnel, London, 1901.

ensured the outside portion of the lock being subjected to tensile strain only from the air pressure.

At either end of the lock is a door opening inwards, that is towards the pressure chamber. These doors were fitted accurately to their frames, the bearing surfaces being provided with rubber strips to ensure an airtight fit.

The lock was fitted with four "mantaps" 1 inch in diameter, for regulating the supply of air to the lock. Two of these were outside the lock, over the doors and could only be manipulated from the pressure chamber or from the outside respectively.

The other two were within the lock, and like the others controlled pipes communicating with the two sides of the bulkhead, the taps being brought together for convenience of handling by one man within the lock.

Four larger taps, $2\frac{1}{2}$ inches in diameter, known as "muck-taps," were also provided, and could be worked either from within or without the lock. These filled and emptied the lock much more rapidly than did the others, and were used for passing material through it.

A pipe, 10 inches in diameter, was provided through the bulkhead for the supply of air to the compressed air chamber. This pipe conducted the air from the compressors through the bulkhead, and had on its inner end a flap valve, so that in the event of the pipe being broken outside, the pressure in the chamber would not be lost by the air escaping back through the pipe.

A waste air pipe 5 inches in diameter was provided to allow of air being drawn off from the pressure chamber, in the event of the working face proving so solid as to necessitate, for reasons of hygiene, changing the air in which the miners were working.

The above form all the essential features of a bulkhead and airlock, which compressed air demands, but there are of course many auxiliary fittings connected with the general tunnel work which are also provided when a bulkhead is put up. Such are, as in the figure under consideration, hydraulic pipes for working the shield, blow-out pipes for removing water from the invert, air pipe for grouting, pipes for electric light wires, etc.

It may be observed here that all service pipes, of whatever nature, inserted in the bulkhead, should be of a diameter to meet every possible contingency which may arise. The extra cost of placing, in the first instance, a somewhat larger pipe than the probable conditions of the work may require is small, and is good insurance against the cost of making an enlargement later.

In Cochrane's patent he provides first for an airlock for shaft sinking, and goes on to say that, the shaft being sunk, one or more locks may be provided in the heading or tunnel driven from it, so that the men only who are working at the face of the excavation, may have to endure the maximum pressure required to keep back the water there, and the remaining operations in the rear carried out under a less pressure.

This idea of differential pressures is not now used : it was, however, a feature of the Blackwall Footway Tunnel as proposed in 1888, and the shield actually constructed for the tunnel at the same place in 1891 was made with locks and chambers in which different pressures could be maintained to suit their different levels ; or to keep the pressure of the work chamber in front higher than that in the tunnel behind.

Cochrane's specification is accompanied by sketches of an airlock, and a sectional elevation of a shaft and tunnel in course of construction by his compressed air method (see Figs. 17 and 18).

His drawing shows also a proposed method of conveying spoil from the compressed air workings underground to the normal atmosphere at the surface by means of a water column, and a bucket and chain dredger.

This has not been used in any work to the author's knowledge : the earliest shafts or caissons sunk by means of compressed air having the locks for ingress and egress so arranged that material and spoil can be passed through them.

Mr. Greathead makes the remark that Cochrane does not appear to have considered the other necessary appliances for tunnelling in loose water-bearing strata which are almost as necessary as the airlock ; indeed, he suggests that the inventor did not contemplate the use of compressed air in tunnels except in materials impervious, or nearly impervious, to water.[1] The wording of the specification hardly justifies this assumption, and perhaps the best explanation of the absence of any reference to the necessity of additional appliances for supporting the face is that it did not occur to Cochrane that air pressure alone would not hold up the face, the head of water being less at the crown of a tunnel than at the invert, and that consequently the pressure which would sustain the face at the one level would not balance the water pressure at the other.

How to do this, however, is a problem the satisfactory solution of which is still wanted.

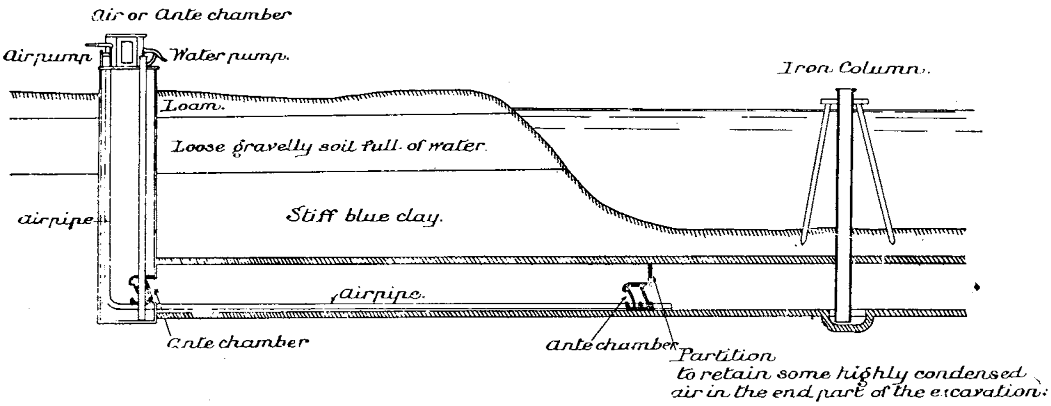


Fig. 17. Cochrane's System of Tunnelling by Compressed Air.
From drawing attached to Specification of Patent No. 6018 of 1830.

It is interesting to note in view of the common practice of to-day in sinking shafts and caissons that Sir T. Cochrane distinctly states in his specification that "in case the column (or shaft) should not prove heavy enough to sink by its own weight when filled with compressed air the workmen may come out from the shaft, and then let the compressed air from it in order that it may sink by means of its own weight : the upward pressure being thus removed."

The system proposed by Lord Cochrane in 1830 was not, however, put to actual use until 1839, when a French engineer, M. Triger, employed it to sink a pit shaft at Chalonnes on the Loire, through the geologically recent water-bearing strata forming the valley of that river to reach the coal-bearing strata below, which previously had been considered inaccessible for mining purposes.

M. Triger gives[2] in his communication describing the operations to the Académie des Sciences, which paper is the authority for the facts given below, but little detail as to the actual carrying out of the work beyond stating that having sunk the tube or shaft, which was some 3 feet 4 inches in diameter, to a depth of

[1] *Proc. Inst. C.E.*, vol. cxxiii. p. 58.

[2] *Académie des Sciences*, 1841, vol. xiii. "Mémoire sur un Appareil à air comprimé." This is a very interesting and lively description of compressed air work of the time. Some of it is quoted in *Proc. Inst. C.E.*, vol. x. p. 361.

about 60 feet, no further progress could be made by loading it, or striking it with a pile driver, but that by the use of compressed air he was enabled to sink the tube completely through the water-bearing strata, and enter the impervious clay beds below them.

The pressure employed seems to have reached two atmospheres above the normal, and the mechanical arrangements resembled in essentials those described in Cochrane's specification and still in use to-day.

The lock used was provided with the usual doors and valves for ingress and egress ; it had also a pressure gauge, and what is more remarkable, a safety gauge. Through the lock passed an air-supply main, and a "blow-out" pipe, the latter being extended into the water at the bottom of the tube "to facilitate the exit of the water, when as a result of the air pressure, this water must be forced out with more rapidity than the leaks between the bottom of the pipe and the ground would allow of."

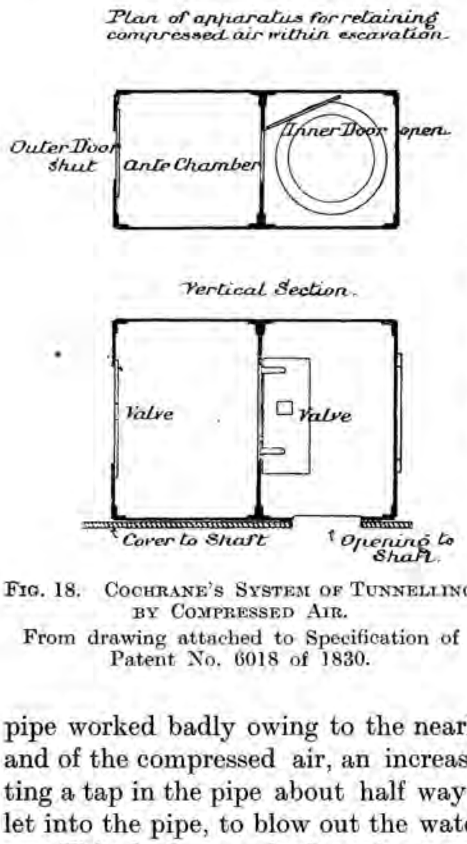


FIG. 18. COCHRANE'S SYSTEM OF TUNNELLING BY COMPRESSED AIR.
From drawing attached to Specification of Patent No. 6018 of 1830.

The pumps and engine for the supply of air were of a make-shift character, but no difficulty seems to have been experienced in maintaining the pressure required.

M. Triger records indeed several "blows," or escapes of air caused by the pressure of air within the tube being in excess of the hydrostatic head, and from his observation of the ebullition produced in the surrounding water (for the shaft was apparently in the river itself) and of the periodicity of the "blows" he deduces a theory as to the causes of the eruptions of the geysers in Iceland—a curiously ingenious suggestion.

Another point noted by M. Triger was that when the excavation of the shaft was at such a depth that the necessary pressure of air could barely be maintained, and when consequently the vertical "blow-out" pipe worked badly owing to the nearly equal pressure of the column of water in it, and of the compressed air, an increased discharge of water could be got by putting a tap in the pipe about half way up, through which compressed air could be let into the pipe, to blow out the water above it.

This device, used often since, was suggested by the results of an accidental blow from a miner's pick which knocked a hole in the "blow-out" pipe.

The explanation given by M. Triger of the effect of such a hole, namely that the mixture of air and water so produced made a mixture of less specific gravity than water alone, is hardly satisfactory.

The real explanation is that an opening having been made in the blow out pipe at a level where the head of water is one-half of that for which the air pressure at the time is adjusted, the air naturally forces out the water, and in doing so acts somewhat in the manner of an injector, and assists in drawing up the column of water in the lower portion of the blow-out pipe.

The effect of compressed air on those entering it is described at some length by M. Triger, in general with great accuracy—and accuracy perhaps the less remarkable as the work carried out at Chalonnes was the first opportunity for observing the effect of continued pressure on numerous persons at the same time, and under similar circumstances.

The sensation of pain in the ears on changing pressure : the necessity for taking a longer period in entering the pressure chamber than in leaving it : the increased rapidity of combustion, and increase of temperature with increase of pressure : the condensation of the moisture in the atmosphere when the pressure drops : the comparative ease with which a man can climb a ladder, and the impossibility of his whistling, under pressure ; are all set forth for the first time, with vivacity and detail : and though some of the statements may require qualification, the description of the objective features of compressed air work is singularly clear and complete.

Later in 1845 M. Triger addressed a letter to Mr. Arago, which was read at the Académie des Sciences,[1] to the effect that the shaft sunk in 1841 was still perfectly sound and that another similar one was in hand.

This letter concludes by recommending the use of compressed air in tunnel construction.

In 1846 a M. Blavier in a communication printed in the *Annales des Mines*[2] describes some operations similar to those carried out by M. Triger, from which in fact, they were copied, at Douchy in North-East France.

A shaft was satisfactorily sunk there by means of compressed air, and M. Blavier records that a pressure of two atmospheres above the normal was employed.

Compressed air sickness (as distinguished from the inconveniences felt in entering and leaving the pressure chamber) was noted there, and was said to be cured, even after lasting some hours, by rubbing the affected part with alcohol.

As a result of the experience gained at Douchy, M. Blavier ventured the opinion that a depth of about 64 feet below water level was the limit of possible working.

Neither M. Triger nor M. Blavier appear to have had their attention drawn to the share that length of immersion has in producing sickness, except that M. Triger notes briefly that two men, after seven hours' continuous work in the shaft, experienced severe pains in the arms and knees, coming on in about half an hour after coming out of the pressure chamber.

But at Douchy a M. Pol, apparently describing the same work on which M. Blavier was engaged, goes into some detail as to the effect of compressed air on the health of the men employed, and among other conclusions drawn from his experience, states that re-immersion is the quickest and safest means of restoration of a man affected by " bends " as the pains in the joints caused by compressed air are called.

About this period was tried in England and in Ireland a method of shaft sinking by exhausting the air[3] in the cylinder or shaft to be sunk, known as Dr. Pott's vacuum system. Although not strictly a part of the history of compressed air work, this process for a short time was a rival to the ordinary one, and should therefore be briefly described.

[1] *Académie des Sciences*, 1845, vol. xx. pp. 444–449.
[2] *Annales des Mines*, vol. ix. p. 349.
[3] *Proc. Inst. C.E.*, vol. x. pp. 356–366–367.

The manner of sinking a shaft by Pott's method consisted in attaching to the top of the cylinder to be sunk by an airtight joint, a box or lock which for some reason was known as the " doctor," provided with two doors, the one communicating with the shaft the other with the open air. When the doors were closed an exhaust pump outside the " doctor " was set to work, and the air in the " doctor " exhausted as far as possible. Then by means of a valve controlled from outside a pipe connecting the doctor with the inside of the shaft was opened, and the inrush of air into the empty doctor created a partial vacuum in the shaft. This had the effect of drawing in the soil at the bottom of the shaft, and so permitting it to sink.

The system was tried in 1850 by Mr. W. H. Hemans at a bridge over the Shannon, but was abandoned after three cylinders of 10 feet diameter had been sunk ; the expense being too great, and the rate of progress unsatisfactory.

It was also tried at Rochester [1] in 1851, but pronounced impracticable, and indeed it is not easy to see how it could succeed except in perfectly uniform fine gravel or silt. If boulders were met with the suction of the air could hardly be effective.

The system, however, appears to have been dropped altogether about 1851.

In England the first large work carried out by means of compressed air was the Chepstow Viaduct [2] (1843–1851), the foundations of which were built under a head of water of 70 feet. But the best description of compressed air work while the system was still in the experimental stage is to be found in Mr. Hughes' account of the rebuilding of Rochester Bridge.[3]

The Rochester Bridge

In 1851 the then existing bridge over the Medway connecting Rochester and Strood having become inadequate to accommodate the increased traffic the construction of a new one was intrusted to Mr. Cubitt, whose design included the placing of the abutments and piers of the bridge on cylindrical piles of cast iron filled with concrete and brickwork, and capped by cast-iron bed plates on which the masonry piers were to be built.

Each pier was supported on fourteen piles or cylinders, 7 feet in diameter, and going down from 40 to 60 feet below mean high water : the piles ultimately resting on the chalk, the beds passed through in sinking consisting of soft clay, sand, and gravel, all water-bearing.

It was originally intended to sink the cylinders by means of Dr. Pott's vacuum system above referred to, and the apparatus was actually installed at the pier nearest to Strood, but it was found impossible to sink the piles by such means through a thick bed of rubble met with, which had formed part of the foundations of an earlier stone bridge.

The vacuum method was therefore abandoned, and the use of compressed air, which it was in the knowledge of the engineers concerned had proved successful at Chalonnes, was resolved on.

The general arrangements for the cylinder sinking were as follows : at each pier, or abutment, a timber stage was erected large enough to afford a working platform around the piles, and provide room for machinery, etc. The cylinders

[1] *Proc. Inst. C.E.*, vol. x. pp. 356, 367. [2] Ibid. p. 367, footnote.

[3] Ibid. p. 353, Hughes " On the Pneumatic Method adopted in Constructing the Foundations of the New Bridge across the Medway at Rochester."

were then sunk as far as possible by gravity, and pitched in their proper positions, a sufficient number of the 9 feet lengths of which each cylinder was composed being built together to bring the top well above water level. This done, to the top flange of the uppermost casting was fixed a wrought-iron plate through which passed

Fig.1.

SECTIONAL ELEVATION

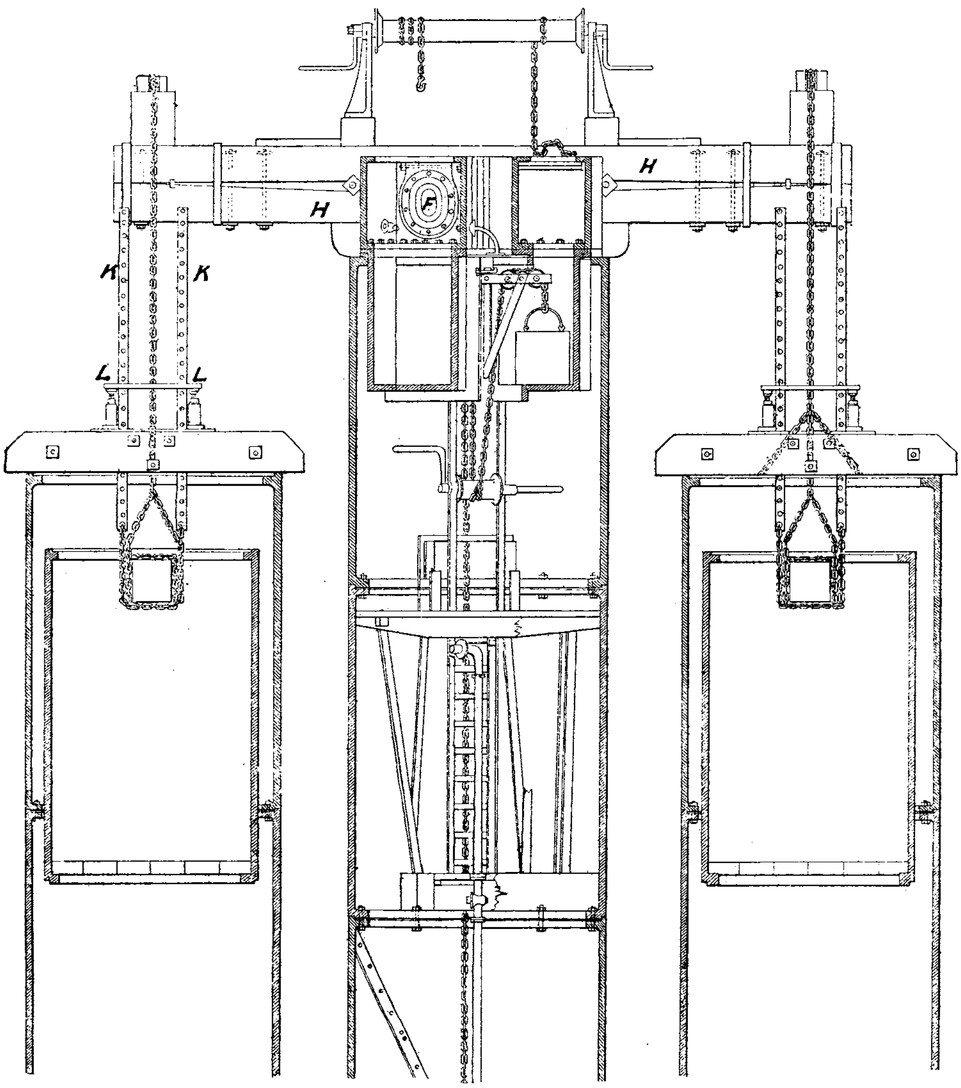


FIG. 19. ROCHESTER BRIDGE, KENT, 1851.
Method of Sinking Cylinders under Compressed Air. Sectional Elevation of Cylinder fitted with Airlock.

"two cast-iron chambers which may appropriately be called airlocks" (the first time this name was applied to them).

These chambers, marked *E E* in Figs. 20 and 21, were over 6 feet in depth and **D**-shaped in plan and provided with doors *F F* in the top and on the flat vertical face for communicating respectively with the outer air and the cylinder below.

The arrangement of the doors by which two airlocks of sufficient size are put on one cylinder only 7 feet in diameter, and so arranged that they can be worked simultaneously with the minimum of obstruction, is very neat, the airlocks being arranged so that their flat vertical sides are on the same diameter of the cylinder but facing in opposite directions.

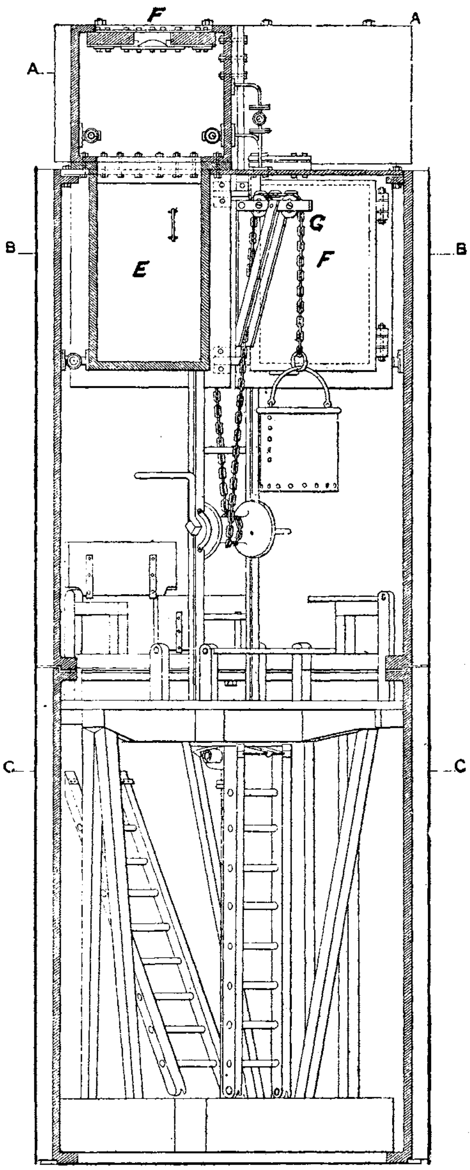


Fig. 20. Rochester Bridge, Kent, 1851. Sectional Elevation of Cylinder on line *D D*, Fig. 21.

Within the cylinder and on a level with the lower doors of the airlocks were fixed two small cranes *G G*, one for each airlock, the jib of each one having a sweep over one-half the area of the cylinder, so that when the lower door of the corresponding airlock is opened, the loaded buckets of excavation brought up by the crane can be swung into the locks. This arrangement of cranes would hardly be satisfactory with the large skips or buckets now in use, but no doubt it answered satisfactorily with the small buckets shown on the drawing.

A double set of valves were provided, the one for the use of men passing through the airlock and the other to enable the men in the cylinder, or the banksman outside, to operate the lock in order to pass material through without entering the lock itself.

The "blow-out" pipe, which passed through the cylinder at a point below the airlocks, formed a syphon, the long leg of which reached the bottom of the cylinder, and the short leg, outside, mean water level.

The actual column of pressure therefore in the pipe was that due to the difference in level between the bottom of the pipe inside the cylinder and the actual water level outside, less the power of suction of the syphon.

It was soon found, however, that the sudden variations of air pressure made possible by leaving the "blow-out" pipe free to act at all times produced so thick a fog in the cylinder as to impede the work, and to remedy this a valve was fitted to its lower end by which the pipe could be opened or shut as required, and the escape of air controlled, by the men working at the bottom of the cylinder. This appears to be the first recorded case in which this control was provided.

The principal and grave objection to the arrangements described above is

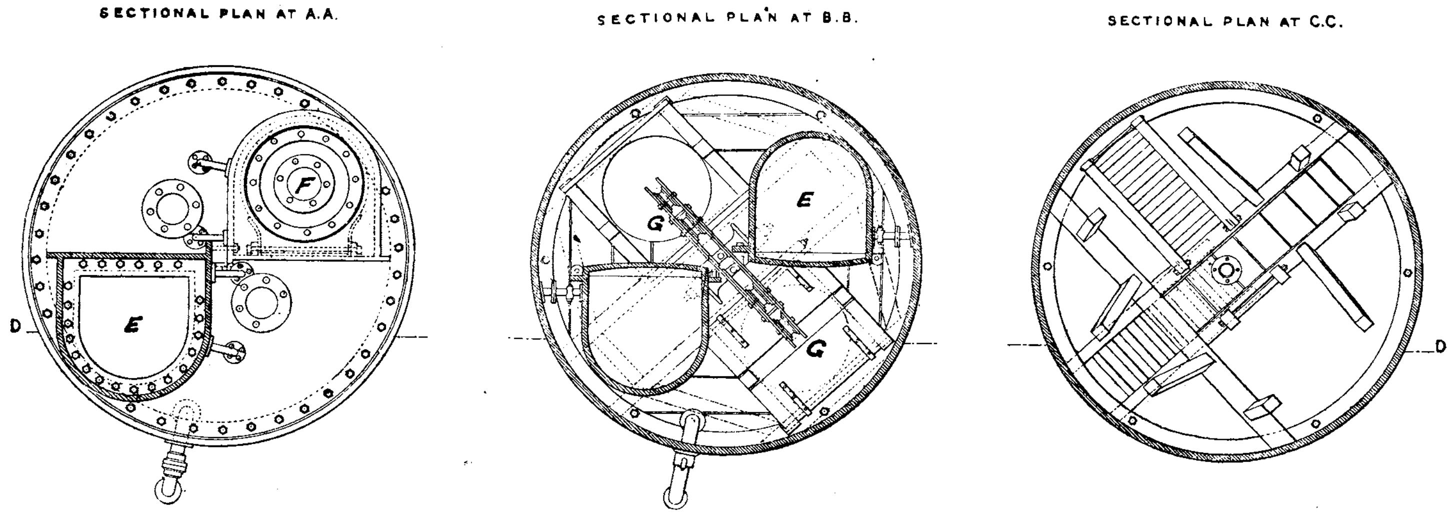


FIG. 21. ROCHESTER BRIDGE, KENT, 1851.
Sections *A A*, *B B*, *C C*, of Cylinder. For Positions of Sections, see Fig. 20.

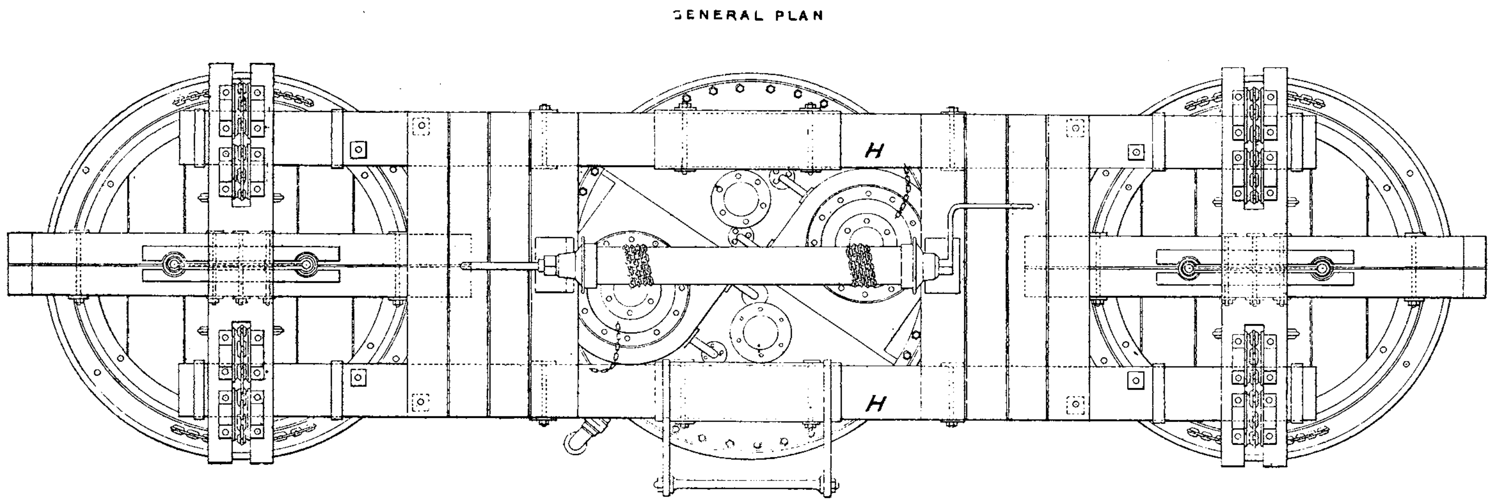


FIG. 22. ROCHESTER BRIDGE, KENT, 1851.
General Plan of Framing above Cylinder for Regulating the Rate of Sinking.

that by fixing the airlocks on the top of the cylinder it was necessary, whenever the cylinder had sunk so that the top of the length erected approached high-water level, to stop the work of excavation, let off the air pressure, and remove the locks in order to erect on the length of cylinder already sunk, more sections of 9 feet length, on the top of which the locks were then replaced.

This probably was not necessary more than once in sinking each cylinder on this particular work, but even on this assumption, ninety stoppages of work would be required during the building of the piers and abutments.[1]

The alternative arrangement, viz., to erect the entire length of cylinder before commencing work under air pressure, would have the double disadvantage that a cylinder perhaps 60 feet long and only 7 feet in diameter would be difficult to pitch accurately and that, as the depth of the cylinder necessary at each point could not be known beforehand, no security could be felt that the length actually erected would suffice.

The true solution of the difficulty is to put the airlocks inside one of the cylinder segments, and so allow them to sink with the cylinder, until this has reached its foundation, when they are removed once and for all.

Another feature in the method of sinking employed which deserves notice is the system of kentledge adopted (see Figs. 19 and 22).

Across the top of the cylinder were laid two beams or yokes *H*, *H* so placed as to clear the upper doors of the airlocks. These beams, about 18 feet long, overhung the adjacent piles on either side which were pitched ready for sinking. At these extremities were fixed pulley blocks, over which passed chains, each chain being fastened at one end to the cylinder below it, and at the other to a segment *J* of the smaller cylinders, 6 feet in diameter, to be used later in the abutments, which thus hung within the larger cylinder, and could travel up and down in it.

The segments *J*, *J*, having each a temporary bottom fitted, could be loaded as desired, and by the device of also hanging these segments to two bars *K*, *K*, which could in turn be supported by pins at *L*, *L*, it was possible at any time to take all the pressure off the chains slung over the beams *H*, *H*.

The cylinders were lowered by excavating for a depth of about 14 inches below the bottom of the cylinder, and the men having withdrawn, dropping the pressure until the cylinder sank, exactly in the manner set forth by Cochrane in 1830.

The work was carried out very successfully, and with very great economy as compared with the probable cost of constructing the foundations by means of coffer dams.

The accounts extant of this undertaking give very little information as to the effect of compressed air work on the men engaged; it is known, however, that there were no fatal cases of illness.[2]

The operations in connexion with Rochester Bridge have been described in some detail as being typical of a large number of other cases, mostly, like them, of bridge foundations below water level. Compressed air was for many years used only for shaft or caisson sinking, and Cochrane's idea that it would be employed in tunnel work remained untested. But in caisson work the system became at

[1] It was not until 1867, in the construction of a bridge over the Garonne at Bordeaux that the airlock was made in the shaft itself, so that the lock went down with the shaft. See *Annales des Ponts et Chaussées*, vol. ii. of 1867, p. 27.

[2] *Dublin Journal of Medical Science*, 1863, xxxvi. pp. 312-318.

once of universal employment. At Chepstow (1843–51), Saltash [1] (1854–59), Szegedin (1856),[2] Bordeaux [3] (1859),[4] Koffre Ozzyat (1859), Argenteuil (1859), Bayonne (1862), Londonderry (1862),[5] L'Orient (1862),[6] and Nantes [6] (1864), the foundations of bridge abutments were built by this method, and by the early sixties may be said to be established as the customary method of carrying such works in water-bearing material.

It was not until 1879 that the system was tried in tunnel work, and then, curiously enough, it was put into practice simultaneously at Antwerp, and at New York.

In the former place Mr. Hersent was carrying out some extensive dock works and river walls, the latter of which he built by means of caissons sunk under compressed air, and having to make, in order to provide for some pumping work, a small tunnel or adit entirely in fine silty sand and water, he employed compressed air to keep up the face. No shield was used, and the lining of the tunnel was of cast iron. The height of the tunnel was barely 5 feet, and consequently no trouble was experienced by the difference in pressure required to balance the water at the crown and at the invert.

The excavation was carried forward in lengths of about 1 foot 8 inches, corresponding to the width of the cast-iron rings of the lining, and no timbering of any kind was used.

But when this small work was in progress in Antwerp, a similar tunnel, but on a much larger scale, was commenced in New York. An attempt was made to build a brick tunnel under the Hudson River through a material of silt or mud so fluid that it would flow through the smallest crevices almost like water : and the engineer in charge, Mr. Haskin, employed compressed air as a support for the roof of the excavation as well as for expelling the water.[7]

The undertaking was not successful, but the use of compressed air fully justified Mr. Haskin in using it, and since then it has been employed in all similar work.

Before going into the details of this and other tunnel works where compressed air has been used, a few pages may be given to the consideration of the peculiar form of sickness produced in some cases by working in compressed air, and of the methods adopted for its avoidance, and, when it occurs, for its cure, or at any rate its temporary alleviation, for the medical treatment of the disease hardly comes within the scope of this work.

Caisson Disease

In these earlier undertakings recorded above the effect of compressed air work on the health of the men engaged in it was in some cases noted, especially by M. Triger at Chalonnes, who gives *inter alia* a very vivacious account of his sensations on being suddenly "locked out" from a pressure of two atmospheres, and by Messrs. Pol and Watelle, who in 1845 made observations on the miners engaged under M. Blavier at Douchy, but naturally in the records extant more attention is given to the engineering than to the medical features of the work. In the case

[1] *Proc. Inst. C.E.*, vol. xx. p. 268.
[2] *Annales des Ponts et Chaussées*, 1859, vol i. p. 355.
[3] Ibid. 1867, vol. ii. pp. 27–115.
[4] Foley's *Du Travail en l'air comprimé*, Paris, 1860.
[5] *Proc. Inst. C.E.*, vol. xxi. p. 265.
[6] *Annales des Ponts et Chaussées*, 1864, vol. i.
[7] See pp. 159 to 167.

of the bridge at Argenteuil (1859), however, Dr. Foley published a monograph giving his observations on the effect of compressed air on the health of the men engaged in sinking the caissons for the piers.[1] In it he recommends re-immersion in all cases when a workman is struck down after leaving the compressed air chamber.

In 1868, a Dr. Jaminet was in charge of the personnel employed in the construction of the St. Louis Bridge over the Mississippi, when the pressure in the caissons reached 50 pounds to the square inch on occasions : and he subsequently embodied in book form his observations, which from the magnitude of the work were made on a scale considerably greater than those of any previous investigator.[2]

He recommended a sliding scale of working hours in inverse proportion to the pressure of the air as under :—

Pressure lbs. per inch.	Hours of Shift.	Number of Shifts.	Hours of Rest.	Hours of Work.
15 to 20	2	Thrice a day	2 between	2
20 ,, 25	2	,, ,,	3 ,,	2
25 ,, 30	2	Twice a day	3 ,,	2
30 ,, 35	2	,, ,,	4 ,,	2
35 ,, 40	1	Thrice ,,	2 ,,	1
40 ,, 45	1	,, ,,	4 ,,	1
45 ,, 50	1	Twice ,,	6 ,,	1
50 ,, 55	1	Once ,,		

He also recommended that the time for entering the chamber through the air-lock, or " locking in " should be one minute for every 3 pounds of pressure ; and for " locking out " one minute for every 6 pounds of pressure.[3]

Among the 600 men employed in the caissons of this bridge, there were 119 cases of compressed air sickness, 14 of which terminated fatally and two of which resulted in permanent disablement.

This gives a very high proportion of illness to the number of men employed, but the air pressure, 50 pounds, was of course very high, and the importance of an abundant supply of air per man per hour without reference to the actual quantity required for the work was not so fully recognized then as now.

In 1871–2, Dr. Smith, whose work, *Compressed Air*, summarizes from the medical point of view the main features of caisson disease and its cure, was medical officer to the Brooklyn Bridge, the immense towers of which are built in caissons constructed by means of compressed air ; and he appears to have been the first to attempt to enforce regulations devised to exclude unfit workmen from, and regulate the actions of the men admitted to, the caissons. These regulations were similar to those enforced in tunnel work at present, except that the supply of air provided for appears to have been inadequate.

The maximum pressure employed was 36 pounds, and owing to the employment of gas as an illuminant it was found that with a supply of 150,000 cubic feet of free air per hour with 125 as a maximum number of men, the amount of carbonic acid in the air was 0·3 per cent., or three times as much as more recent practice considers satisfactory.

[1] Smith's *Compressed Air*, pp. 13–15 and 74.

[2] Jaminet's *Physical Effects of Compressed Air*, St. Louis, U.S.A., 1851.

[3] Smith recommends one minute for every 3 pounds for " locking in " : one minute for every 6 pounds for " locking out."

Under these circumstances 110 cases of sickness in four months, three of which were fatal, are not more numerous than might have been expected, the daily working gangs numbering 125 men.

At the maximum pressure, the hours of work were two-hour shifts with four-hour intervals or eight hours in a twenty-four-hour day.

To mitigate as much as possible the effect of the sudden drop of temperature on the men when " locking out " pipes heated by steam were fitted to one of the airlocks on this work. This has not been done again so far as the author is aware.

The most interesting portion of Dr. Smith's book is that in which he suggests as a practical remedy for cases of caisson sickness, their treatment in a specially prepared hospital or chamber, the air in which could be compressed up to the pressure of the working chamber from which the sufferer had come.

He anticipates, indeed, the arrangements devised and constructed by Mr. E. W. Moir later at the Hudson River Tunnel,[1] which proved so successful there, and elsewhere since, in alleviating the suffering caused by caisson disease.

" My plan,"[2] he writes " would be as follows :—Let there be constructed of iron of sufficient thickness a tube 9 feet long and 3½ feet in diameter, having one end permanently closed, and the other provided with a door opening inward, and closing airtight. This tube to be placed horizontally and provided with ways upon which a bed could be slid into it. Very strong plates of glass set in the door and in the opposite end would admit the light of candles or gas jets placed immediately outside. This apparatus should be connected by a suitable tube with the pipe which conveys the air from the condensers to the caisson. An escape cock properly regulated would allow the constant escape of sufficient air to preserve the necessary purity of the atmosphere within.

" The bed containing the patient having been slid into the chamber, the door is to be closed, and the pressure admitted gradually until it nearly or quite equals that in the caisson.

" This should be continued until the patient indicates by a signal previously concerted that the pain is relieved. The pressure should then be reduced by degrees, carefully adjusted to the effect produced, until at last the normal standard is reached. By occupying several hours, if necessary, in the reduction of the pressure, it is probable that a return of the pain could be avoided. . . . I should expect the very best results from it in cases of extreme pain or in the very outset of paralysis not dependent upon extravasation of blood.

" Of course the secondary conditions which arise in protracted cases would not be capable of direct relief by simply reproducing the physiological conditions existing in the caisson. The most that might be hoped for in such cases would be that the pressure might result in giving a new impulse to the circulation in the congested part, and thus favour resolution."

The arrangement described above is practically (except that at the Hudson tunnel the air bath or hospital was entered by means of a lock) that first employed by Mr. E. W. Moir in New York in 1889. It is to this engineer that the credit of bringing into general use this most useful appliance belongs.

The peculiar malady which is produced in some conditions as a consequence of prolonged immersion in compressed air, is of great interest from the medical point of view, but its pathological phenomena hardly comes within the scope of this work. The symptoms may be briefly described, however, before detailing the practical precautions against and remedies for the disease.

Caisson disease must not be confounded with the purely mechanical troubles experienced by persons trying to go into compressed air, having their eustachian tubes, which connect the cavity of the middle ear with the external air, in a blocked condition, caused, for example, by a cold in the head. In such a condition, the increasing air pressure of the lock exerts its full effect on the outside of the ear

[1] *Journal of the Society of Arts*, May 15, 1896.
[2] Smith's *Compressed Air*, pp. 74, 75.

drum, while the pressure in the inside remains normal and as a result intense pain is caused in the ears, which can only be relieved by closing the mouth and nostrils, and blowing so as to dislodge the obstruction in the tubes and so increase the pressure inside the drum of the ear, when the pain is immediately relieved.

This trouble disappears altogether after a short period when men are working regularly in compressed air, and there is no danger of a rupture of the drum of the ear, even in the case of a man with obstructed tubes going into an airlock for the first time, provided that the increased pressure is admitted with reasonable slowness so as to give the sufferer time to make his trouble known.

The more serious illness which is produced by compressed air work carried on under certain conditions, is known as caisson disease, and has of late years been the subject of careful study by competent observers (see footnote on page 22).

Though the pathology of the disease can hardly be said to be perfectly understood, the observations made of it have enabled engineers and contractors engaged in this class of work to draw up certain general regulations for the control of their men, and the supervision of their health, which have given beneficial results.

Caisson disease is one "depending upon increased atmospheric pressure, but always developed after the pressure is removed. It is characterized by extreme pain in one or more of the extremities, and sometimes in the trunk, and which may or may not be associated with epigastric pain and vomiting. In some cases the pain is accompanied by paralysis more or less complete, which may be general or local, but is most frequently confined to the lower half of the body. Cerebral symptoms, such as headache or vertigo, are sometimes present. The above symptoms are connected, at least in the fatal cases, with congestion of the brain and spinal cord, often resulting in serous or sanguineous effusion, and with congestion of most of the abdominal viscera." [1]

The peculiar feature of the malady is that, although caused by the effect of air pressure above the normal, it is not until the pressure is removed that the symptoms manifest themselves, and, as mentioned above, in most cases re-immersion in compressed air relieves, at least for a time, the sufferer.

The most common form of the disease is that known among the miners as "bends," in which the sufferer is suddenly seized with pains, usually in the knees, and of such excruciating character that the strongest men are subdued by them.

In these cases re-immersion always gives relief, at any rate temporarily.

In its more serious form, the compressed air sickness ends in paralysis, and sometimes in death; but with increased knowledge of the causes of the disease have come improved methods of precaution against it, and the more recent tunnelling undertakings have been comparatively immune from serious cases. A careful medical examination of all men offering themselves for work in compressed air, with rigid rejection of the unfit, and a re-examination of those accepted at least weekly, as well as the exclusion of all suffering from any temporary ailment, have the effect of weeding out all men with any natural defects for working in compressed air; while an increased knowledge of the causes of the disease has enabled engineers to draw up regulations as to the hours and conditions of work, and the supply of fresh air, which have greatly reduced the percentage of cases among the men employed.

The principal causes of compressed air sickness are (1) excessive pressure, (2) impurity of the air in the pressure chamber and (3) too prolonged immersion. It

[1] Smith's *Compressed Air*, p. 47.

is found that the effect caused by any of these three conditions is intensified by the coincidence of the others.

To maintain the miners in good health, an increase of pressure demands greater purity in the air, and shorter hours of labour ; bad air, that is air having an amount of carbonic acid of over 0·1 per cent., is more dangerous in conjunction with increased pressure than with a lower, and makes short shifts imperative :[1] and it is found that the period of safe working for men varies above a certain density inversely as the pressure, and directly as the purity of the air.

Under satisfactory conditions men can work eight-hour shifts with sixteen hours' rest per day in pressures up to 35 pounds per square inch ; an interval of forty minutes for a meal being given in the middle of the shift. Above that pressure the length of the shift must be reduced as the pressure increases, until at 50 pounds pressure, as at the St. Louis Bridge, the length of the shift is not more than one hour.

The selection of the men in the first place, and their re-examination at intervals afterwards, should be of course the work of a properly qualified medical officer, who after eliminating the obviously unsuitable men, such as those with weak hearts, or diseased lungs, of gross habit of body, or suffering from alcoholism, should at least once a week examine the working gangs, and weed out those who show any signs of ill health or loose living.

At the Greenwich Tunnel (1899) it was found necessary to reject 13·9 per cent. of those presenting themselves for employment in the tunnel, and subsequently of those accepted in the first place 5·7 per cent. were rejected after a longer or shorter period of work. The total percentage of rejections was 18·8 of the original number examined, or very nearly one in five. This proportion appears high, but it is probable that the knowledge that they would be vigorously examined deterred many from presenting themselves, and that therefore the actual percentage of working men who are unfit to work in compressed air is larger than that given by the medical officer's returns quoted.[2]

When once the men are passed by the medical officer, the enforcement of any regulations he may make and of such general rules as past experience has shown to be useful, are matters for the engineer in charge of the work.

It is usual to provide for the men rooms, which can be warmed in winter, in which they can change their clothes and rest after leaving the pressure chamber ; and provided also with hot water, etc. A medical lock is a necessity, and where the number of men employed is at all large it should be compulsory ; its cost is a very small item in the equipment of the contractors' yard.

When, as is usually the case, the men in coming out of the pressure chamber have to ascend some height to leave the works, a lift should always be provided for them.

The medical officer in charge should after each examination of the men give to each ganger a signed list of the men passed for his gang, the ganger being then made responsible for seeing that no workmen except such as are in the list enter the compressed air with his shift.

[1] Dr. Hunter, in a thesis on *Compressed Air*, presented for his degree of M.D., now in the Library of the University of Edinboro', says in reference to the sinking of the caissons at the Forth Bridge that the worst conditions for the men were (1) when they were removing soft silt, containing much moisture and decaying matter, and (2) when concreting was going on, considerable generation of CO_2 taking place.

[2] Macmorron, *Notes in Caisson Disease* (privately printed), London, 1901.

The following general rules for the men's health should always be enforced :—

(1) No one suffering from any temporary illness from any cause whatever which may affect his normal state of health should be allowed to go into the air chamber. This particularly applies to a man under the effect of excessive drinking, but any stomachic derangement unfits a man for compressed air work. Any case of illness, even if occurring after the man has left the works, should be reported at once to the medical officer.

(2) No one should enter the air chamber with an empty stomach. For men working in compressed air a generous diet is necessary.

(3) Every one, on leaving the pressure chamber, and before locking out, should put on a warm overcoat, and on getting out be supplied immediately with a hot drink, preferably of coffee, which is a mild stimulant.

(4) Arrangements should be made so that men coming out of compressed air are not required to climb ladders or stairways to gain the surface. All exercise for some time after leaving the air chamber is unadvisable.

(5) When, as is usually the case, an interval for a meal of from half an hour to an hour is given in the middle of an eight-hour shift, it should be made an invariable rule that the men should leave the pressure chamber for that period.

(6) The rate at which the pressure is increased when the men are passing through the lock into the pressure chamber, or "locking in" as it is termed, is regulated solely by the men's convenience; the rate of reduction of pressure, however, in "locking out" is a matter which should be strictly regulated by the engineer.

(Dr. Smith goes so far as to say that if sufficient time were allowed for passing out through the lock, the disease would never occur,[1] and he goes on to say that at least five minutes should be allowed for each atmosphere of pressure, or say one minute for every 3 pounds.

This appears a somewhat long "locking out." In practice, in an ordinary lock about 14 feet long, and 6 feet diameter, a pipe $1\frac{1}{4}$ inch diameter is a safe aperture for allowing the air to escape ; but to ensure this being used, it is necessary to make stringent regulations against the employment of the "muck tap," which is usually of 3 inches aperture, in passing men through the lock.)

(7) The amount of free air supplied to the pressure chamber should be at least 4,000 cubic feet per man per hour, and

(8) The amount of carbonic acid in the air in the pressure chamber should never exceed 1 part in 1,000.

Nos. 1, 2, 5 and 6 of the foregoing are matters for the foremen and gangers to see to ; Nos. 3, 4, 7 and 8, and also the provision of the medical lock, should be the subject of special stipulations in the contract for the work, as they involve an extra outlay on the part of the contractor.

Properly warmed rooms for the men to change, warm coats for locking out and hoisting gear to bring the men up the shafts are all indispensable, and should be specified for.

The abundance and purity of the air supplied to the pressure chamber are so important to the wellbeing of the men that the minimum quantity of air supplied per man per hour, which of course regulates the purity also so far

[1] Smith's *Compressed Air*, p. 64.

as relates to the proportion of carbonic acid contained in it, should certainly be specified.

This is particularly necessary in cases, when, as in tunnelling in good material but under heavy buildings, compressed air is used, not to expel water, but merely to hold up the excavation. In such cases, unless a clause specifying the amount of air to be supplied is inserted in the contract, the contractor will not have to pump more air than is sufficient to just maintain the pressure required, an amount which may well be below the minimum necessary for the health of the miners.

When the escape of air through the surrounding material is less than the amount of fresh air necessary to keep the atmosphere of reasonable purity, the only means of equalizing the ingress and egress of air, so as to keep down the percentage of carbonic acid is the waste or "blow-out" pipe which is provided in all tunnels for the purpose of blowing out by means of the pressure in the air chamber water which may find its way into the tunnel.

But this pipe is necessarily fitted with a valve, and consequently its use depends on the miners themselves, who control it; and unfortunately, one of the main difficulties which those in charge of tunnelling in compressed air have to overcome, is the difficulty of making miners carry out orders, the object of which they imperfectly understand. But it is all important for the health of the men that a certain amount of free air per man per hour should pass into the tunnel; and this condition only becomes the more necessary as the pressure increases.

An increase of pressure accompanied by an increase of impurity, that is of carbonic acid, is almost sure to prejudicially affect the workmen.

The amount of carbonic acid (CO_2) in the air of the pressure chamber should never exceed 0·1 per cent., or 1 part in 1,000; if it passes this limit an increase of caisson sickness is to be expected.

The ordinary proportion of carbonic acid in the atmosphere is 0·04 to 0·05 per cent.; in an office or room with many occupants 0·10 per cent. or more; in mines, it is said, it is sometimes as high as 0·75 per cent.

At the Greenwich Tunnel (1899) careful observations were made by the chemical staff of the London County Council, and it was found that on the average of twenty-four analyses of the air made regularly during three months, with an air pressure of 22½ pounds and a temperature averaging 6½ degrees above the outside air, the percentage of carbonic acid in the pressure chamber was 0·0786 per cent. as against 0·0475 in the engine room where the air was taken in by the compressors. To maintain this degree of purity, an average of 5,774 cubic feet of free air per man per hour was pumped into the tunnel.

The amount pumped never fell below 4,100 cubic feet per man per hour; and all the rules suggested above as necessary were put in force.

Under these circumstances the health of the men was very satisfactory, only nine cases, three of them serious but none fatal, of caisson sickness occurring during the thirteen months during which work was carried on under compressed air.

At the Blackwall Tunnel (1892–7), where careful observation was also kept on the men and the conditions of work in compressed air were the same, a proportionately equal immunity from serious illness resulted. Dr. Snell, the Resident Medical Officer of the London County Council on the work, whose book, *Compressed Air Illness*, before referred to, details his observations at this tunnel, states that during the period of construction only two hundred cases, none of them fatal and many of them trivial, of caisson disease, occurred. This tunnel was more than twice the diameter of the Greenwich one, and probably the working gangs employed in it were at any time five times as numerous as those at Greenwich.

The results obtained in these two cases are the most satisfactory yet recorded in compressed air work.

It is interesting to note that at both tunnels cases of caisson sickness occurred owing to excess of carbonic acid at periods when the air pressure in the tunnel was considerably below the maximum.

At Greenwich, where the maximum pressure was about 28 pounds, three out of the nine cases recorded occurred at a time when the pressure was only 12 pounds, and at Blackwall, when the maximum pressure reached 37 pounds, cases of sickness occurred at a lower pressure and with an air supply of 6,500 feet per man per hour. In both cases there were causes extraneous to the amount of pressure which caused the increase in sickness. At Greenwich the men affected were all suffering from severe colds ; and at Blackwall they were working in a compartment of the shield where an explosive generating carbonic acid was in use. These cases confirm the results of earlier experience stated above, namely, that impurity of the air and bad conditions of health of the men count almost as much as the density of the air in producing caisson sickness.

At Blackwall Tunnel, Dr. Snell made careful observations with the view of determining, if possible, the general conditions to be laid down for the safe prosecution of similar work in the future.

His observations as to the effect of increased pressure on the health of the men merely laid down in exact form conclusions generally accepted, but they are interesting as the first series of tabulated observations on a sufficiently extended scale to give general value to his results.

His table [1] giving the percentages of cases of sickness occurring on 215 days on which the air pressure was but little above or little below 20 pounds, and the length of the shifts eight hours each shows clearly the effect of increased air supply in the men's health.

Free Air pumped per Man per Hour Cubic Feet.	No. of Days.	No. of Cases.	No. of Cases per 100 Days.
Below 4,000	56	16	28·5
4,000 to 8,000	47	9	19·1
8,000 to 12,000	71	8	11·2
Above 12,000	41	0	0·

In this table (one of several) of the three conditions affecting the sickness, amount of pressure, length of immersion, and amount of air, two are constant, and the third, the amount of air pumped per man per hour, is a variant, with the result that the amount of sickness is seen to vary inversely with it.

Dr. Snell also observed, so far as he was able, the proportion of sickness among men of different ages, and from his figures it would seem that while men under twenty are immune from the disease, men of all ages from twenty to forty are about equally susceptible to it, while men over forty-five are entirely unsatisfactory.

[1] Snell's *Compressed Air Illness*, p. 141.

His figures are as under :—[1]

Men's Age.	No. of Men Passed.	Cases of Sickness.	Cases per cent.
15 to 20	55	0	0
20 ,, 25	145	15	10·3
25 ,, 30	152	37	24·3
30 ,, 35	91	19	20·9
35 ,, 40	61	14	22·9
40 ,, 45	38	10	26·3
45 ,, 50	3	5	166

The figures are doubtless correct, but, even if the men over forty-five years of age be ignored in making the calculation, it would appear that after the men had been passed by the doctor over 17 per cent. were affected by the compressed air work, a high percentage considering that only for a short time in sinking the shafts did the pressure reach 35 pounds.

The figures in this table do not, however, give the total number of men passed or injured, but only those whose ages were known.

One reason of the high percentage of the table may be that at the Blackwall Tunnel it was optional for men, once passed by the doctor as fit to work in compressed air, to present themselves for inspection again. The regular weekly inspections insisted on at the Greenwich Tunnel a little later resulted in the weeding out of 5·7 per cent. of those who had previously got past the doctor.

The London County Council, fixed in the cases of these two tunnels, as also in the one now in course of construction at Rotherhithe, the minimum amount of free air to be pumped per man per hour at 8,000 cubic feet. Much less than this, however, if actually pumped (for specifications and contractors' actual compliance with them are somewhat different), should keep the air purer than that of most workshops.

The general conditions of compressed air work laid down in the specification for the Rotherhithe Tunnel now commencing are so complete as regards the securing of healthy conditions for the men, and also cover the ground so well in the other matters connected with the compressed air plant of the tunnel that they are given in extenso below.[2]

Extract from the Specification attached to the Contract for the Rotherhithe Tunnel.

Plant.

Clause 25. Throughout the whole of the time occupied by these works the Contractor shall, without extra charge, provide in duplicate for each working face sufficient hydraulic machinery, airpumps, engines, airlocks, grouting apparatus, etc., and he shall keep the same ready for use. He shall make sure that in case of a breakdown in one set of appliances another set can immediately be used in its place, each set being by itself fully capable of doing the maximum work which has to be done in the most extreme cases.

Ventilation of working faces.

26. The Contractor shall, without extra charge, have all the working faces properly ventilated, and the amount of carbonic acid gas present at any time shall not be allowed to exceed 0·08 per cent. A minimum of 8,000 cubic feet of free air per hour per man shall be pumped into the tunnel, and shall be brought to the working face. When working in compressed air at the bottom of the caisson, similar conditions shall apply. The blow-out pipe shall be used at the

[1] Snell's *Compressed Air Illness*, p. 154.

[2] Compare the specification for compressed air work in the East Boston Tunnel, chap. ix.

working faces once at least in every hour. Suitable lifts and resting places for the men, including a compressed air chamber fitted with bunks, and a drying room for clothes must be provided. In all airtight floors and bulkheads for the shafts and tunnel, a small emergency airlock must be provided, in addition to the ordinary working airlock, with access thereto from the ordinary working levels.

Emergency exits.

27. The tunnel and shafts shall, without extra charge, be lighted by electric light during the progress of the works . . . . and generally the Contractor shall provide every means and appliance which may in any way conduce to the safety of the works and the men employed in them.

Refreshments and arrangements for men.

28. Whenever possible each man coming out of the compressed air chamber shall be provided with a cup of hot coffee, and arrangements shall be made that it shall not be necessary to climb any stairs immediately after coming out. Proper sanitary conveniences, in all respects satisfactory to the engineer, shall be made for the men working in the tunnel and shafts. The greatest care shall be taken that all portions of the work being carried out, whether under compressed air or otherwise, shall be kept in a thoroughly sanitary condition. The carrying out of the whole of the conditions of this clause shall be considered as a contingency on the cost of the work.

Sanitary condition.

Medical Officer.

29. The Council may engage the services of a qualified medical practitioner to look after the well-being of the men employed, and should they do so the Contractor shall, without extra charge, follow out all the reasonable instructions of the same from time to time.

Fitness of men.

30. No workman shall be engaged for the compressed air work without his fitness for such duties being proved by such medical examination as the Council may direct.

In addition to providing in the specification for the health of the men working in compressed air, special clauses were inserted in the Act authorizing the construction of the tunnel, whereby the Council was authorized to pay, in the cases of men working in compressed air, compensation for injury caused by such work, and these are given below :—

(63 and 64 Vict.) THAMES TUNNEL. (Ch. CCXIX.)
(ROTHERHITHE AND RATCLIFFE)
ACT 1900

Compensation to workmen in special cases.

55. The Council shall have power in their discretion to pay compensation to any workman or person employed in the construction of the tunnel who may be injured by reason of working under compressed air, and to the widow and children or any of them of any such workman or person who while so working as aforesaid shall die or sustain injury resulting in death.

Such compensation as aforesaid may be paid either in one sum or by periodical payments at such times and extending over such period as the Council may think fit, and the Council may if they think fit contract (for such consideration to be paid by the Council as they may think proper) with any insurance office society or company for the payment by such office society or company of any such compensation as aforesaid.

The expenses of the Council under this Section shall be considered as expenses incurred by them in the compensation of the tunnel, and shall be defrayed accordingly.

Nothing in this Act and no compensation which may be paid or become payable thereunder shall take away or prejudicially affect any right or claim to damages or compensation which any such workman or person as aforesaid or his widow or children may have in respect of any accident against any person or body.

Various methods have been suggested for removing from the air of the tunnel the carbonic acid which affects so unfavourably the health of the workmen employed in tunnels constructed with the aid of compressed air, but hitherto no attempt has been made to purify the air pumped into a tunnel on a scale large enough to deduce any definite results.

The simplest way of taking up the free carbonic acid in the air is by passing the air through or over a substance like lime or caustic soda for which carbonic acid has a strong affinity. But there are practical difficulties in the way of applying this well known chemical action to actual work in the engine-room. In the first place the volume of air pumped in a large tunnel is so great and the section of the delivery pipe so small in proportion, that the flow of air through any scrubber or similar appliance filled with a saturated solution of lime and inserted between the air compressors and the tunnel, is too rapid for any effectual cleaning to be possible unless the cleaning apparatus extended to a length and bulk which very few contractors' yards would admit of.

If the purifying apparatus were placed outside the compressors a special arrangement of the compressors and engine-room would be necessary to ensure that all the air pumped had previously passed through the purifiers.

The placing of purifying tanks in the pressure chamber of the tunnel is impossible : considerations of space forbid it.

When acting as Resident Engineer of the Greenwich Tunnel, the author was requested by the Chief Engineer of the London County Council to inquire into the possibility of purifying the air in the tunnel by eliminating some of the carbonic acid (which in ordinary air amounts to about 0·05 per cent. by volume) from the air pumped into the tunnel ; and the London County Council made a grant of money for carrying out experiments with that object. At the time the experiments were authorized the tunnel was more than half completed, and no serious alteration of the air-compressing plant was possible. The engines were built by Messrs. Walker Brothers, and were entirely satisfactory in working ; but from their construction and the arrangement of the engine house, it was not possible in any way to box them in so as to arrange that all the air entering the compressing cylinders should first pass through a purifying chamber, or an installation similar to the purifiers or scrubbers used in gas making. It was equally impossible to interpose a purifying chamber between the engines and the tunnel, even if it had been permissible to incur the risk of a temporary break in the supply of air. Consequently the experiment was limited to trying what could be done in the tunnel itself under working pressure.

Under these circumstances, the use of lime in solution was prohibited by reasons of space, but a saturated solution of caustic soda, which bulk for bulk is more effective in taking up carbonic acid than lime, was experimented with, and although the limited space available rendered it somewhat doubtful whether any marked results could be obtained by its use, a purifier of somewhat primitive design was constructed, and the results obtained with it were observed by officials of the Chemists' Department of the London County Council, who had also previously from time to time made analyses of the air in the tunnel.

The purifier consisted of two rectangular trunks of wood, one above the other, open at one end, and having sliding doors at the other end. The ends fitted with doors were connected with the air inlet of the tunnel by a conical box, the connexion with the airpipe being made airtight by a flexible joint. By opening one or other of the sliding doors, the air was made to pass through either the upper or the lower trunk, as required. Each trunk had one side removable, and each contained eight removable wire boxes containing pumice stone broken small, which, before being put into the trunks, were dipped in a saturated solution of caustic soda. When the upper trunk was filled with freshly dipped boxes, the door of the lower trunk was closed, and its boxes were taken out, dipped and replaced. The bottom door was then opened, and the top one closed, thus diverting the course of the air from the upper to the lower trunk ; the boxes in the upper trunk could then be removed and dipped afresh in the caustic-soda solution. A constant relay of fresh boxes was kept up day and night ; and the deposit of carbonate of soda on the pumice stone soon showed that some effect was produced upon the air.

The purifier was in operation for a month, and analyses of the air in the shield were made on fourteen different dates. The results are given in the Table at the end of this chapter which shows, in addition to the amount of carbonic acid in the air, the air pressure, the temperature of the tunnel as compared with that of the engine-room, and the amount of air supplied per man per hour, on the days when the tests were made. It will be seen that after the purifier had been taken into use, the average proportion of carbonic acid present in the tunnel showed a decrease on that observed before. If there were no other factors to be considered, such a result would be conclusive, but there are so many circumstances which modify the result that the author would confine himself to saying that the apparatus employed was responsible for some of the improvement ; and that, as some effect was produced by its use, a similar purifying apparatus properly elaborated might reasonably be expected to eliminate the excess portion of the carbonic acid in the air.

The last two lines of the Table give the averages for all the observations before and after fitting up the purifier. The average diminution of CO_2 by volume, apparently consequent upon the use of caustic soda, is 0·01 per cent. The average amount of free air supplied per man per hour was a little less, and the pressure per square inch $3\frac{1}{2}$ pounds less, after the purifier was put in, than previously : so that these two important factors in determining the amount of CO_2 in the air do not vary much. The variations in the quantity of CO_2 in the free air of the engine-room were probably caused by momentary contamination of the air, due to the proximity of the boiler furnaces. The samples of air in the tunnel were taken at floor level ; and the percentages given in the Table are the averages of two, and sometimes of three, separate samples, one of which was always taken a few yards behind the shield. On the whole, the results of the analyses are encouraging ; they appear to show that the purifier produced some beneficial effect.

The experiment, however, was inconclusive, owing to the conditions which prevailed. When the observations were taken the pressure was comparatively low, and the amount of air supplied to the men considerably in excess of that provided in most compressed air undertakings.

It would be interesting for some further experiments to be made with caustic soda under more severe conditions of pressure and quantity of air, and this could be done at comparatively small cost.

The expense of the experiment made by the author was about £1 per day, but with a little more elaboration of the plant this amount should be reduced.

The temperature of the air supplied to the pressure chamber is of course considerably raised above that of the free air of the engine-room where it is taken into the compressors by the very act of compression, and the friction of the delivery pipes through which it rushes with considerable velocity augments its heat. This is remedied in part by passing the air through a cooling tank or air reservoir the shell of which is kept cool by jets or streams of water playing on it.

TABLE GIVING THE RESULTS OF SOME EXPERIMENTS MADE AT GREENWICH FOOTWAY TUNNEL IN 1901, WITH A VIEW TO TESTING CAUSTIC SODA AS A PURIFIER.

Date.	Air-Pressure per Square Inch.	Temperature in Shield above or below that of Engine-room. Fahr.	Free Air Supplied per man per hour.	Percentage of CO_2 by Volume.			Remarks.
				In Engine-room.	In Tunnel.	In Shield.	
1901.	Lbs.	Degrees.	Cub. Ft.				
March 5	24	+10	6,000	0·047	0·073	0·196	Men working.
,, 11	21	+19	5,280	0·055	0·097	0·218	End of shift.
,, 18	24	+15	5,600	0·045	0·064	0·189	,, ,,
,, ,,	—	—	—	—	—	0·124	After blow-out pipe had been used.
,, 25	23	+15	5,280	0·047	0·058	0·125	End of shift; blow-out pipe used four times.
,, ,,	—	—	—	—	—	0·098	After blow-out pipe had been used.
April 1	25	+13	5,280	0·051	0·087	0·186	Men working; blow-out pipe used at intervals.
,, 15	26	+ 6	5,280	0·049	0·084	0·173	,, ,,
,, 22	24	− 7	5,280	—[1]	0·098	0·223	—
,, 29	22½	−10	5,280	0·043	0·080	0·170	Blow-out pipe in use.
May 6	17	+ 5	7,000	0·049	0·076	—	Shield closed.
,, 13	18	− 2	7,460	0·042	0·069	0·100	—
,, 15	—	—	—	—	—	—	Purifier in working order.
,, 20	19	− 2	5,900	..[1]	0·056	0·097	—
,, 22	17	− 3	6,000	0·067	0·074	0·111	—
,, 24	16	− 3	6,870	—[1]	0·072	0·126	—
,, 27	18½	− 7	7,195	..[2]	0·066	—	—
,, 29	17	− 9	6,580	0·047	0·077	—	—
,, 31	23	+ 1	5,280	0·052	0·073	—	—
June 3	21	+ 5	5,280	0·049	0·075	—	—
,, 6	20	+ 1	5,430	0·068	0·077	—	—
,, 7	18	+ 1	5,430	0·059	0·057	—	—
,, 10	20	− 5	4,260	0·042	0·066	—	—
,, 11	21	—	4,240	0·039	0·072	—	Doubtful.
,, 12	20	+ 5	4,100	0·045	0·068	—	—
,, 13	19½	+ 6	4,500	0·039	0·062	—	—
,, 14	18½	+ 2	4·260	0·049	0·068	—	—
—	22½	+ 6½	5,774	0·0475	0·0786	—	Average before using purifier.
—	19		5,330	0·0505	0·0688	—	Average when using purifier.

[1] Sample spoilt. [2] Sample spoilt. Shield in south shaft.

Chapter III

CAST-IRON LINING FOR TUNNELS

Its Use in Tunnels Suggested by its Employment in Pit Shafts—Telford's Iron Centres, 1824—Rhiza's Iron Centres and Face Jacks, 1860—Ease of Construction and Immediate Security Ensured by its Use—Circular Tunnels most Convenient when Cast-Iron Lining is Used—Proportions of the Cast-Iron Segments—Examples from Recent Work—The Key—The Joints—Central London Railway—Waterloo and City Railway—Baker Street and Waterloo Railway—Blackwall Tunnel—Greenwich Tunnel—St. Clair Tunnel—Great Northern and City Railway—Rotherhithe Tunnel—Lea Tunnel—Casting of Tunnel Segments—The British Hydraulic Company's Moulding Machine—Tables—Quantities per Yard Forward of some Typical Iron-Lined Tunnels

Cast-Iron Lining for Tunnels

THE use of cast iron built up in successive rings, each comprised of several segments, as a material for tunnel construction only dates from 1869, when it was employed in the Tower Subway, but Brunel had proposed its use in 1818, and it is possible that the Thames Tunnel would have been constructed in iron, had the circular section first proposed been adopted. As is known, a rectangular tunnel was decided on, and almost as a necessary consequence a masonry tunnel was preferred to a cast-iron one.

For lining shafts, however, cast iron has been employed for more than one hundred years, and no doubt that use of it suggested its employment in tunnels to Brunel.

In 1795 " tubbing in circles " was used for the first time at the Walker Colliery on Tyneside, and in 1796, tubbing made of cast-iron segments was put in the shaft of Percy Main Colliery.[1] The use of cast-iron lining or tubbing in shafts in water-bearing strata has since been the universal practice in the North of England, the portion of the shafts in solid ground being brick-lined in the ordinary way.

Although not used as a permanent lining to tunnels until 1869, the convenient way in which frames of cast iron could be built rapidly and securely for centering and the like, and be with equal facility taken down, recommended it early in the last century to Telford, who in the second Hardcastle Tunnel, built in 1824, constructed centres made up of sixteen segments bolted together, which could be used again and again ;[2] and about 1860, a M. Rhiza invented and used in various tunnels in Central Europe a system of centres and of " face rams or jacks " in combination with them which, save for lack of mobility, presents many of the advantages of the shield method ;[3] indeed, he worked out his system with such

[1] Society of Engineers, 1893. *Collieries and Colliery Engineering*, by R. Nelson Boyd.
[2] Rickman's *Life of Telford*. See plates.
[3] Drinker's *Tunnelling*, p. 680, et seq.

detail and completeness, that it is surprising he stopped short of the use of iron as a permanent lining.

The great advantage iron tunnel lining has over masonry construction is that it attains its full strength at once, and that the process of erecting it is simple, rapid, and easily supervised ; so that given fairly satisfactory castings, it is easy to ensure a sound job.

For use in tunnels constructed with shields the first qualification is the more important ; the advance of the shield being relatively so rapid that a masonry lining has not time to set properly before it is called on to sustain, not only the pressure of the ground around it, but also the back thrust of the shield rams. Various methods have been tried to obviate this latter difficulty, and some will be considered in describing the use of roof shields for large masonry tunnels, but in any case the pressure of the ground above must be sustained immediately the shield is moved forward, and, if the tunnel to be driven passes undei heavy and valuable buildings the extra cost of an iron lining is well repaid by the increased security against damage obtained by its use.

The actual ratio of the cost of iron lining to that of masonry varies considerably with the size of the tunnel.

Speaking generally, the larger the tunnel the less the cost of an iron lining exceeds that of brickwork ; not so much on account of the comparative approximation in cost of the two materials as the diameter of the tunnel increases, but on account of the saving in the amount of excavation made by the use of a cast-iron lining. In a tunnel for a single line of railway, like the Hudson Tunnel shown in Fig. 102, the proportions of the area excavated to the area of the inside of the tunnel in the case of an iron-lined and brick-lined tunnel respectively, 1·22 and 1·60 to 1·00.

Especially do the foregoing remarks apply to tunnels driven through water-bearing strata, where masonry is particularly difficult to construct in a sound manner, while an iron-lined tunnel can be made reasonably watertight with very little trouble, however great the pressure due to the head of water outside may be.

The universal practice in England since 1868 has been to use the shield in conjunction with a cast-iron lining to the tunnel, of circular section, and composed of successive rings, which again are made up of a number of segments, and a closing piece or key. (For a typical cast-iron tunnel, see Fig. 30.)

This section is the most suitable for iron-lined tunnels for several reasons. In the first place, the circular section when the tunnel is made in fairly solid homogeneous material is economically the best, as, save for the inequality caused by the difference of level between the crown and invert, the pressure on the lining is normal to the circle. In semi-fluid material of different densities there is, of course, no means of determining the economical sections for every case. In the second case the erection of the cast-iron lining would be made much more troublesome and slower if in order to obtain a section other than a circular one cast-iron segments of different shapes were employed. In a circular tunnel, with the exception of the two immediately adjoining the key (and even those in some cases) all the segments are interchangeable, and consequently no time is lost in sorting out, in the dim light in which tunnelling operations are necessarily carried on, the different pattern of segment required for each part of the lining. In the third place it is easy, if the tunnel be circular, to " break joint " with successive rings, and so greatly increase the stiffness of the tunnel, without increasing the number of patterns required.

And finally a circular tunnel is convenient in view of the fact that every shield rotates more or less on its horizontal axis, and that consequently a circular section is the only one which will be always the same, relatively to a vertical axis, whatever position the shield may take.

Cast-iron tunnels, 30 feet in horizontal diameter, with a flattened invert, have been built for cross-over roads in the Great Northern and City Railway (finished 1903). They were built, however, without the use of shields.

They are the only ones in which the circular section has not been adopted, except the small one constructed at Antwerp in 1879, which was almost rectangular in form (see Fig. 14).

The size and weight,[1] as well as the thickness of the segments forming the tunnel rings are determined more by practical considerations of facility of casting, and of erection, than on any theoretical grounds.

The depth of the flanges of the segments, that is, the thickness of the lining from inside to outside, is, however, a dimension which must have some relation to the diameter of the tunnel ; which proportion will be less or more, according to the nature of the surrounding material : which, if made unnecessarily large, will seriously affect the cost of the tunnel by increasing the amount of excavation required ; and, if too small, will permit of distortion of the lining from a true cylindrical form and consequently of the setting up of bending movements round the joints.

The following table will show the proportion of the flange depth to the external diameter of the tunnel of some typical recent works :—

	External Diameter.		Depth of Casting.	Proportion of Depth of Casting to Diameter.
Tunnels in London Clay :—	ft.	in.	in.	
City and South London Railway, Small Tunnel, (1886)	10	$10\frac{3}{4}$	$4\frac{3}{8}$	·033
Ditto Station Tunnel (1899) . . .	22	6	$7\frac{3}{4}$	·029
Ditto Cross-over Tunnel (1899).	25	0	9	·030
Ditto Large Station Tunnel (1899) . . .	32	0	12	·031
Central London Railway, Small Tunnel (1896) .	12	6	$4\frac{7}{8}$	·032
Ditto Station Tunnel	22	6	$7\frac{3}{4}$	·029
Waterloo and City Railway, Small Tunnel (1894)	13	0	$5\frac{1}{8}$	·033
Tunnels in Water-bearing Strata :—				
Baker Street and Waterloo Railway (portion) .	12	$9\frac{3}{4}$	$4\frac{7}{8}$	·031
Mersey Tunnel (1888)	11	0	6	·045
Greenwich Tunnel (1899)	12	9	6	·039
Glasgow Harbour (1890)	17	0	6	·029
Hudson River Tunnel (1879)	19	6	9	·033
Blackwall Tunnel (1891)	27	0	{ 10 12	{ ·030 ·037
St. Clair Tunnel (1888)	21	0	7	·027
Rotherhithe Tunnel (1904)	30	0	14	·038

For tunnels in the London Clay an average depth of casting equal to ·031 of the external diameter of the tunnel has proved, therefore, satisfactory for tunnels up to 32 feet in outside diameter, while those in variable water-bearing strata,

[1] For these details in various tunnels see Tables at end of chapter.

although, as might be expected, showing less uniformity in the proportions, have an average depth of cast iron equal to 0·035 of the external diameter, the size of the tunnels ranging from 10 feet to 30 feet outside measurement. In the most recent large tunnels, however, the thickness of the iron lining bears a higher proportion than in the earlier ones to the diameter.

The width of a tunnel ring depends in the first place on the diameter of the tunnel. The greater the diameter of the tunnel the greater the length of stroke which can be given to the shield rams without making the shield too long in proportion to its diameter (and of course every inch added to the width of a ring adds two to the length of the shield), and when a tunnel is built with either horizontal or vertical curvature, it is very important to keep the shield as short as possible, in order to facilitate the driving of it.

In small tunnels too the impossibility, by reasons of lack of space, of using mechanical means for handling the segments limits their size by the weight the miners can conveniently handle; in larger tunnels, where mechanical erectors are used, this consideration has no weight, and the width of the segments is settled on other grounds.

Speaking generally, with any given depth of flange from back to front, an increase in the width of a segment beyond a certain limit, means that, in order to secure a good casting, the thickness of the web or skin of the segment must be increased beyond what is necessary for strength.

The practical experience of the last eighteen years has fixed 1 foot 6 inches to 1 foot 9 inches as a satisfactory width for tunnel segments in tunnels of all sizes; one important work only, the Blackwall Tunnel (to which must soon be added the Rotherhithe Tunnel) is built with segments greatly exceeding these dimensions.

Even in tunnels as large as that at Rotherhithe, where the ordinary rings are 30 inches wide, it has been found advisable to reduce these on the curved portions of the tunnel to 18 inches.

In the numerous railway tunnels of 10 feet 6 inches to 13 feet 6 inches diameter in London Clay, the width of a ring is now invariably 20 inches; in the larger tunnels for stations in the same material from 20 feet to 30 feet in diameter, 18 inches is the width always adopted.

In certain cases, when the small underground passages in the stations of the Central London Railway were constructed in iron without a shield, the rings were made of special tapered castings where the curves of the tunnel were of small radius: but these cases were few in number, and from their character of small importance.

In the Greenwich Footway Tunnel, where there are two vertical curves of 800 feet radius for a distance in each case of 60 feet, special tapered rings were specified, and, the tunnel being in water-bearing strata, undoubtedly made for improved tightness in the joints. But the confusion likely to occur in actual tunnel work from the employment of differing patterns of segments varying but little in dimension the one from the other is to be deprecated. When, as at Greenwich, it is specified that the segments of adjoining rings shall break joint, a double set of patterns is required for, and much extra trouble caused by, these tapered rings.

The thickness of the metal in the web or plate of a segment is decided on practical grounds. Given a flange depth of 5 inches or thereabouts, and a width of segment of 20 inches, a minimum of $\frac{3}{4}$ inch in the web is about the limit of sound casting, even with the best inspection, when segments are to be supplied by thousands, and in general, in work in London Clay, which is the most favourable material for tunnels in the matter of uniformity of pressure, $\frac{7}{8}$ inch is the thickness of web adopted. The flanges are usually made thicker to allow for the stress produced by unequal bolting up, particularly such flanges as do not form surface joints, but have an intermediate cushion of pine or other material. Each segment has usually at least one hole pierced in it, about $1\frac{1}{2}$ inches diameter, to receive the nozzle of the grouting hose. In water-bearing strata, these holes are, after grouting, tapped and plugged.

The number of segments in a ring is determined solely by considerations of convenience of handling, and of casting.

In the City and South London Railway (1886) in tunnels of 10 feet 2 inches and 10 feet 6 inches diameter a ring is formed of six segments and a key piece; in the Waterloo and City Railway, with rings 12 feet $1\frac{3}{4}$ inches internal diameter, there are seven segments and one key; and in the Greenwich Footway Tunnel of heavier metal, there are eight segments and key to a ring 11 feet 9 inches internal diameter.

The length of the ordinary or large segments in these rings, is respectively 5 feet 9 inches, 5 feet $8\frac{3}{4}$ inches and 5 feet 2 inches, all of convenient size to carry on a trolly or for handling by four men.

In the larger tunnels about 21 feet in diameter, built in the London Clay for railway stations, the length of the segments is about the same, 5 feet 10 inches, for the same reasons, though the actual erection of the segments is generally done by mechanical power. In this latter case, each segment has cast in the inside of the web at about its centre a lug by which it can be attached to the arm of the mechanical erector.

The key, or closing piece of the ring, is generally made sufficiently wide to abmit of one bolt at least in the end flanges. In some cases, a solid key has been used. When, however, it is desired to make the successive rings of a tunnel break joint, it is necessary to make the width of the key equal to the pitch of the bolt hole in the circumferential joint of the ring, or some multiple of that pitch, and to have one bolt hole or more in its end flanges, if all the bolt holes in adjoining rings are to be filled.

At the Blackwall Tunnel a solid tapered key was used; the later practice is, however, to have a hollow key with parallel flanges.

This of course involves making the two adjacent segments on either side with flanges to fit the key, and hence it follows that in every ring there are two segments having one end or longitudinal flange which instead of being the normal to the tangent at that point is parallel to the axis of the tunnel, passing through the centre of the key.

The difference between the two different flanges is not very perceptible, even in tunnels of small diameter, and less so in larger ones, and consequently the usual practice is, in order to facilitate the identification of these segments, to make them of a different length to the ordinary ones If the rings are to break joint the difference in the size of the segments must be a multiple of the pitch of the bolts in the circumferential flange or a multiple of it. Usually these segments are made shorter by a bolt hole than the others (see Fig. 30).

The segments are bolted together and to the adjoining rings, the bolt holes being usually made $\frac{1}{4}$ inch larger than the diameter of the bolts. In some cases the holes have been cast longer on the axis parallel to the skin of the segments than on the other (see Fig. 26), but this does not appear necessary, and, in the author's opinion, the size of the bolt holes might, if the segments are made to break joint, be with advantage made to fit the diameter of the bolts more closely than is the usual practice.

The diameter of the bolts used varies from $\frac{7}{8}$ inch in small tunnels to $1\frac{1}{2}$ inches diameter in the large tunnels at Blackwall.

Grummets are always specified to be used under the washers where required, and in tunnels in water-bearing material are essential.

In the Greenwich Tunnel, lead washers or seals were introduced with very satisfactory results. Short lengths of lead pipe were slipped over the bolt under the iron washers when the bolt was put in the hole, the ends of which were bevelled off to form a receptacle for the lead.

When the nut of the bolt was tightened up the lead pipe was forced into the bolt hole (see Fig. 32) filling up the ends of the hole completely.

The exact length of the pieces of lead pipe being once determined, a water-tight seal was obtained with certainty and with much less trouble than by any other form of caulking the holes. The risk of electrolysis being set up does not appear sufficiently great to form an objection to the use of this lead packing. An objection which was raised at the time to their use, namely that the inelasticity of the lead might cause a leaky joint, after the tunnel had been subjected to changes of temperature, has proved to be baseless.[1] The daily amount of infiltration in this tunnel, which is 1,200 feet long, and surrounded by water throughout its length, is only some 240 gallons.

The flanges of the cast-iron segments are in general made somewhat thicker than the web or skin, and for convenience of casting are tapered from the bottom to the top edge.

The horizontal or longitudinal flanges, each of which, in a circular tunnel, is radial to the circle, act as skew backs to the flange of the adjoining segment, and are on this account of more importance than the circumferential flanges, which perform no such work, and, only by the bolts connecting the adjoining rings, distribute in case of the settlement of one ring some of its load to the next.

So long as the horizontal joints of a ring are closed so that the flanges of adjacent segments are in contact for the entire depth of each flange, the ring, being subject to pressure from without only, is as strong or stronger at the joints than elsewhere.

If, however, by carelessness in the foundry, or in the work of erection of the ring, these joints are open so that adjoining segments bear only on the extreme inner or outer edge, then any movement of the ring due to pressure from outside is restrained only by the strength of the bolts holding the segments together, and by them only if in the first instance they have been tightly screwed up, a condition which is not always to be counted on.

These considerations have led to the adoption of various kinds of joint, but the general opinion in recent years is that, both in dry and water-bearing material a horizontal joint formed of flanges planed or milled and in contact for their entire depth, save only for a caulking space, is the best.

The cast-iron tunnels of the Glasgow District Subway were constructed with horizontal joints having fillets at the back, wood packings being used between the faces, and Mr. Simpson, the engineer of the work, defended this design on the ground that, the fillets being once in contact, the joint cannot open inwards by pressure

[1] See pages 53 and 63.

from outside, and that any tendency to open outwards is prevented by the solidity of the grouting behind. This line of reasoning appears to assume that the bolts in the horizontal flanges are not only capable of resisting any tendency to open inwards, as they in a well designed tunnel are, but also that they are perfectly screwed up, which is not always the case. This type of horizontal joint has not been used since, and most engineers are in accord with the opinion of Sir B. Baker that "were he a contractor he would have planed joints even if he had to pay the extra expense of them himself."

The system, now becoming more common, of breaking joint in successive rings, ensures that a weak place in one ring due to bad fitting does not coincide with a similar point in the adjacent ones, and has the further advantage that it checks at once any tendency in the tunnel to get out of shape.

That the cast-iron segments of a tunnel should be so arranged that wherever the key of a ring be placed all the bolt holes of that ring should be true with holes in the next rings is now an accepted condition of this class of work, and if this system be adopted the exactness of the horizontal joint is not so important as when all horizontal joints are in a continuous line.

One advantage of the horizontal joint with an outside fillet and wood packings is that, in water-bearing strata, it is possible, if leaks show themelves after the tunnel is constructed, to tighten the joints by driving in hard wood wedges. This was done in many places in the Glasgow Subway, and the cost of such work in compressed air is given as 1*s*. 5*d*. per yard of joint, rust jointing under the same conditions costing from 2*s*. 3*d*. to 2*s*. 6*d*. per yard.

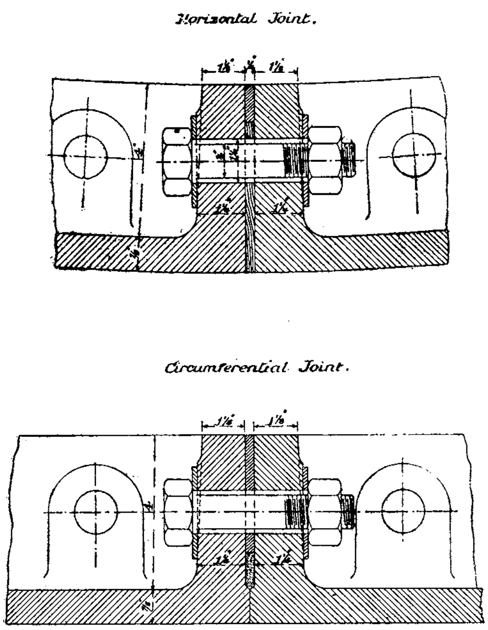


Fig. 23. Central London Railway.
Details of Joints of Cast-Iron Lining for Tunnels 11 feet 8¼ inches in internal diameter.

The circumferential joints are not so important to the strength of the tunnel as the horizontal ones, and consequently the variations in their type are dictated more by the necessity or otherwise of having a watertight connexion than by considerations of strength.

SOME EXAMPLES OF IRON-LINED TUNNELS

The Central London Railway

The cast-iron segments used on the Central London Railway are a good type of the tunnel lining used in the London Clay. These are shown in Figs. 23, 24 and 25.

In the small tunnels of this railway the flanges of the segments at the horizontal joints are unplaned, and between the segments is placed a creosoted pine packing, a little narrower than the metal flanges, pierced with holes for the bolts, $\frac{7}{8}$ inch in diameter, which hold the segments together.

The packing is made narrower than the flanges, to allow of subsequent pointing of the joint with cement.

In the circumferential joints the flanges are made with a fillet at the back (or outside) $\frac{7}{8}$ inch wide, and $\frac{1}{8}$ inch deep. Immediately within this fillet, and behind the bolts, is placed a rope of tarred hemp, sufficiently thick to make a joint fairly impervious to moisture when the rings are well bolted up.

When the grout is being forced behind the tunnel the tarred hemp prevents its return through the joints into the tunnel, and in cases where, as happens sometimes even in London Clay, water is met with, it keeps the joint fairly dry until the rust cement permanent jointing which in such cases is usually employed has time to set.

In ordinary circumstances the circumferential joint is pointed with Medina cement.

In the larger tunnels for the stations and cross-over roads on this railway, the horizontal joints are, as shown on Fig. 25, metal to metal, the surface of the

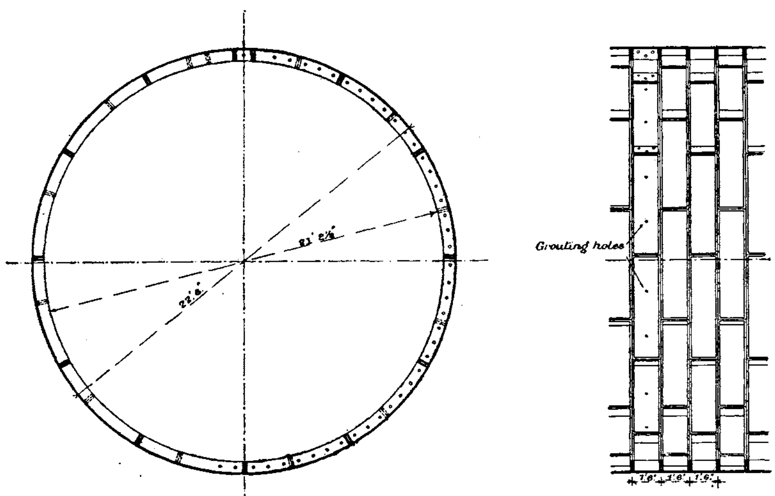


FIG. 24. CENTRAL LONDON RAILWAY.
Cast-Iron Lining for Tunnels 21 feet $2\frac{1}{2}$ inches in internal diameter.

flanges being machined smooth. The circumferential joints are similar to those of the smaller tunnels.

The bolt holes in these large tunnels are $1\frac{3}{8}$ inches in diameter, for $1\frac{1}{8}$-inch bolts, and in the horizontal joints were staggered ; in the circumferential joints they are arranged so that the successive rings of the lining may break joint when required, as is the case also with the smaller tunnels.

This work was the first in which the condition that the rings should break joint was laid down.

In the small tunnels, 11 feet $8\frac{1}{4}$ inches internal diameter, the rings were always built with continuous horizontal joints and the key at the top, unless for some special reason, such as the necessity for an opening in the side of the tunnel at some particular level, the segments of one or two rings were swung round ; but in the larger tunnels all rings were made to break joint.

In these tunnels no special castings were used for those lengths on horizontal or vertical curves, although some of the large 21-foot tunnels were built in five-chain curves and one of the smaller ones on a 200-feet one.

The necessary packing of the joints to keep the tunnels true to the curves was done in the case of small tunnels by the use of iron-plate liners which were inserted, two to each segment, in the circumferential joints.

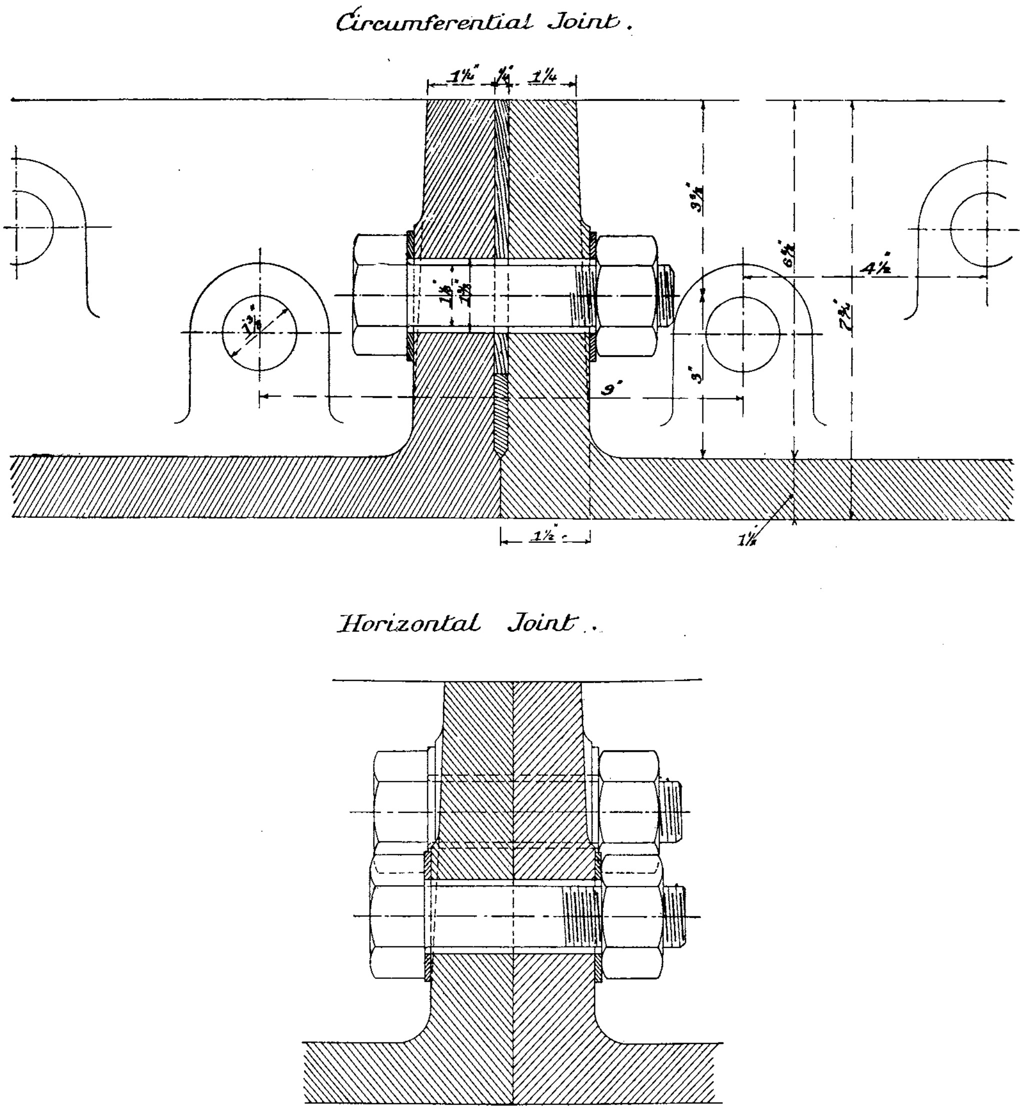


FIG. 25. CENTRAL LONDON RAILWAY.
Details of Joints of Cast-Iron Lining of Tunnels 21 feet $2\frac{1}{2}$ inches internal diameter.

In the two larger tunnels at the Bank Station, built respectively on a five-chain and 300-feet curve, hard wood packings of graduated thickness were used.

In the latter case the castings on the outside of the curve required packings 1·31 inches thick.

The Waterloo and City Railway

In the Waterloo and City Railway [1] ordinary tunnels, 12 feet internal diameter, the flanges of the segments are somewhat differently treated (see Fig. 26).

The horizontal flanges are planed, and no pine packing is used, the joint being metal to metal. In ordinary clay the flanges are planed for their entire depth; in water-bearing material a $\frac{3}{4}$-inch caulking space on the inside of the flange is provided, which is made solid with rust jointing. This form of horizontal joint is the most satisfactory of all, provided that care is taken that the flanges are actually in contact.

The circumferential joints, so far as regards their shape, are similar to those of the Central London Railway tunnels, the flanges being made with a fillet at the back, unplaned, so that packing can be inserted between them. The methods of making the joint are, however, somewhat different.

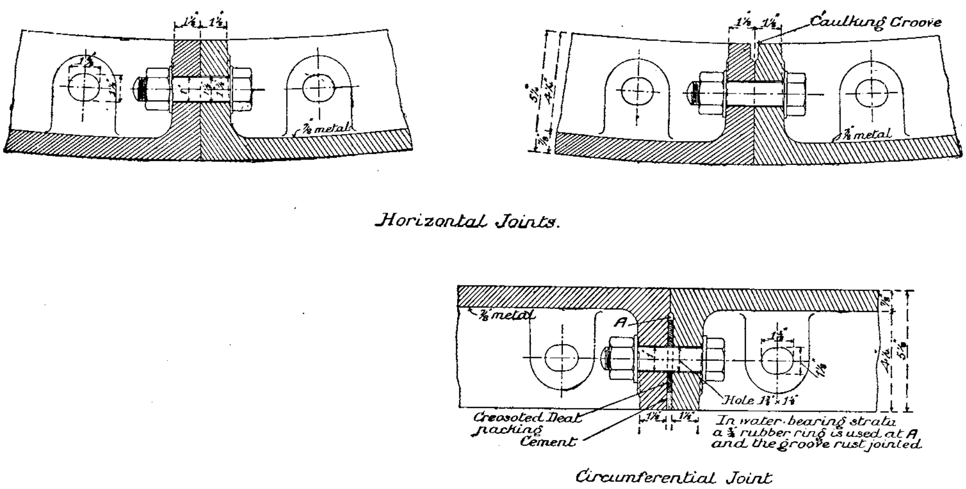


FIG. 26. WATERLOO AND CITY RAILWAY, LONDON.
Details of Joints of Cast-Iron Lining for Tunnels of 12 feet $1\frac{1}{2}$ inches internal diameter.

Where the tunnels are in London Clay a tarred hemp rope is placed immediately within the fillet, a packing of creosoted yellow deal of varying thickness as required filling the rest of the joint to within $\frac{3}{4}$ inch of the inner face, the remaining space being pointed with neat Portland cement.

In water-bearing strata, the rope of tarred oakum is replaced by a $\frac{3}{4}$-inch round red rubber packing, the remainder of the joint being caulked with rust cement. The use of the rubber had the effect of keeping the joint free from water until the rust jointing was set hard, but it is an expensive material to use, and, as is pointed out by Mr. Dalrymple Hay in his account of the work, no better than yarn as a solid joint for keeping the tunnel in shape.

To obviate this difficulty, hard wood packings were used in the joints from time to time to keep the tunnel in alignment.

It is also said that, in water-bearing strata, the ordinary white wood packings were in the first place put in the joints with the rubber packing behind, and when

[1] *Proc. Inst. C.E.*, vol. cxxxix. p. 32.

it was necessary to commence the rust jointing, were cut out again, and the full depth of the joint caulked with rust. It is not easy to see how with the best inspection the complete removal of the wood was effected, nor to understand how an open joint extending behind the bolts was satisfactorily caulked with rust afterwards.

In practical tunnel work, it is fairly well proved now, that a rust joint can only be made satisfactorily tight if the groove to be filled is free from all obstructions such as bolts make. The caulking groove shown in the horizontal joint in Fig. 26 can with ordinary care be made watertight by rust cement with little trouble ; it is doubtful if the attempt to caulk the groove of the circumferential joint in the same figure would result in obtaining a tight joint beyond the bolts ; that is, the extra labour spent in trying to make a deeper joint is probably wasted.

The larger tunnels for the City Station of this line were similar in their joints to the smaller ones just described.

A feature in both tunnels is that the bolt holes were all made ellipsoidal or slotted in shape, measuring in the smaller or ordinary tunnels $1\frac{5}{8}$ inches long by $1\frac{1}{8}$ inches broad for $\frac{7}{8}$-inch bolts, the longer axis being parallel to the edge of the flange.

The design of these two tunnels typifies fairly well the construction of cast-iron tunnels in solid fairly dry material, but tunnels constructed in water-bearing strata or in material of varying density require a more careful system of caulking than those just described, not only on account of the necessity of making the joints watertight, but also on account of the irregularity of the pressure which they may have to resist, and in consequence greater care is given to the jointing of the segments in such material than when the tunnels are in an almost watertight bed like London Clay.

The Baker Street and Waterloo Railway

The Baker Street and Waterloo [1] Railway passes under the River Thames at Charing Cross in two tunnels, 12 feet in internal diameter, and the iron lining of these tunnels shows in the details of the flanges an interesting compromise between the type of flange generally adopted for tunnels in London Clay, and that used in most subaqueous tunnels.

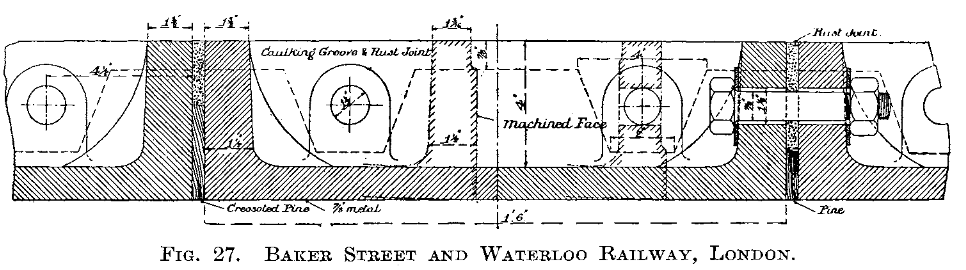


FIG. 27. BAKER STREET AND WATERLOO RAILWAY, LONDON.
Details of Joints of Cast-Iron Lining for Tunnels 12 feet in internal diameter.

The section of cast-iron tunnel lining shown in Fig. 27 was used in the part of the railway under the River Thames, the material passed through being in part clay, and in part gravel of a very open character, with very little sand, so that the tunnel was for some distance driven under the worst possible conditions. Satis-

[1] *Proc. Inst. C.E.*, vol. cl.

factory results were obtained by the adoption of the pattern of joints figured, under a head of water of about 60 feet.

The horizontal flanges were made with machined faces, but instead of the caulking groove being about $\frac{7}{8}$ inch deep on the inside of the joint, it was carried back round the bolt holes to enable the rust cement to be packed round the bolts. The form of circumferential joint ultimately adopted is that shown in the figure, machined joints having been first used. The circumferential flanges were not planed, and between the flanges a creosoted pine packing, cut as shown in the two circumferential joints, shown to have a packing space round the bolts. The packings were made slightly tapered, being thicker on the outside than inside, generally $\frac{5}{8}$ inch as compared with $\frac{1}{2}$ inch. When the rings were compressed together by the pressure of the shield, a watertight joint was thus ensured, even in cases where the joints were uneven, until the caulking was complete, and the joint made permanently secure.

In this tunnel the cast-iron rings are only 18 inches wide instead of the 20 inches usual in tunnels of this size.

The bolts are $\frac{7}{8}$ inch diameter, in $1\frac{1}{8}$-inch circular holes.

The thickness of the metal in the skin or web of the castings is $\frac{7}{8}$ inch, which for tunnels in such a situation is somewhat thin.

The machined flanges were painted before being put together with a mixture of red lead and Stockholm tar.

In these tunnels no grouting holes were provided in the lower segments of the rings, the idea being doubtless that at the bottom of the tunnel they were unnecessary, as the grout if put in at the sides of the tunnel would always run down to the invert.

This is no doubt correct in clay and similar beds, and in tunnels in waterlogged material it is of advantage to reduce the number of grout holes as much as possible, as they require, after grouting has been done, and before the air pressure in the tunnel is taken off, to be tapped, and closed with a plug.

But under ordinary circumstances anything which increases the number of different patterns of segments is to be deprecated, and in open water-bearing ballast, and when working under air pressure, the grouting, to be efficacious, should be blown in at as many places as possible.

The Blackwall Tunnel under the Thames

In the Blackwall Tunnel (1891),[1] which is a circular iron-lined tunnel of 27 feet external diameter, and is built for the most part in water-bearing strata, the crown of the tunnel being for some distance within 5 feet of the bed of the River Thames, and its invert for a distance of 1,200 feet some 80 feet below Thames high water, the whole of the flanges, horizontal and circumferential, of the segments are planed for their full depth, except only on a 2-inch caulking groove on the inside edge. No packing is used in the joints, nor any painting or smearing with red lead; but sometimes when a web joint was found, owing to imperfect fitting of the flanges, soft lead wire was caulked into the groove to keep the water from the rust cement until this had set.

Two sections of lining were used as shown in Figs. 28 and 29, the heavier consisting of segments 12 inches deep over all, with webs 2 inches thick, and flanges

[1] *Proc. Inst. C.E.*, vol. cxxx. p. 13.

proportionately thicker; and the segments of the lighter pattern being 10 inches deep, with 1½-inch webs.

The first section was used under the river and in the deeper parts of tunnel, and the second for a short length where the tunnel was nearer the surface.

In both patterns the rings are 2 feet 6 inches wide, each ring consisting of fourteen segments, and a solid tapered key about 6 inches wide. Each segment is 6 feet long (on the outside measurement).

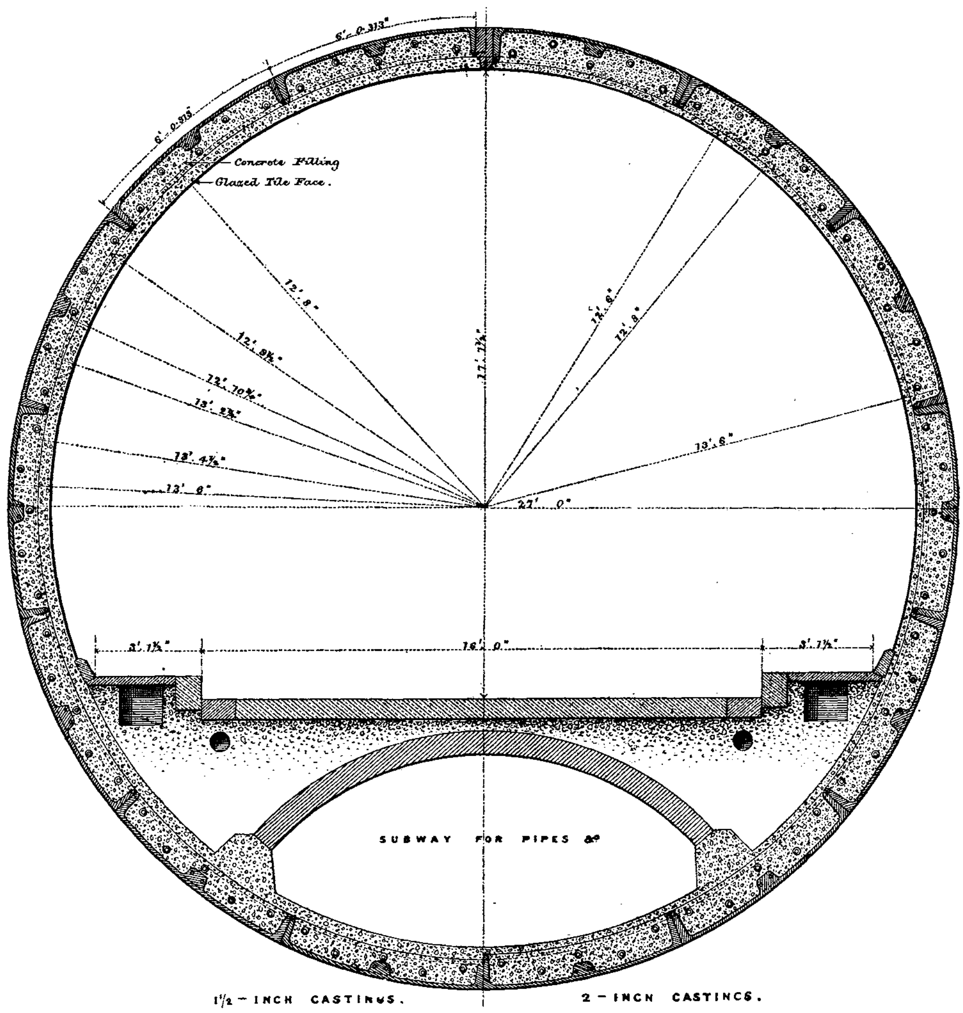


FIG. 28. BLACKWALL TUNNEL, LONDON.
Cross Section of Tunnel, showing two patterns of Cast-Iron Lining Employed.

The segments were not made to break joint, which, with a solid key, would not have been possible to do without leaving some blank bolt holes. The use of a tapered key has some advantage in case of fitting, but the almost universal practice at present is, as stated above, to arrange the segments of a ring, so that all the bolt holes in the circumferential flange will fit the bolt holes of the adjoining one even if the two rings break joint. To do this a hollow key, the width of which is not less than the pitch of the circumferential bolts, and if more, a multiple of the pitch, is necessary.

The rust jointing used in the joints is mixed in the proportion of ¼ pound of sal ammoniac to every 100 pounds of iron filings.

The grout holes in the castings are closed with screw plugs when the grouting is done, and are made tight with red lead and grummets.

The fixing of these and the caulking of the joints followed as soon as convenient after the erection of the rings, the immense saving of air resulting from

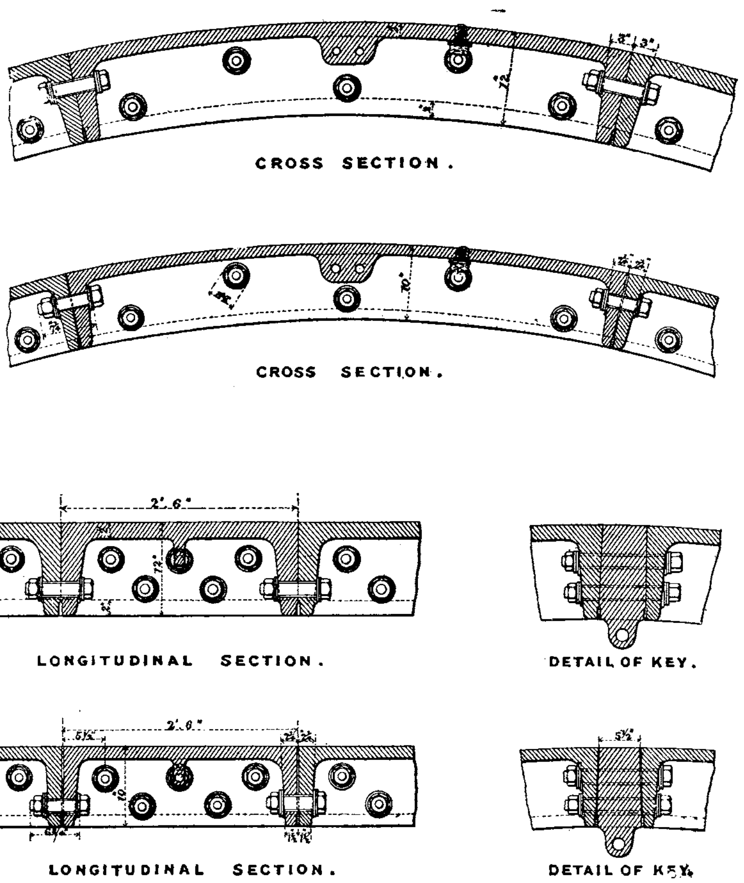


FIG. 29. BLACKWALL TUNNEL, LONDON.
Details of Joints of Cast-Iron Lining.

making the tunnel joints tight making it to the contractor's interest to lose no time in completely finishing the caulking making the tunnel watertight.

Observations were taken on the rigidity of the rings when the segments were put together and well bolted up. It was found that the rings of heavier section, each of which weighs 14 tons 16 cwt., did not when set up singly on the surface of the ground with only their own weight to support, deflect more than 2 inches. The same rings when fixed in the tunnel at a depth of 80 feet flattened to the extent of 4 inches, that is their horizontal diameter exceeded the vertical by that amount.

In the case of the lighter rings, each of which weighs 10 tons 10 cwt., the deflection was 2½ and 5 inches on the surface and in the tunnel respectively.

This tunnel lining has given highly satisfactory results. Excluding the open approaches, the tunnel proper is 4,464 feet long, of which 3,697 feet is iron-lined. The iron-lined portion contains over 180,000 lineal feet of rust jointing, and over 210,000 bolts, and in addition to the possible infiltration from these weak points, a certain amount doubtless comes in from the brick-lined parts of the tunnel, 767 feet long in all, yet the entire quantity of water pumped from the tunnel in dry weather only amounts to 3,500 gallons per day. (This quantity was measured in 1904.)

The Greenwich Tunnel under the Thames

In the Greenwich Footway Tunnel (1899),[1] which, like the Blackwall Tunnel,

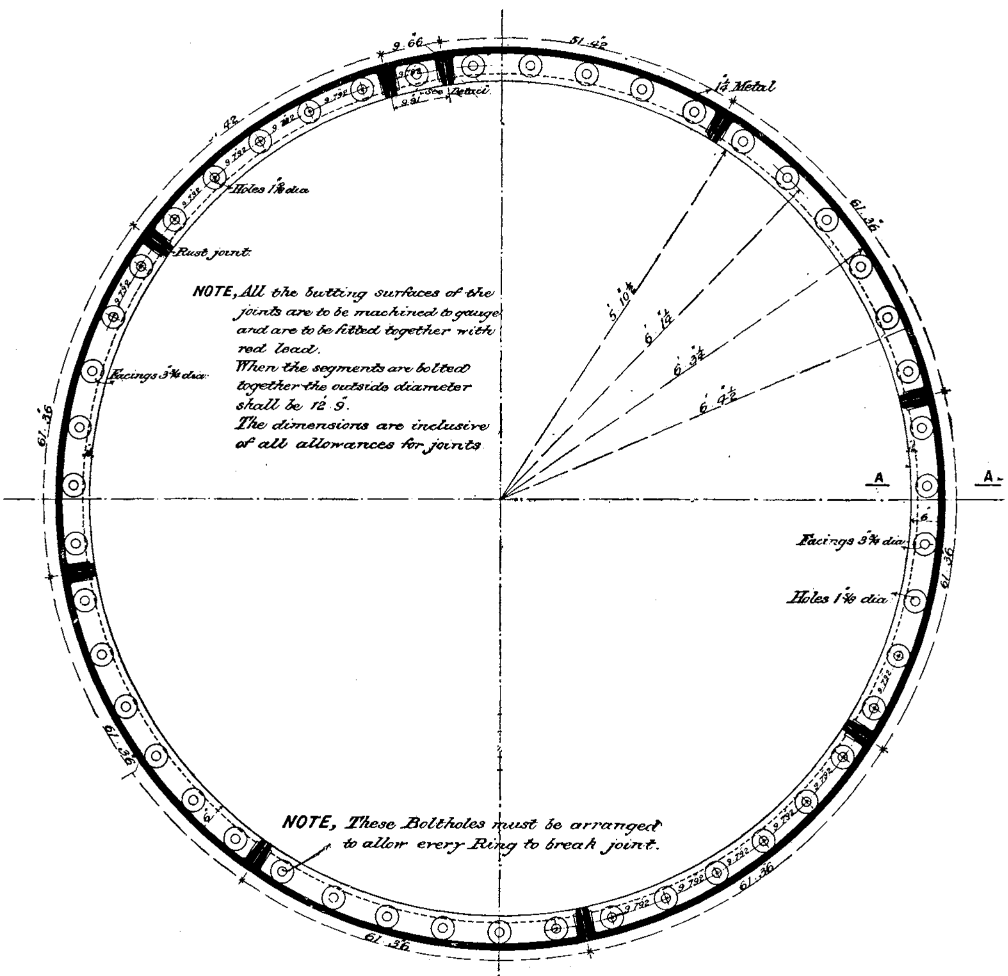


FIG. 30. GREENWICH TUNNEL, LONDON.
Cross Section of Cast-Iron Lining.

was carried out by the engineers of the London County Council, the details of the cast-iron lining differ but little from the Blackwall pattern. Some variations,

[1] *Proc. Inst. C.E.*, vol. cl. p. 12.

however, were made in details. The tunnel is 11 feet 9 inches in internal, and 12 feet 9 inches in external diameter, and for its whole length of 1,200 feet is in water-bearing material, and for 1,100 feet actually under the river the invert being, at the lowest point, about 68 feet below Thames high water (see Figs. 30, 31 and 32).

All the flanges of the segments were planed over their entire surface with the exception of a caulking groove as at Blackwall, and rust jointing was of course used. In this work, however, in all cases the grooves were first caulked with lead wire. This which at first was considered a superfluous precaution fully justified its use. When the air pressure in the tunnel was removed less than a dozen places in the 12,000 lineal yards of caulked joints required cutting out and caulking.

The bolts also were provided with lead washers (see Fig. 32), which proved very efficacious in keeping out water.

All bolt holes are made with their outer edges bevelled off. When the bolts were put in, lead washers (short lengths cut from lead pipes) were slipped on them under the ordinary iron washers, and, the bolts being screwed up, the lead washers were forced into the spaces made by bevelling off the ends of the bolt holes, completely filling them. This arrangement has proved very successful, and comparatively few bolts were found to be leaking when the air pressure was removed.

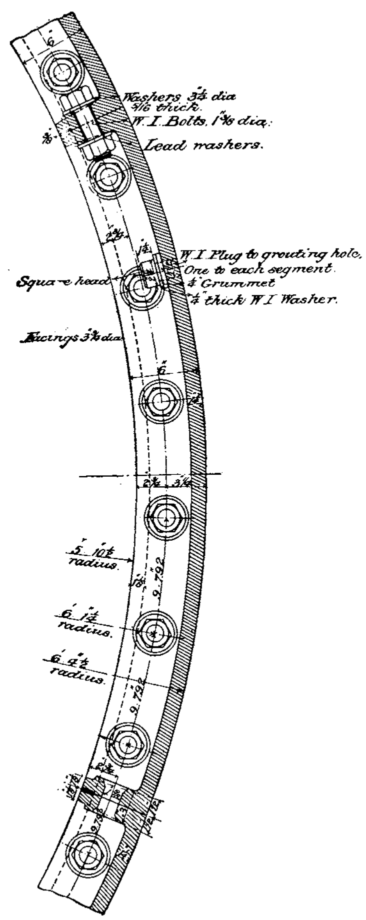


FIG. 31. GREENWICH TUNNEL, LONDON.
Detail of Cast-Iron Lining.

Each ring consisted of eight segments and a key, arranged so that successive rings can break joint. Until this tunnel was built, the cast-iron rings had only been erected in this way in the station tunnels of the railways in the London Clay, although the Central London Railway ordinary 11 feet 8 inch tunnels were constructed to do this when required.

The Greenwich Tunnel is the first of its size [1] in which every ring has been made to break joint with its neighbours.

The thickness of metal in the segments is heavier than usual, the weight of the lining being 4 tons $2\frac{1}{2}$ cwt. per lineal yard of tunnel as compared with 3 tons $10\frac{3}{4}$ cwt. in a similar tunnel under the Thames of the Baker Street and Waterloo Railway which is at nearly the same depth.

The bolts also are heavy for a tunnel of small diameter. As regards water-tightness, this tunnel lining is very satisfactory, the amount of water entering the tunnel by infiltration being only 240 gallons in twenty-four hours.

[1] The East River Gas Tunnel, New York, was made to break joint.

The St. Clair River Tunnel

The St. Clair River Tunnel, constructed in 1888–90, is on the line of the Grand Trunk Railway, which it carries under the river near Sarnia and Port Huron on the Canadian Boundary with the United States.

It is a cast-iron-lined tunnel, 2,000 yards long, and is almost entirely built in a soft clay, which again is overlaid by sand and silt, and these materials also were met with as pockets in the clay at the tunnel level.

It was built with a shield and compressed air, and the segments were designed to make watertight joints everywhere.

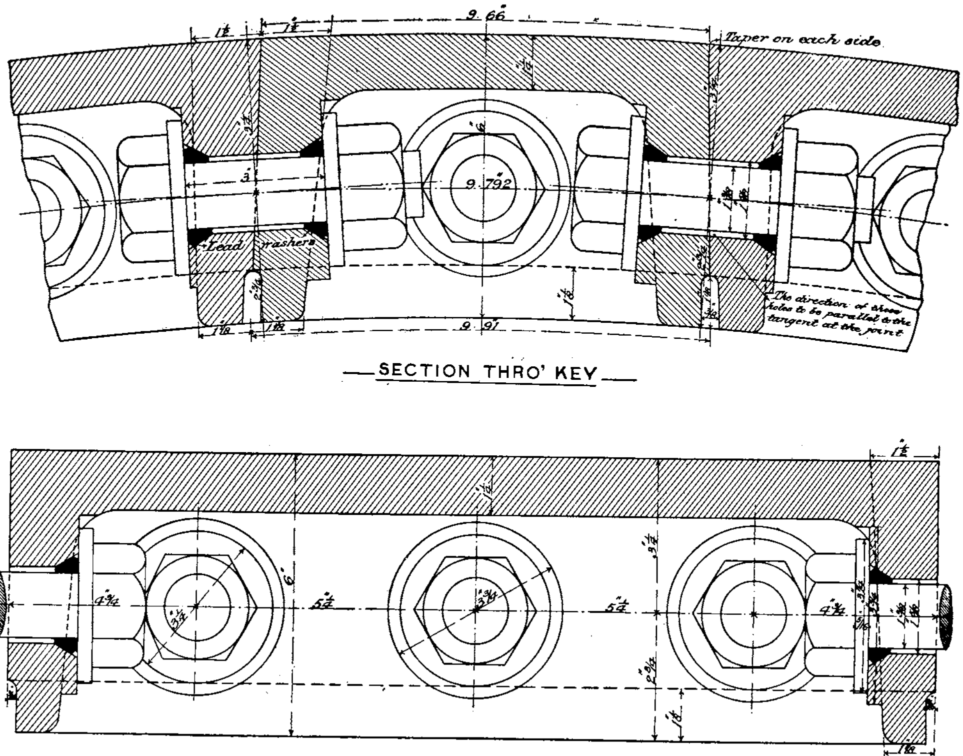


Fig. 32. Greenwich Tunnel, London.
Details of Cast Iron Lining.

The tunnel is 21 feet in external, and 19 feet 10 inches in internal diameter. Each ring is 1 foot $6\frac{1}{4}$ inches wide, and consists of thirteen segments and a key, each segment being about 5 feet long on the outside.

The details of the joints are shown in Fig. 33. For the horizontal joints the flanges of the segments are planed, but are not, as is usually the case with machine castings, built metal to metal. Between them is fixed a white oak packing, $\frac{3}{16}$ inch thick, which, after being bolted into its place, is swelled by the absorption of moisture from behind the tunnel lining, and so makes a perfectly sound joint. The machining of the flanges seems a somewhat unnecessary expense when the wood packing is used. In the Baker Street and Waterloo Railway, as just mentioned (see page 58), a watertight circumferential joint was made with a wood packing between unplaned flanges, which were, however, subsequently caulked. The life of these wood packings is somewhat uncertain, there being no data to go upon, as the period since they were put in is so short.

The circumferential joints were differently designed. The faces of the adjoining flanges are not planed, and the joints are made tight in the first place

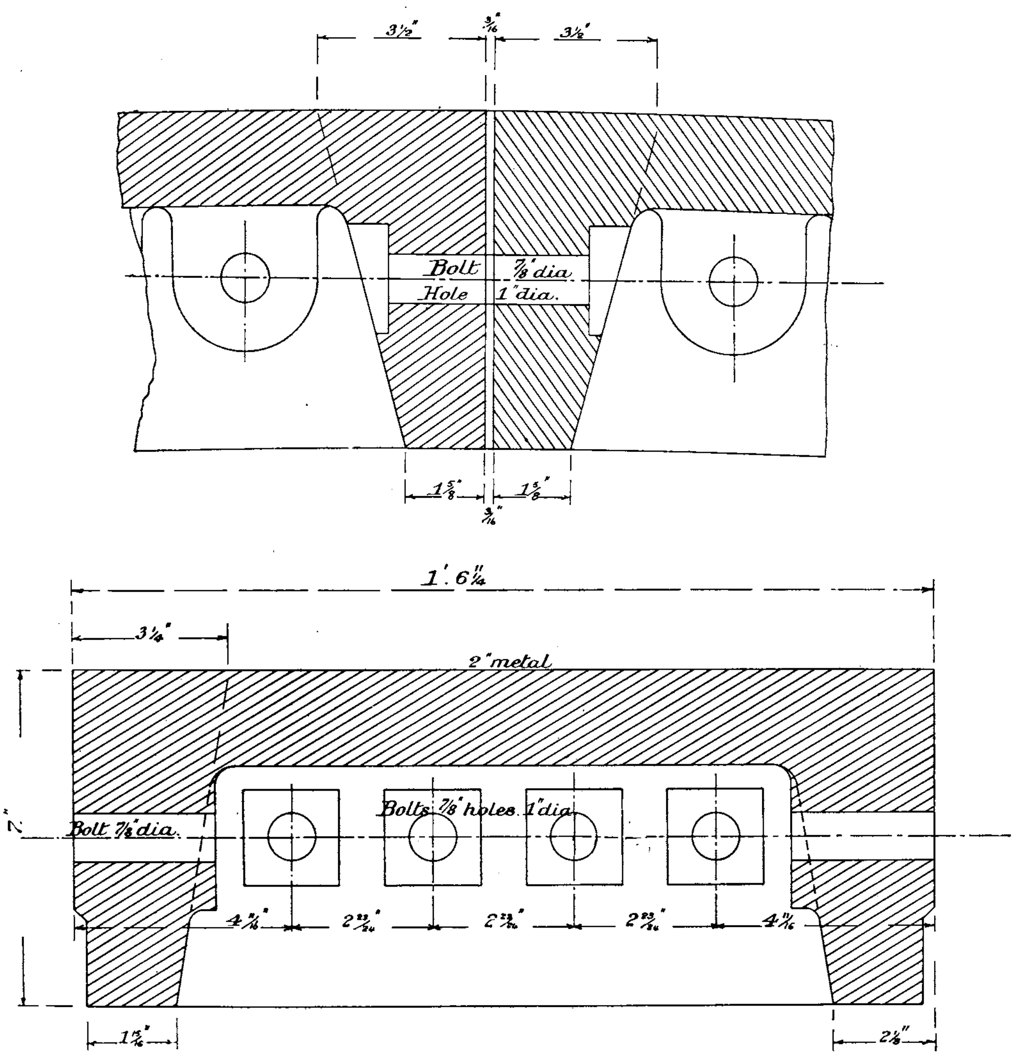


Fig. 33. St. Clair Tunnel, Canada.
Details of Cast Iron Lining.

by inserting between the flanges a layer of tarred canvas, and subsequently filling the caulking space provided on the inside with soft lead.

It is stated that these lead joints become absolutely watertight, but the general opinion is against the use of lead alone as a permanent caulking material. The lead being entirely non-elastic, and not making any bond with the cast iron, any movement of the tunnel after the joint has been caulked must open the joint, and cause a crevice to be found between the metals.[1]

[1] See pp. 53 and 63.

It is found that the tunnels under the Thames at Blackwall and Greenwich, which being open to public traffic are under daily inspection, invariably leak more after the prevalence of three or four days' cold weather than at other times ; the explanation usually given being that it requires that time for the reduction in temperature to affect the water in the beds under the river.

These tunnels are rust jointed, and the leaks observed in cold weather are found regularly in the same places, thus showing that the contraction in the tunnel lining caused by the cold always takes effect at the same points. The infiltration (for it is nothing more) can therefore be provided for ; but were the joints all made with lead packing, it appears to the Author that all movements in the tunnel lining due to temperature changes would result in small movements in an increased number of joints, with consequent increased difficulty of dealing with them.

The segments were cast of a mixture consisting of 80 per cent. of old wagon wheels and 20 per cent. of Scotch pig.

The specification as to error of size and weight allowable was strict, $\frac{1}{32}$ inch being the permissible error in castings 5 feet long.

The segments when finished were heated to 400° Fahr. and then dipped in tar.

This tunnel was not grouted outside as are the tunnels in the London Clay. The lower half of the tunnel was made solid behind by pouring into the grout holes in the segments by means of a funnel liquid Portland cement grout, the space left round the upper half of the tunnel by the removal of the shield skin being allowed to become solid by the settlement of the clay above.

This, no doubt, was perfectly satisfactory under the River St. Clair, where no property or buildings could be affected by a slight movement of the ground ; it is not, however, a method to be recommended even in such a case.

In this tunnel a concrete floor is put in to carry the sleepers and rails, as is done in all the other railway tunnels constructed in iron, and in the lower half of the tunnel a lining of concrete is made, covering to a depth of about an inch the segment flanges, and offering a smooth surface in case of any derailment of a train.

It was also feared that without some such protection, the dripping of brine from the refrigerating cars might damage the metal of the tunnel lining.

The upper part of the tunnel is simply tar painted and cleaned from time to time.

The actual amount of pumping necessary to keep down the water leaking through the tunnel lining amounts to some 22,000 gallons daily, which, compared with the results obtained in other places, appears a large amount.

The Great Northern and City Railway

The Great Northern and City Railway (1898) connecting Finsbury Park on the Great Northern Railway with the City of London differs somewhat from the other tube railways in the London Clay, both in the size of the tunnels and in the use of brickwork as well as of cast iron on the permanent lining of the tunnel (see Fig. 34).

The ordinary running tunnels are 16 feet in internal diameter, each cast iron ring as originally erected being 1 foot 8 inches wide, and comprised of eight segments and two key pieces. The flanges for the horizontal joints were not planed, but between them was inserted a wood packing as in the Central London Railway Tunnels. The circumferential flanges also followed the usual pattern. But the provision of two keys, the one in the invert and the other at the soffit of the tunnel, was a novel feature, the bottom key being provided to allow—the complete tunnel lining having been built in the ordinary way under shield—of the lower portion being removed in short lengths, and a brick lining substituted.

This was actually done, the lower key in each ring being removed, and so permitting the removal of the adjoining segments.

The two lower segments on either side of the key were removed, leaving practically the upper half of the original cast-iron lining in place.

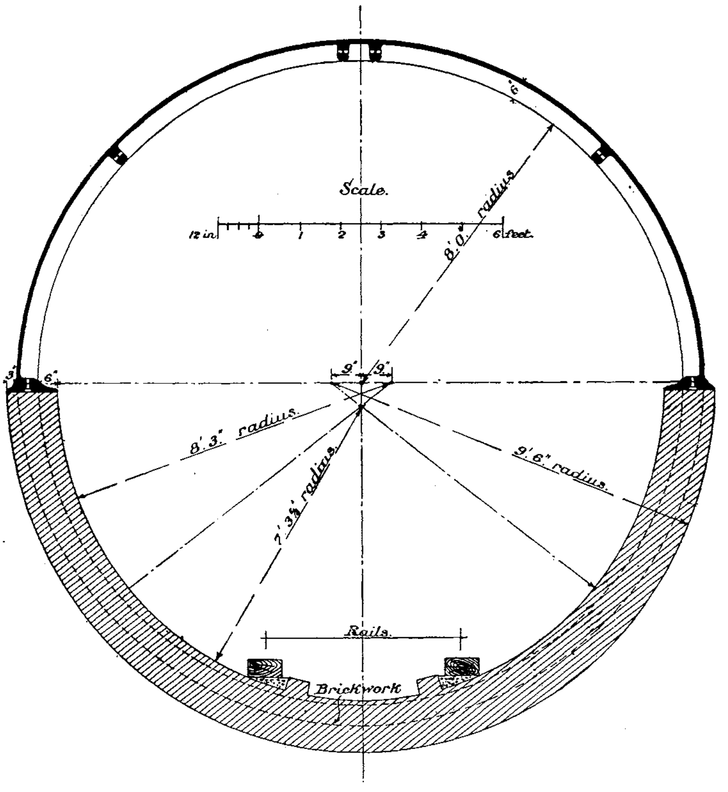


FIG. 34. GREAT NORTHERN AND CITY RAILWAY, LONDON.
Cross Section of Tunnel in Cast Iron and Brickwork.

The lower half of the tunnel was then enlarged by cutting out round the excavation already made 4 or 5 inches more of clay. This done a three-ring brick lining was built, having its internal diameter some 8 inches less than that of the original iron tunnel. The junction between the brick and iron was by means of a shoe or sole plate, the lower face of which was the full width of the brick lining.

It is claimed that this brick invert greatly diminishes the noise made in the tunnels by the trains and the vibration caused by them in buildings on the surface, but in any case vibration caused by the running of trains at a considerable depth in the London Clay, unless very heavy locomotives are used, is an inappreciable quantity, and the diminution in noise in a tunnel smooth lined as compared with one in which the iron segments are left bare is very small.

As to this latter advantage it may be pointed out that the Waterloo and City Railway was lined smooth with concrete through its entire length with the view of deadening the sound, but when this railway was opened, the effect of the expensive lining was found to be so small that the engineers of the Central London Railway then under construction abandoned the idea of lining the tunnels, which was specified in the original contract for the construction of the line, and the tunnels of that railway, excepting of course the station tunnels, were left of bare cast metal.

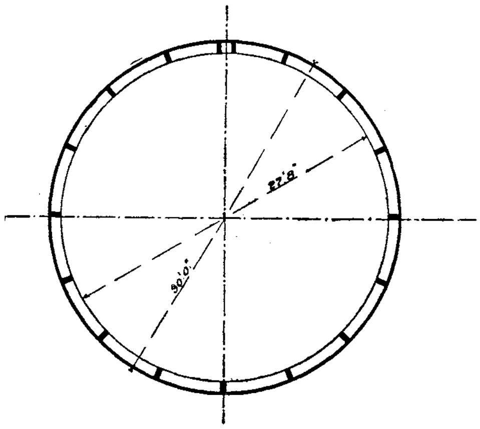


Fig. 35. Rotherhithe Tunnel, London.
Cross Section of Cast Iron Lining.

On grounds of practical improvement of the railway this compound system of tunnelling does not appear very satisfactory ; but it is possible that some economy in construction may be made by the substitution of brick for cast iron in cases where the price of cast iron is higher, and the cost of labour lower, than in this country. But the advantage in the matter of cost would hardly outweigh the disadvantage of building the tunnel in two operations, and so nullifying the main advantage of a cast-iron lining ; that is, the possibility of putting in, once and for all, a permanent lining which at once attains its full strength.

Another feature in this work presenting some novelty is the type of large tunnels used for containing the cross-over roads or scissors crossings at the station

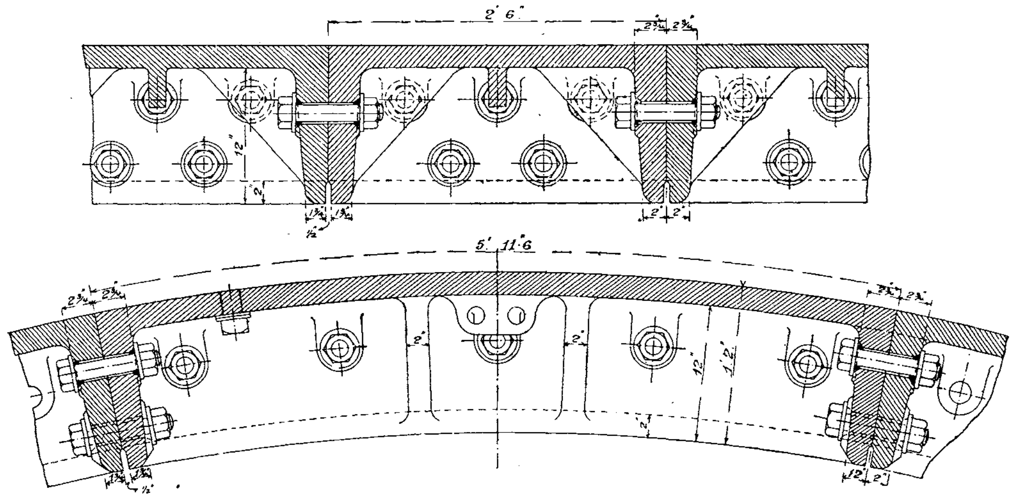


Fig. 36. Rotherhithe Tunnel, London.
Details of Cast Iron Lining.

where are junctions between the running lines. These tunnels, which were not built under shield, are not circular. The upper half is a true circle of 15 feet radius, the lower half being flattened in the invert, and the sides below the springing line of the roof made of sharper curves. The effect of this construction is to gain greater width of tunnel at the rail level.

The horizontal flanges in these large tunnels were planed, and the joints bolted up metal to metal, a caulking space being left in the inside face of the casting.

The Rotherhithe Tunnel under the Thames

The Rotherhithe Tunnel under the Thames is now in course of construction (1904), and the details of the cast iron lining designed for it are shown in Figs. 35, 36, 37 and 231. In general they resemble the work at the Blackwall and Greenwich Tunnels, and the details of the flanges are only shown here as this tunnel is the last and largest built in iron, its external diameter being 30 feet.

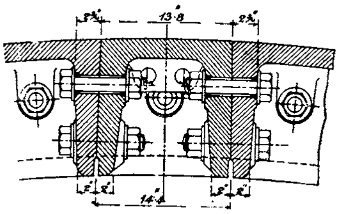


FIG. 37. ROTHERHITHE TUNNEL, LONDON.
Details of Key.

The rings are 2 feet 6 inches wide, each having twelve segments and one key.

They are made to break joint.

The flanges are similar to those at Blackwall and Greenwich, but they are specified to be smeared with red lead before being fixed in position and bolted up.

The Lea Tunnel

A cast iron tunnel, 11 feet 6 inches in internal diameter, under the River Lea, was built in 1891–2, as a part of the additional outfall sewer on the north side of the Thames carrying the drainage of London to the Outfall Station at Barking Creek. It passes under three branches or arms of the River Lea, and for the

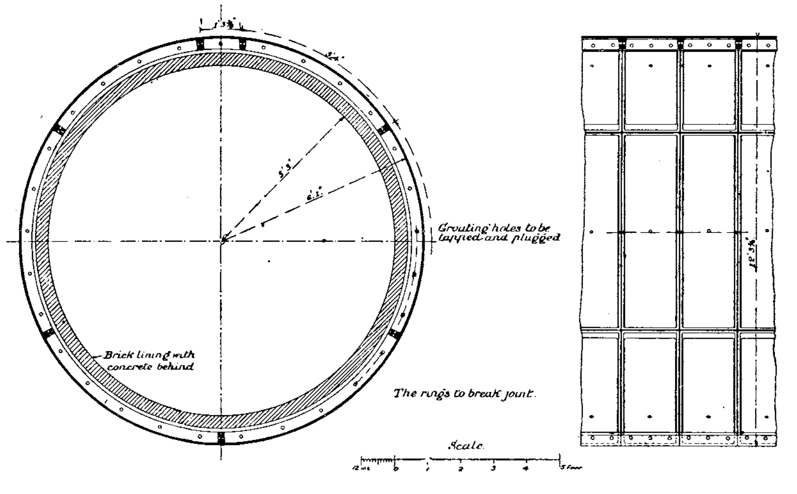


FIG. 38. LEA TUNNEL, LONDON.
Sections of Cast Iron Lining.

greater part of its length is made in open ballast and peaty clay. The depth of the tunnel beneath the surface of the ground is not great, about 20 feet being the largest cover over the tunnel, and the bed of the river being within 8 feet of the shield face.

The iron lining was therefore made lighter in section than the tunnels in water-bearing strata previously described (see Figs. 38 and 39), the web or skin of the plates being only ⅞ inch thick, and the flanges in proportion. The flanges were all planed, a grouting space being left within. The caulking was done with rust cement.

When completed the iron tunnel was lined first with concrete, made to cover

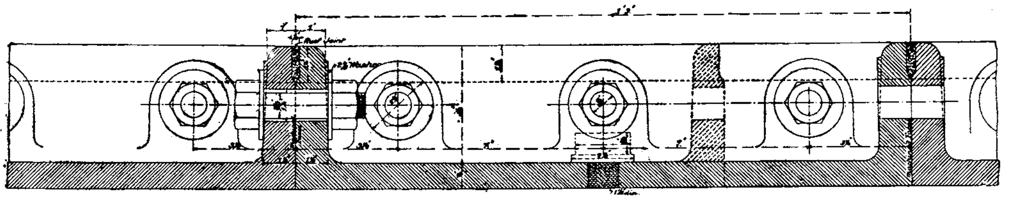


FIG. 39. LEA TUNNEL, LONDON.
Details of Cast Iron Lining.

the flanges to the depth of 1½ inches, and this concrete was again lined with a brick ring 4½ inches thick, the upper half being of ordinary pressed bricks, the lower of blue bricks.

The sewer when finished was found to be absolutely watertight, which, considering the small head of water, some 30 feet, on the invert was to be expected.

Casting of Tunnel Segments.

The casting of the cast iron segments for tunnel lining does not differ greatly from other foundry work.

The mixture used for the Blackwall tunnel segments was made as under :—

	cwt.
No. 3 Pig Iron (English or Scotch)	10
Hematite	2
Scrap (machinery, chain, etc.)	6
,, (heads and gates)	2
	20

The tests employed were 8 tons tensile strength per square inch of section ; and for transverse strain, a bar 3 feet long between supports, and 2 inches deep by 1 inch wide had to bear 28 cwt. at the centre.

Test bars were run twice a day.

The moulds for these castings,[1] as well as those used in the Greenwich Footway Tunnel, were made in a patent moulding machine designed by the British Hydraulic Company, the sub-contractors for the material.

This Machine (see Figs. 40 and 41) rests on three main cast iron girders, 9 inches deep by 9 inches wide on the flanges, supporting the main cast iron framing, on whose top is carried the pattern.

The main cast-iron framing is 8 feet 3 inches by 4 feet 4 inches by 2 feet deep, and forms the recess into which the sides of the pattern are retired previous to drawing the body of the pattern.

[1] *Proc. Inst. of Engineers and Shipbuilders in Scotland*, 1895. Carey on "Cast Iron Segments."

The moulding box surrounding the pattern is 7 feet by 3 feet 4 inches by 1 foot 8 inches deep.

The essential feature of the machine is that the main framing is hinged, and revolves on large bearing surfaces turning completely over, and carrying bodily with it both pattern and mould.

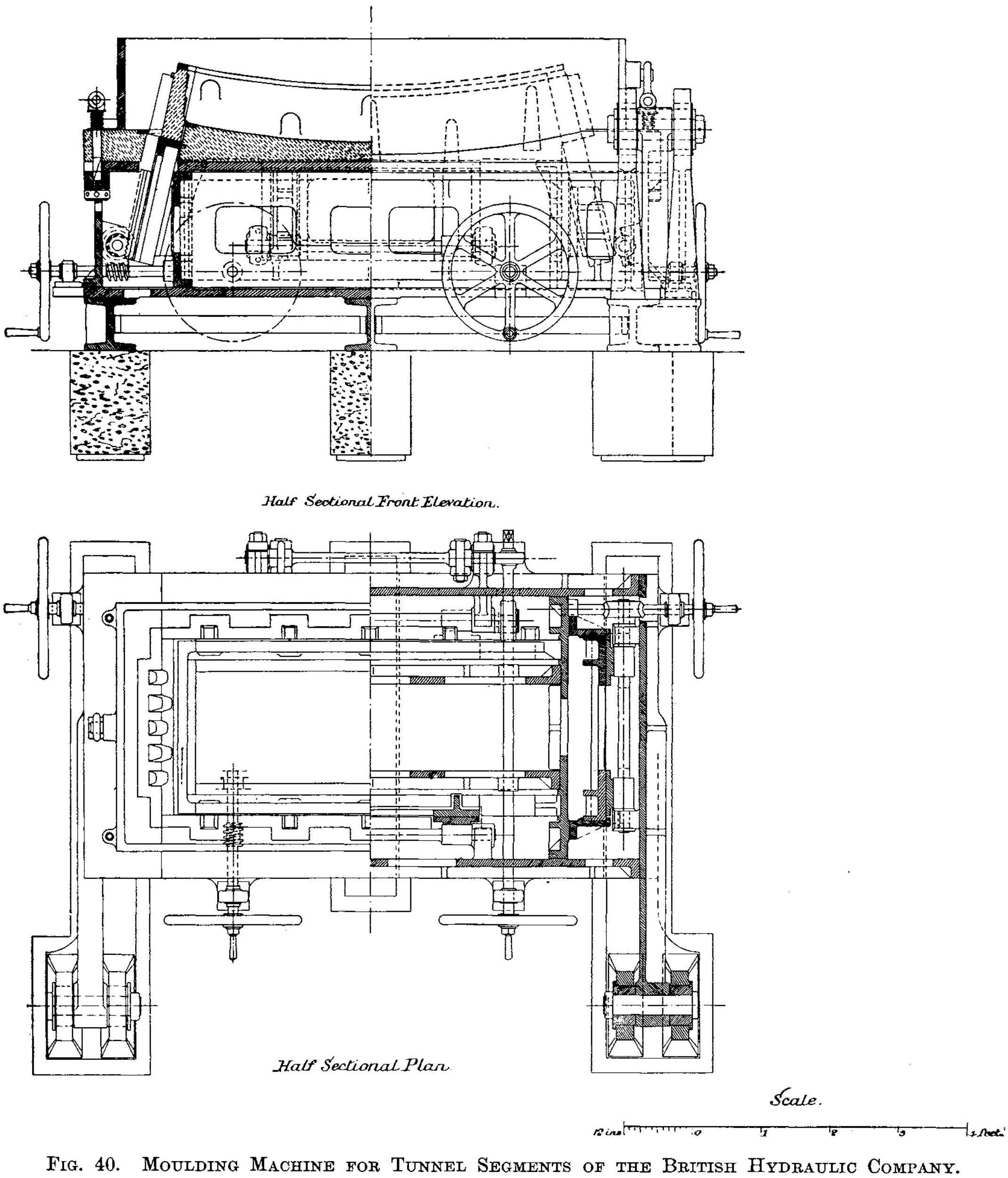


FIG. 40. MOULDING MACHINE FOR TUNNEL SEGMENTS OF THE BRITISH HYDRAULIC COMPANY.

Four hand wheels 24 inches diameter actuate worms and raise or lower the flange of the pattern to enable the mould to leave the same, the travel being the height of the flange.

The moulding box is held down by two screw clamps, one at either end.

The girders rest on blocks of brickwork, the H beams being bolted together by Cast Iron distance pieces.

The pattern, which is made of mahogany, is brass bound at the edges.

Operations are conducted as follows :—

The mould box being in place, with the flanges in position, the box is filled with sand and the pattern rammed up; a cast iron plate forming a lid is then clamped on to the top of the moulding box and the whole main frame with moulding box and pattern is turned over by means of an hydraulic crane.

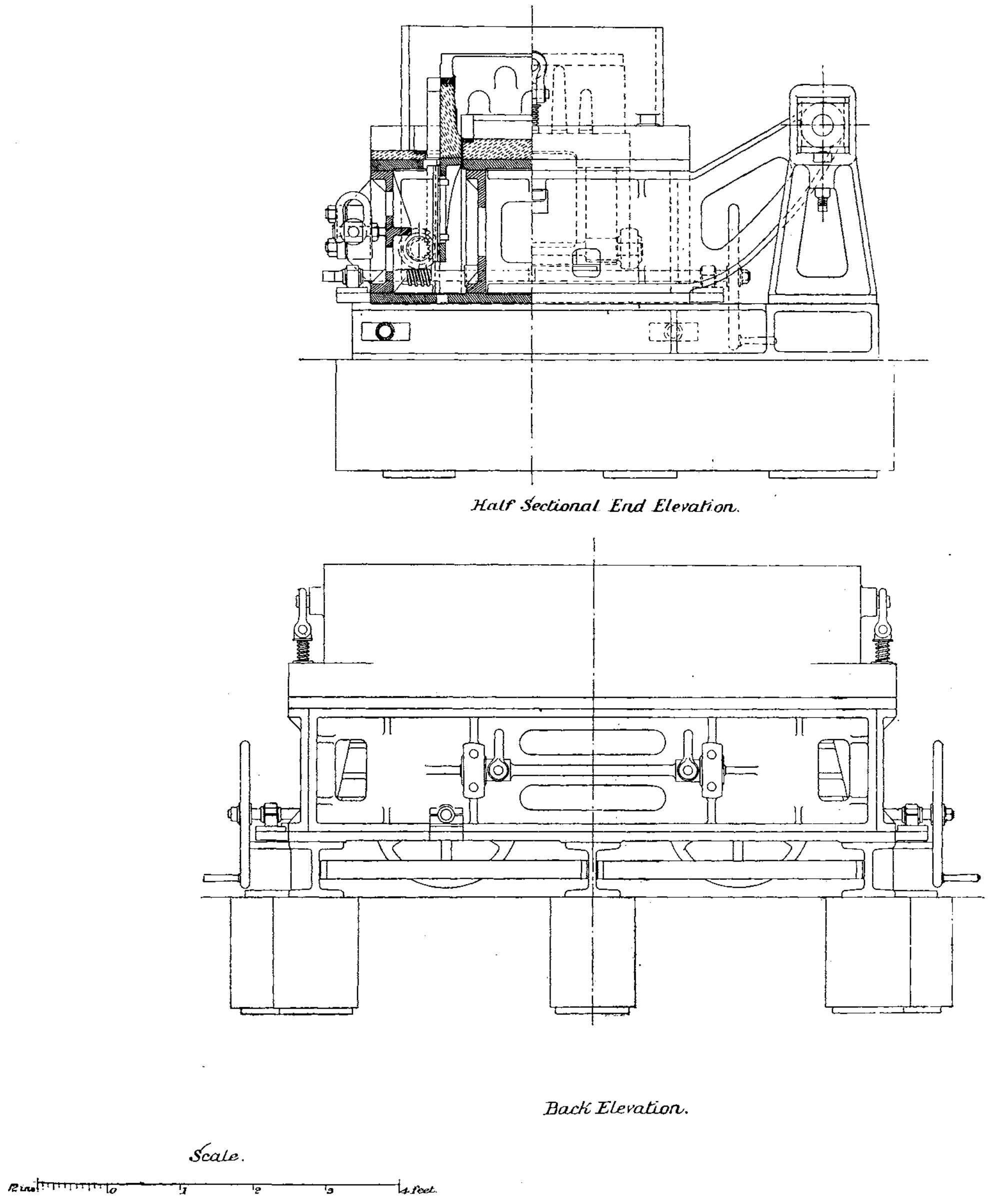


FIG. 41. MOULDING MACHINE FOR TUNNEL SEGMENTS OF THE BRITISH HYDRAULIC COMPANY.

The flanges are then withdrawn by means of the four handles already described, and the clamps holding the moulding having been released, the main frame is turned back again by the hydraulic crane into its original position, leaving the mould ready for coring, finishing and receiving the top part which has in the meantime been moulded by hand.

The cores are made by hand in the usual way, and call for no special remark.

The facing sand consists of—
2 parts white rock sand }
1 part Belfast red ,, } with equal bulk of old black sand.
1 ,, Coal dust }

The segments were all dipped cold into Angus Smith's composition and kept in until the solution was made to boil.

The faces of the joints were milled, and extremely accurate results were obtained.

The small keys were moulded by hand.

IRON TUNNELS IN LONDON CLAY

QUANTITIES PER YARD FORWARD.

Internal Diameter. Feet.	Excavation. C. yds.[1]	Cast Iron. Tons.	Wrot. Iron in Bolts, etc. Cwts.	Grouting. Sup. yds.[2]
10·5	11·3	2·50	1·75	12·00
11·5	13·63	2·83	2·00	12·90
11·68	14·00	2·85	1·95	13·09
12·42	15·70	3·01	1·95	13·90
12·58	16·01	3·05	1·95	14·05
13·00	17·52	3·25	3·00	14·66
15·00	24·00	5·70	3·50	17·00
21·20	45·16	8·25	6·45	23·56
25·00	62·44	11·55	10·25	27·75
27·00	73·40	14·15	10·68	30·40
30·00	91·50	20·00	12·00	34·00

NOTE.—The quantities in tunnels of the same diameter on different railways vary a little. For the most part the figures given above are those of the Central London, and of the City and South London Railways.

[1] Measured net sectional area of outside tunnel.
[2] Measured net outside surface of tunnel.

CAST IRON TUNNELS IN WATER-BEARING STRATA

Quantities of Material, etc., per Yard of Length

Name of Tunnel.	Date of Comt.	Internal Diameter. Feet.	External Diameter. Feet.	Depth of Flanges. Inches.	Thickness of Metal. Inches.	Width of Rings. Feet.	Wt. of Cast Iron. Tons.	Wrot. Iron in Bolts, etc. Cwts.	Grout holes to tap. No	Joints to Caulk lin. yds.	Grouting. Sq. yds.[1]	Dia. of Bolts. Inches.	Excavation. Cub. yds[2]	Remarks.
Mersey (Fidler's Ferry) . . .	1890	9·00	10·00	6	1·68	1·50	4·10	—	—	—	10·48	—	8·69	Alluvial beds, silt and gravel.
Greenwich . .	1899	11·75	12·75	6	1·25	1·66	4·125	7·5	14·25	31·00	13·40	1·375	14·25	Gravel, shelly clay, sand. 273 lead washers to bolts.
Baker Street and Waterloo Rly. (Portion under Thames) . .	1898	12·00	12·81	4·875	1·00	1·50	3·48	2·04	6	33·80	13·40	0·875	14·25	London Clay and gravel. Groutholes in upper segments and key only.
Hudson River . .	1879	18·00	19·50	9	1·25	1·68	8·11	—	—	—	20·42	—	33·11	Soft silt.
St. Clair River .	1889	19·83	21·00	7	2·00	1·52	12·5	6·67	—	55·50	22·00	0·875	38·5	Hard and soft clay.
Blackwall (1) .	1892	25·00	27·00	12	2·00	2·50	17·17	11·52	—	44·00	28·27	1·50	63·6	Heavy section under river Clay and open ballast.
,, (2) .	1892	25·33	27·00	10	1·50	2·50	12·60	11·52	—	44·00	28·27	1·50	63·6	Lighter section.
Rotherhithe (1) .	1904	27·66	30·00	14	2·00	2·50	22·56	16·31	20·4	52	31·41	1·50	78·54	Heavy section under River.
,, (2) .		27·66	30·00	14	1·75	2·50	22·04	15·56	20·4	52	31·41	1·50	78·54	Lighter Section. 383 lead washers for bolts.

[1] Measured net outside area of tunnel.

[2] Measured net sectional outside area of tunnel.

Chapter IV

THE GREATHEAD SHIELD IN LONDON CLAY

The Shield—The Assisted Shield—General Conditions of Tunnel Work in London Clay—Movement of the Exposed Face—Type of Station Shafts—Details of their Lining—Break up for Shield—City and South London Shield the Prototype of all Subsequent Machines in London Clay—Detailed Description of it—The Grouting Pan—The Various Operations of Working the Shield—General Observations—Speed an Essential—Wedges for Breaking down the Face—Guiding of the Shield—Hay's Patent—Cost of Labour Employed—Glasgow District Subway Shield—Central London Railway Small Shields—Employment of Pumps on Shield—Special Shield for use with Thomson's Excavator—Thomson's Excavator—Price's Combined Shield and Excavator—Great Northern and Strand Shields—Arrangement of Shield Rams and Removal of Diaphragm—Greathead Shields of Larger Diameter than 13 Feet—Station Shields of the Waterloo and City and Central London Railways—Great Northern and City Railway and Kingsway Subway, Shields—The Segment Erector of these Latter—Method of Working of the Kingsway Subway Shield on a Face having Ballast at the Top—A Method of Supporting a Clay Face in an Iron Lined Tunnel of Large Diameter

AFTER the construction of the Tower Subway and of the Broadway Tunnel in 1869, which works may be said to have proved the practicability of tunnelling by means of the modern shield, no further work of the same kind was done until 1886, when the "London and Southwark Subway," afterwards called the "City and South London Railway," of which Parliament had authorized the construction in 1884, was commenced.

The railway connects the City of London with the suburb of Clapham on the south side of the River Thames, under which it passes, and with Islington on the north. It is, with the exception of a short distance near Stockwell, constructed entirely in London Clay.

The portion of this railway between the City of London and Stockwell Station was the length included in the first project of 1884, and on it, for the first time on a large scale, the shield designed by Mr. Greathead was put to the test. The remarkable success of the undertaking from an engineering point of view speedily resulted in the application of the system to other enterprises of like nature, and to-day tunnelling under shield in London Clay is reduced, one may almost say, to an exact system, but in the general design of the shield for tunnels under 14 feet in diameter, practically no change has been made since construction of the first tunnels of the City and South London Railway.

The later shields differ somewhat in the details of the mechanical appliances, and there are now used shields of larger diameter than those of the South London Railway, but the method of working them remains substantially unchanged since 1886, whether the work to be done is in London Clay or in less easily worked material.

A description, therefore, of the shield as used on that railway and of the method of working it will serve as a general introduction to all subsequent work under shield, the variations introduced from time to time in the structure of the shields employed in water-bearing material being considered afterwards.

For a short distance the tunnels on the City and South London Railway were constructed through water-bearing beds of open gravel, by employing the method known in somewhat awkward English as the " assisted shield " method.

This method of working has since been employed in the Glasgow Harbour Tunnels, the Glasgow Circular Railway, on the Waterloo and City Railway (for a portion of the work in water-bearing strata) and in other places.

It consists in protecting the excavation in front of the Greathead shield by timbering of similar character to, but lighter than, that employed in ordinary tunnel work, and it is of course open to the objection that unless very carefully carried out, some settlement of the superincumbent material which it is the principal merit of the shield system of tunnelling to prevent, is almost certain to occur.

As the ordinary Greathead shield is not adapted for work in loose water-bearing material, or, indeed, in loose material of any kind, either with or without compressed air, it is better, when any considerable length of tunnel has to be driven through such material, to provide a more suitable shield, such as are now made, at the outset of the work, and so, by the sacrifice of some of the ease of working on good material possible with an ordinary shield, to obtain better protection and increased rate of progress in the places where the material met with is bad.

But, as even in London Clay, pockets of ballast are not infrequently met with, cases may arise in the future, as in the past, when the ordinary Greathead shield requires the assistance of timber work in the face for short distances, and, therefore, the " assisted shield " is dealt with in the next chapter.

Before describing the working of the Greathead shield in the clay, a short description may usefully be given of the general conditions under which deep level tunnelling work is carried on in London, and which are common to all the " tube railways." Under the greater part of London, from Hampstead on the north to Kennington on the south, and from the City on the east to the open country on the west, is a bed of thick homogeneous clay, known as London Clay. This is usually found from 10 to 30 feet below the present ground level, and it has a thickness of generally 70 to 100 feet. It varies little in character ; in some places it is apparently softer than in others, judging by the rate of tunnelling operations ; occasionally " backs " are found which require care when working a large face, and in places, particularly under old watercourses, the clay is found " short " and rotten, but generally speaking it is a perfect medium for tunnelling operations, its entire immunity from faults or dislocations of any kind enabling tunnel work to be estimated for without having to take into account so largely as is usual in tunnel contracts possible contingencies of that nature.

Like other clay, exposure to the air has a disintegrating effect on London Clay, and in working in it with a shield, when a considerable face is always exposed, the rate of advance is an important point on this account ; but a more important reason for speed in tunnelling is the fact that the clay when laid bare, as in the face of a tunnel, actually moves, being pushed forward by the pressure behind it, and that the disturbance thus started extends to the surface of the clay, and affects the heavy buildings which everywhere cover it in London. Cases have come under the author's own observation of small movements in houses in the street where tunnels were being driven, but considerably ahead of the working face, which were undoubtedly caused by the tunnelling operations. These cases occurred during the driving of small tunnels 11 feet 8 inches in diameter ; in the case of large 21 feet tunnels (station tunnels) some movement is usually caused, but in these cases any disturbance of the strata is usually first started in the construction of the " break-up " for the shield chamber in which the shield is erected, and this being some 25 feet in internal diameter, involves the construction of an ordinary timbered length. Of course the amount of damage caused by tunnelling under shield is, with ordinary precautions in the working, very small indeed as compared with the disturbance caused in similar conditions by the older method of tunnelling with

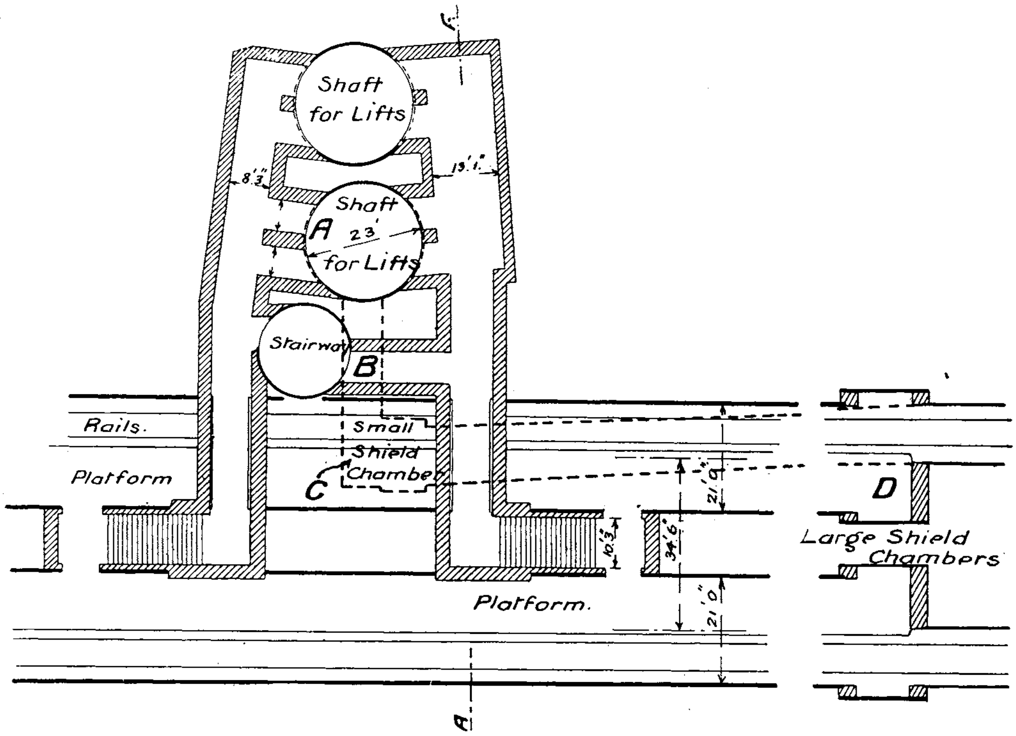


FIG. 42. CENTRAL LONDON RAILWAY.
Plan of Marble Arch Station Tunnels.

timbered excavation and permanent brick lining, but some movement always takes place.

This movement in the clay is usually, indeed, so small that its effects count for little in the cost of the tunnel work. When, however, the tunnels are driven under or near buildings of especial weight, or of importance from the historical or aesthetic point of view, or by their construction specially likely to be affected by any movement of the subsoil, compressed air at a moderate pressure is usefully employed. When the Central London Railway was driven under the Holborn Viaduct, the tunnels, 11 feet 6 inches in diameter, running under the viaduct and its approaches, supported on light piers for their entire length, the employment of compressed air at a pressure of about 15 pounds per square inch avoided any risk of damage in a structure little calculated to withstand any uneven settlement of its foundations.

Where the same railway was constructed in front of the Mansion House, the Bank of England, and the Royal Exchange, all buildings of importance, and in the case of two of them of great weight, the same precautions were adopted in driving the tunnels of the Bank Station, 21 feet in diameter, and built on 300 and 330 feet curves respectively, with complete success. The solid homogeneous character of the clay practically prevented any escape of air, and the full effect of its pressure (in this case about 20 pounds) was employed in holding up the face, and the ungrouted parts of the tunnel.

The only movement observed in any of these important and valuable buildings was a fissure in the foundations of the Mansion House, which, however, was probably not caused by the tunnels 80 feet down in the clay, but by some of the works of the upper station only a few yards below the surface of the street.

Water is never met with in the London Clay, and the little that is sometimes tapped in sinking the shafts which give access to the tunnels, through the superincumbent made ground (the accumulated débris of centuries amounts on the average to a thickness of 10 feet all over the City of London) and gravel, is easily dealt with without the use of compressed air. It is only in the case of large pockets of gravel, or of gravel deposits in some depression of the clay eroded in prehistoric times so far below the surface that the deep level railway tunnels pass through them that compressed air is required to keep water out of the workings.

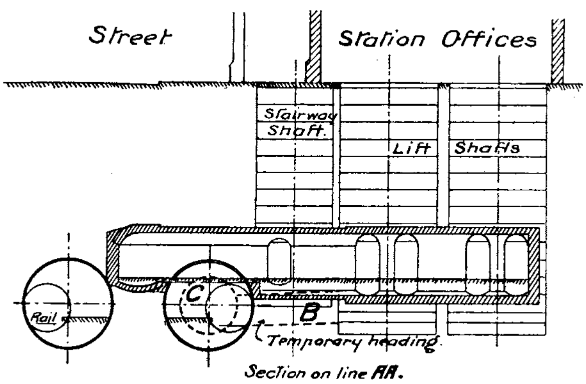


FIG. 43. CENTRAL LONDON RAILWAY.
Marble Arch Station Section in line *A A*, Fig. 42.

The railway tunnels under London (and, with few exceptions, all the shield-built tunnels in London Clay have been constructed for railway purposes) are laid in all cases under the public streets, and follow their windings, the cost of purchasing the properties necessary to build an "airline" between two points being prohibitive, and Parliament not viewing favourably the granting of easements to a railway company under private property.[1]

This fact necessitated the placing of the shafts which gave access to the tunnels during construction, and subsequently contain the lifts and stairways of the public stations, off the line of the tunnels, and this arrangement affected of course the method of initiating and prosecuting the tunnel work.

The shaft not being on the line of the tunnels, it was in the first place impossible to erect the shields for driving the tunnels at the bottom of the shafts, whence they could start directly on their course;[2] and secondly, owing to the arrangement of the stations rendered necessary by the position of the shafts

[1] The general arrangements of these railways, except as they affect the tunnelling operations, do not come within the scope of this work.

[2] This was however done in the case of those railways passing under the Thames, when a temporary working shaft was sunk through the bed of the river in the line of the tunnels, the cost of the shaft being repaid by the economy of water carriage so gained.

in regard to the lines it was not possible in the great majority of cases to place a convenient working adit or tunnel from the shafts so as to serve as a permanent passage of the station later.

Figs. 42 and 43 show a characteristic type of station, and indicate how, in order to give access to both tunnels from the shafts, it is necessary to place the

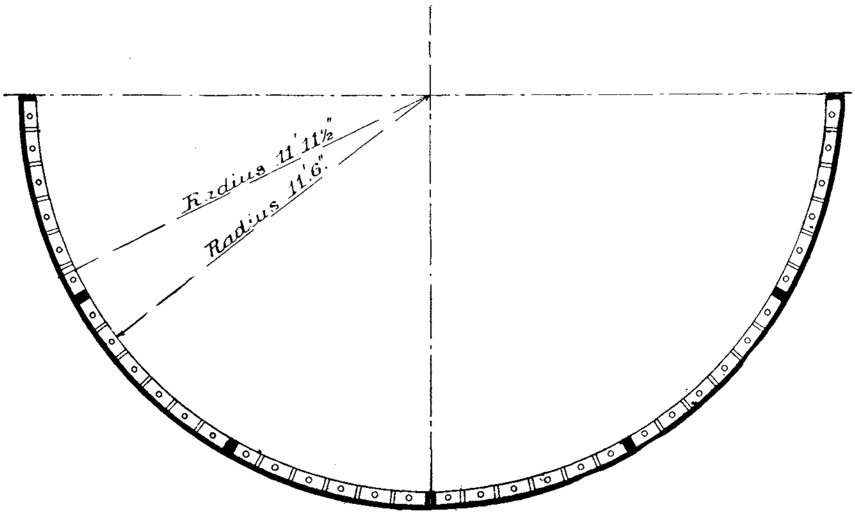


FIG. 44. CENTRAL LONDON RAILWAY.
Half Sectional Plan of Cast Iron Lined Shaft, 23 feet internal diameter.

station passages about 10 feet above the rail level, while for construction purposes an adit approximately on the rail level is most convenient.

The position of the shafts, too, adds greatly to the difficulty of setting out the centre line of the tunnel. The base line by which the underground alignment is started is usually about 18 feet long (the shafts being 20 to 23 feet diameter), and

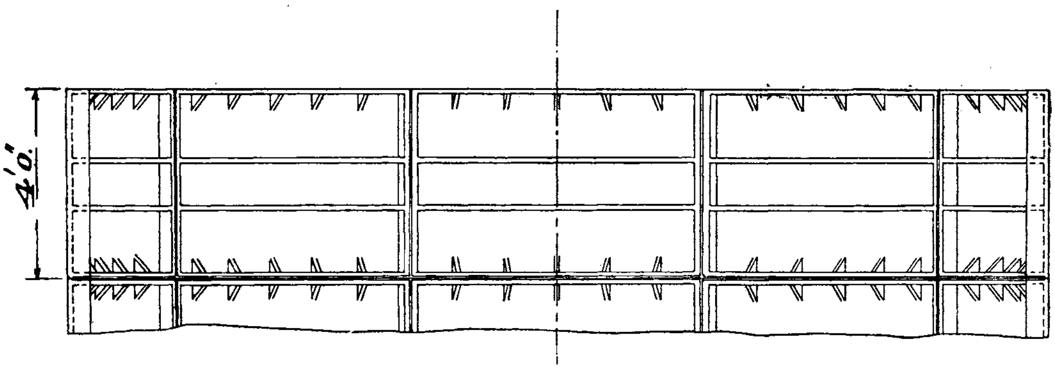
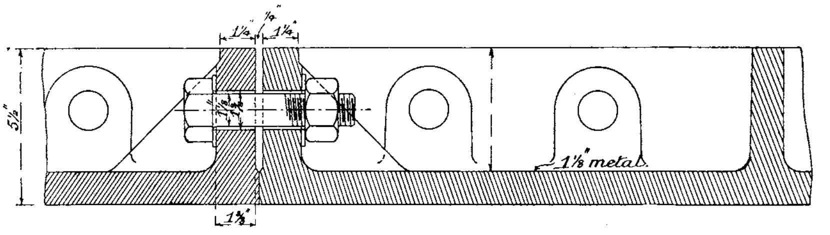


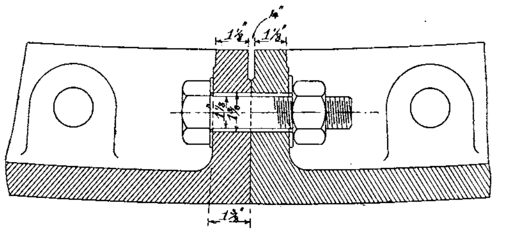
FIG. 45. CENTRAL LONDON RAILWAY.
Part Elevation of Cast Iron Lining of Shaft 23 feet internal diameter.

this base is on a line perhaps 100 feet long, generally at right angles or thereabouts to the centre line of the tunnels, which usually were driven a distance of half a mile before connecting up with the next station. In other words it is not usually possible to start the alignment of the tunnel directly from the surface centre line itself, but triangulation above ground and below is required, which adds to the possibility of error. The sinking of boreholes from the surface of the street above in order to check the alignment of the tunnels beneath is quite useless for any exact observations, and altogether not worth the expense, which for a 6-inch hole is usually about £1 per foot of depth.

Work is commenced by sinking the shafts which are lined with cast-iron rings formed of segments of varying number, a 30-foot shaft having as many as sixteen segments in a ring (see Figs. 44 and 45). The rings are usually 4 feet in depth, and are not made like the tunnel rings with a key to make the closing piece of the ring, it being found that, by excavating a little wider for the last segment, it can be got into its place without difficulty, other than the necessity of an extra amount



Horizontal Joint.



Vertical Joint.

FIG. 46. CENTRAL LONDON RAILWAY.
Details of Cast Iron Lining for Shaft 23 feet internal diameter.

of grouting behind it to fill the extra excavation. The joints of these segments (see Fig. 46) follow the usual lines adopted in the tunnels. On the Central London Railway both vertical and horizontal joints were made with chipping strips on the outside, $1\frac{1}{4}$ inches wide, and having for the rest of the joint a caulking space $\frac{1}{4}$ inch thick. The caulking usually consists of Medina cement. On some of the later tube railways the vertical flanges of the segments have unplaned faces, which make a close joint with the adjoining segments save for a small caulking space, 1 inch deep and $\frac{1}{4}$ inch wide (see Fig. 46).

In actual practice, no leakage of any importance has occurred in shafts of this class, nor has any deformation of the cast-iron lining been observed, so that the joints appear to do what is required of them. But as in the case of the tunnels, a planed joint would cost so little, and make so much more finished a job, that for the vertical joints it is to be recommended.

With the most ordinary care in sinking these shafts no disturbance of the adjoining buildings is to be feared. Many of the shafts of the Central London Railway are sunk almost touching the walls of adjacent buildings which, however, have not been in the least affected.

The shafts are sunk below the depth necessary to give access to the permanent passages of the station which are, as stated above, usually some 10 feet above rail level, in order to make, for construction purposes, a tunnel approximately on the level from the shaft bottom to the line of the tunnels.

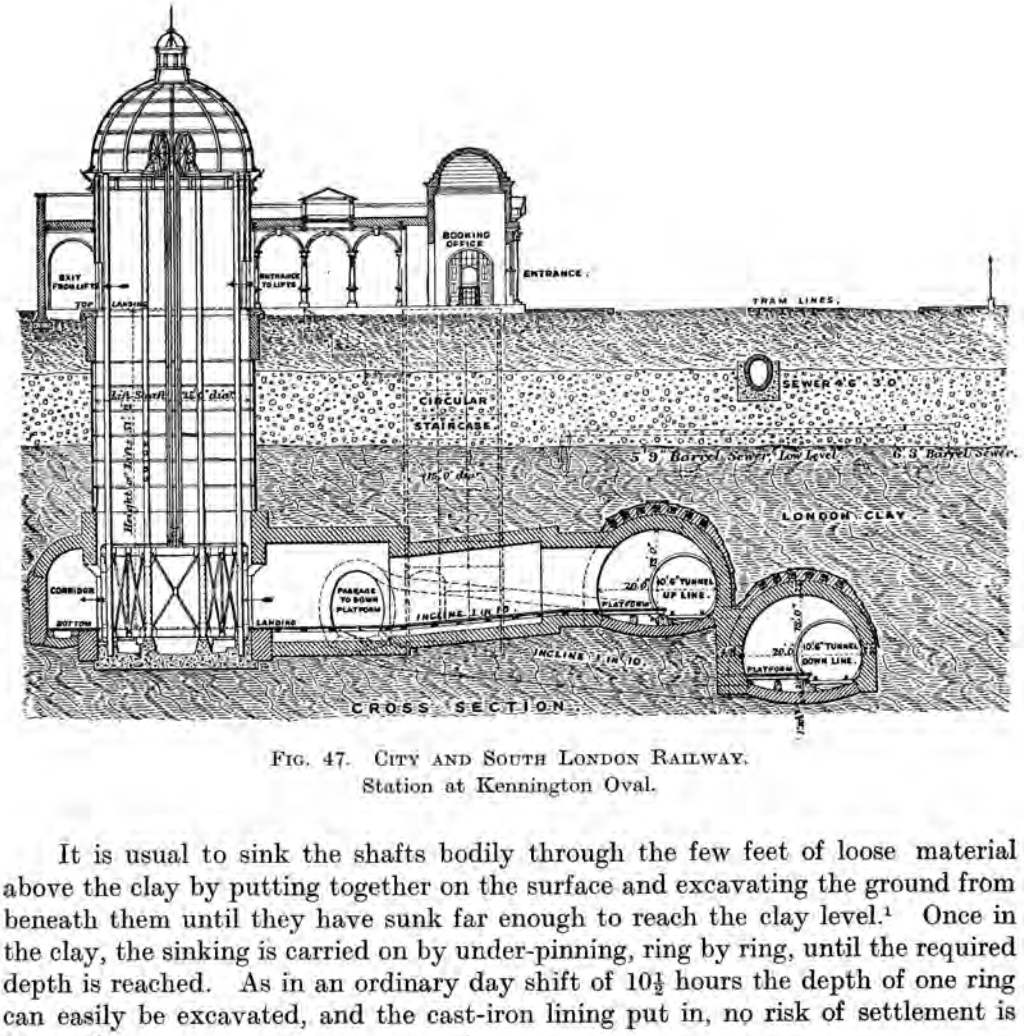


FIG. 47. CITY AND SOUTH LONDON RAILWAY.
Station at Kennington Oval.

It is usual to sink the shafts bodily through the few feet of loose material above the clay by putting together on the surface and excavating the ground from beneath them until they have sunk far enough to reach the clay level.[1] Once in the clay, the sinking is carried on by under-pinning, ring by ring, until the required depth is reached. As in an ordinary day shift of 10½ hours the depth of one ring can easily be excavated, and the cast-iron lining put in, no risk of settlement is incurred.

The successive cast-iron rings have the bolt-holes in the horizontal flanges arranged so that they can be made to break joint. This is hardly necessary for strength, but is very useful in placing the segments at the level of the passages of

[1] A bottom ring 18 inches deep having no flange on the lower edge is sometimes used as a "cutting edge."

the underground station in convenient positions for their subsequent removal to form doorways in the shaft.

In the earliest railway built under the new conditions the lower portions of the shafts were built in brickwork (see Fig. 47) ; all the more recent shafts have been, however, built entirely in cast iron, and the necessary openings at the bottom made by removing some of the cast-iron segments of the shaft, substituting where necessary special castings to fit the doorways.

When the first shaft at a station from which it is proposed to start a shield is sunk, a heading, generally constructed in cast iron, and about 8 feet in diameter, is driven to the centre of the tunnel whence it is proposed that the actual driving of the tunnel should start. In order to advance the work as rapidly as possible it is customary, although the tunnels in front of the shaft are usually of large diameter for the station platforms, to construct in the first place a shield chamber for the erection of a shield for the single line tunnel about 12 feet in diameter, which is pushed forward without delay, and the larger tunnel opened up later.

In Figs. 42 and 43 this arrangement is shown in dotted lines. From the shaft *A* a working adit or passage *B* is shown terminating in a shield chamber *C*, which is constructed of cast-iron rings about 3 feet more in diameter than the shield to be erected in it. In one or two cases on the Central London Railway chambers of this kind were constructed in brickwork, but both in money and in the time spent in constructing them they compared very unfavourably with the iron-lined ones. From this chamber starts a tunnel (single line), and when this tunnel is well advanced a " break up " from it, *D*, is started at the extremity of the station, in which is erected the shield for driving the station tunnel in the reverse direction to the smaller shield. The shield chamber *C* is constructed in the first place much as a timbered length in ordinary tunnel work, and the break-up for the larger tunnel to be constructed round the smaller one is necessarily on the same lines. Some variations in detail, however, make it worth while to describe the process of constructing this chamber.

When the single line tunnel has been driven past the end of the station where it is proposed to start the station or larger tunnel shield, a convenient segment of the tunnel lining having been omitted at that point to facilitate matters, a vertical box-heading or shaft *D* (see Fig. 48)[1] is driven upwards in the centre line of the proposed larger tunnel.

It is usually 4 feet 6 inches by 3 feet 9 inches, and is close timbered all the way up. This is driven upwards in 3 feet 6 inch lengths (the miner working at the clay above his head) with poling boards and walings until within 6 feet or so of the top, the last 6 feet being taken out at one time ; the roof is then supported by head trees, carried on side trees, which rest on footblocks.

From the top of this shaft a horizontal heading, *E*, is driven in the usual way for the full length of the break-up and timbered all round.

When the heading *E* is completed, the two central crown bars consisting of steel joists *F*, *F* are got into the heading and propped off stump props, which are provided in the case shown in the figures with a special hook plate *G* which prevents them coming in by the pressure of the ground behind.

The two faces of the heading are timbered with creosoted poling boards, wedged tight from the stump or ground props, which are given a slight rake and rest on

[1] The figures 48, 49, 50 and 51 are from drawings prepared by Mr. H. A. Bartlett.

half timber foot-blocks *H*, being driven up tight to take the weight with a pair of oak folding wedges. The crown bars are chogged apart with seven hard wood chogs *J*, *J*.

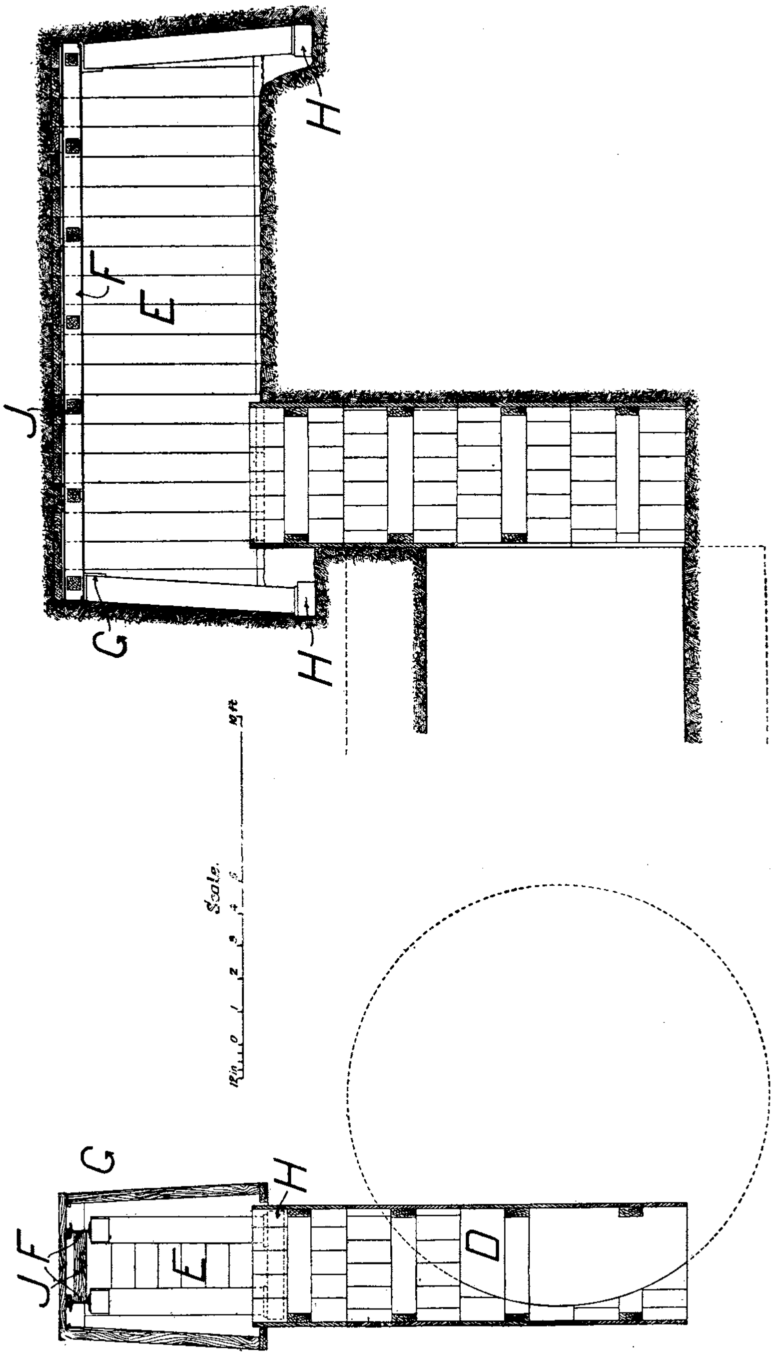


FIG. 48. BAKER STREET AND WATERLOO RAILWAY, LONDON.
Break-up for Shield Chamber for 21-foot Tunnels. First Stage.

The top weight being thus taken by the crown bars and props, the side trees are knocked away and the ground excavated on both sides of the heading for its full

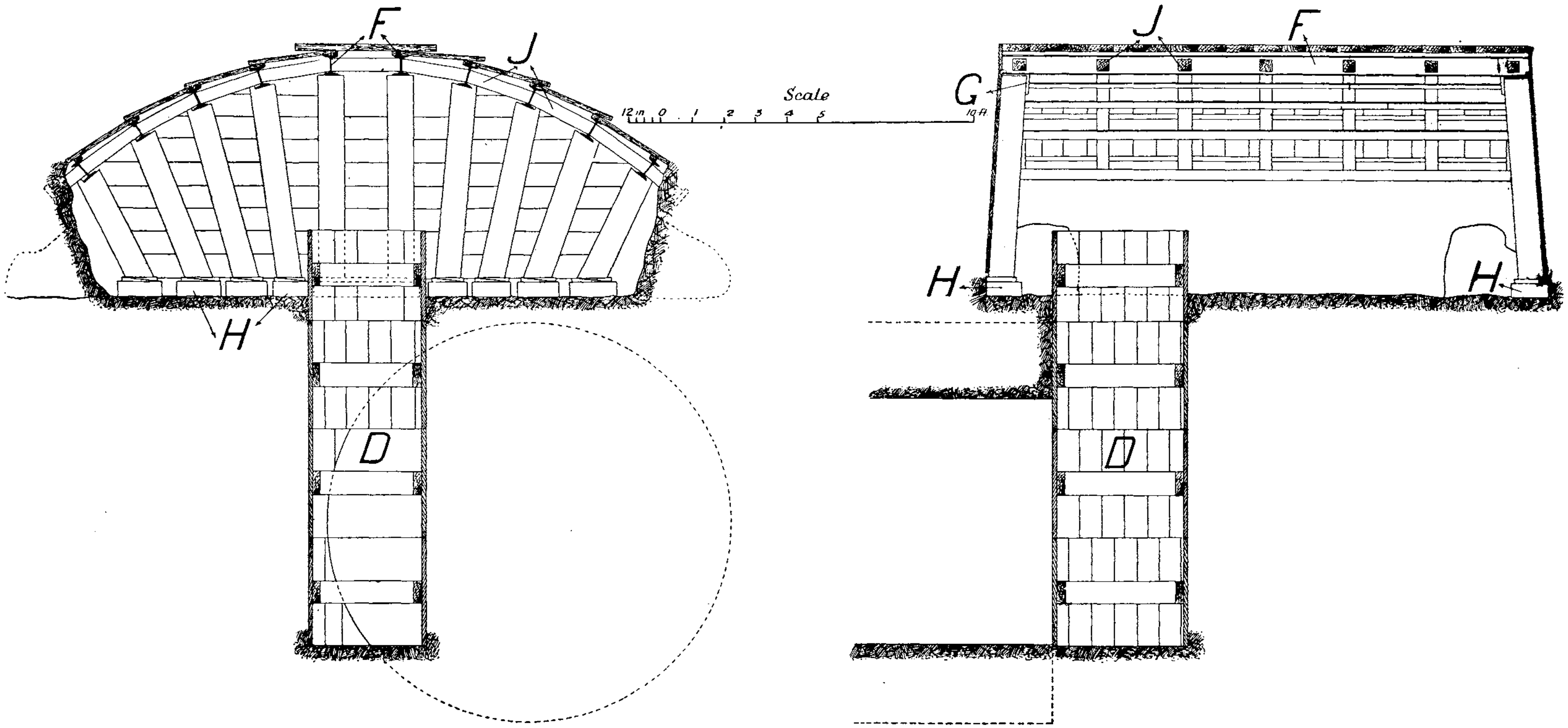


Fig. 49. Baker Street and Waterloo Railway, London.
Break-up for Shield Chamber for Tunnel 21 feet diameter. Second Stage.

length to a distance of about 2 feet 6 inches. The top is timbered with creosoted poling boards 3 feet long, one end of each resting on the crown bar, and the other

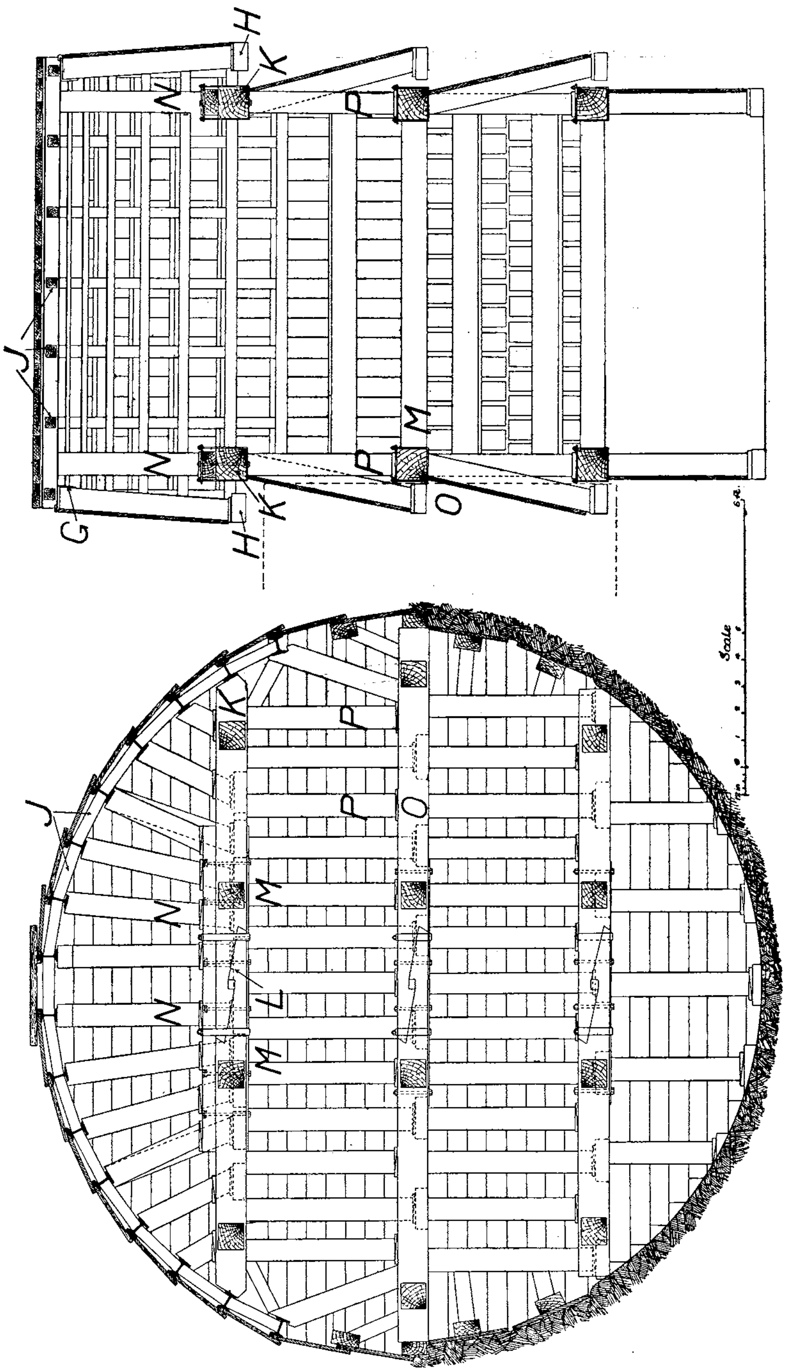


FIG. 50. BAKER STREET AND WATERLOO RAILWAY, LONDON.
Break-up for Shield Chamber for Tunnel 21 feet diameter. Third Stage.

temporarily propped on a vertical poling board, which also serves to hold the sides of the excavation. Two more crown bars are then got into the heading and propped

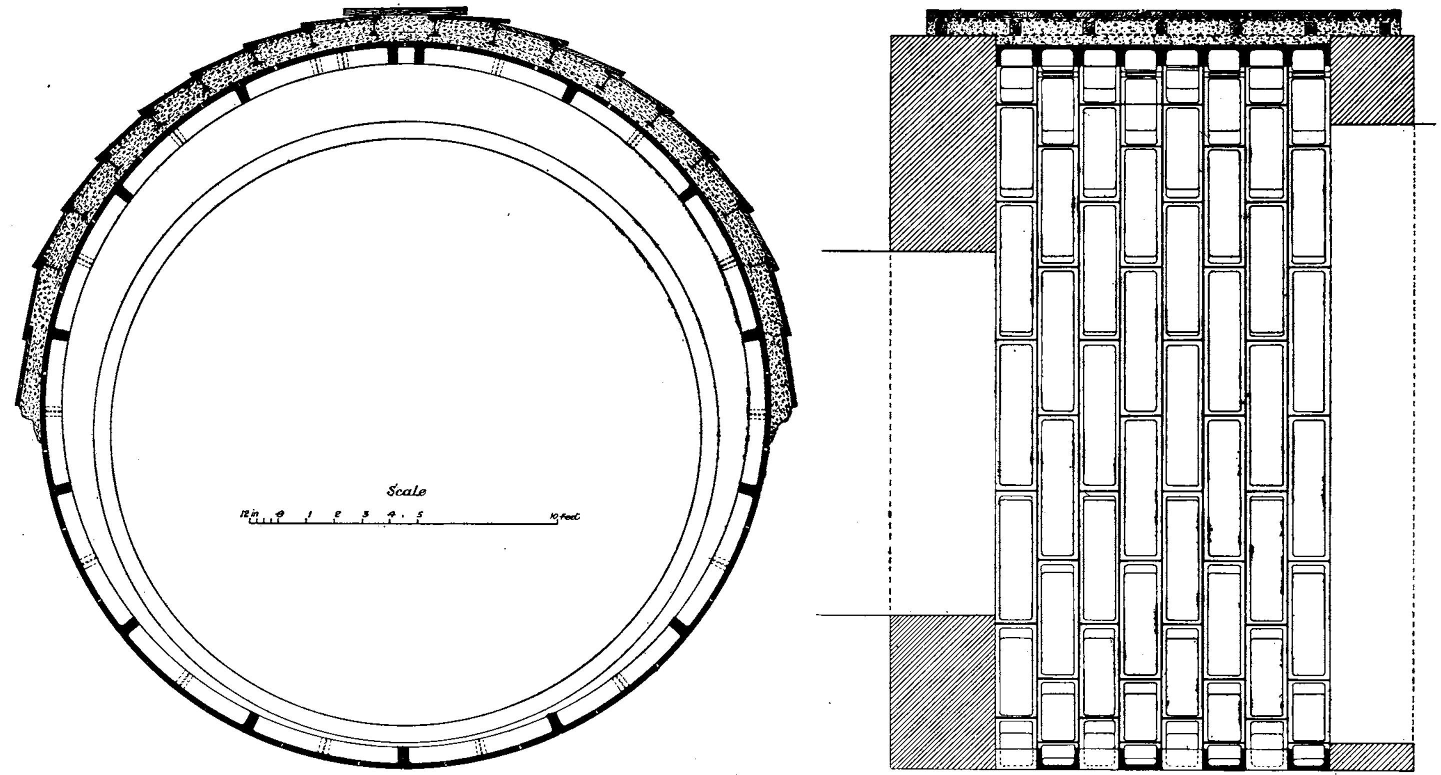


FIG. 51. BAKER STREET AND WATERLOO RAILWAY, LONDON. FINAL STAGE
Break-up for Shield Chamber for Tunnel 21 feet diameter. Final Stage.

as before with ground props. This operation is repeated until ten bars are in position. Each pair of bars are grouted up as they are placed in position, which is very important (see Fig. 49).

The two top cills K, K are then got in. These are made in two pieces scarfed together. The scarf L is made as shown in Fig. 50, with a wrought-iron plate at the bottom and a saddle piece on top, and the whole is fixed with wrought-iron

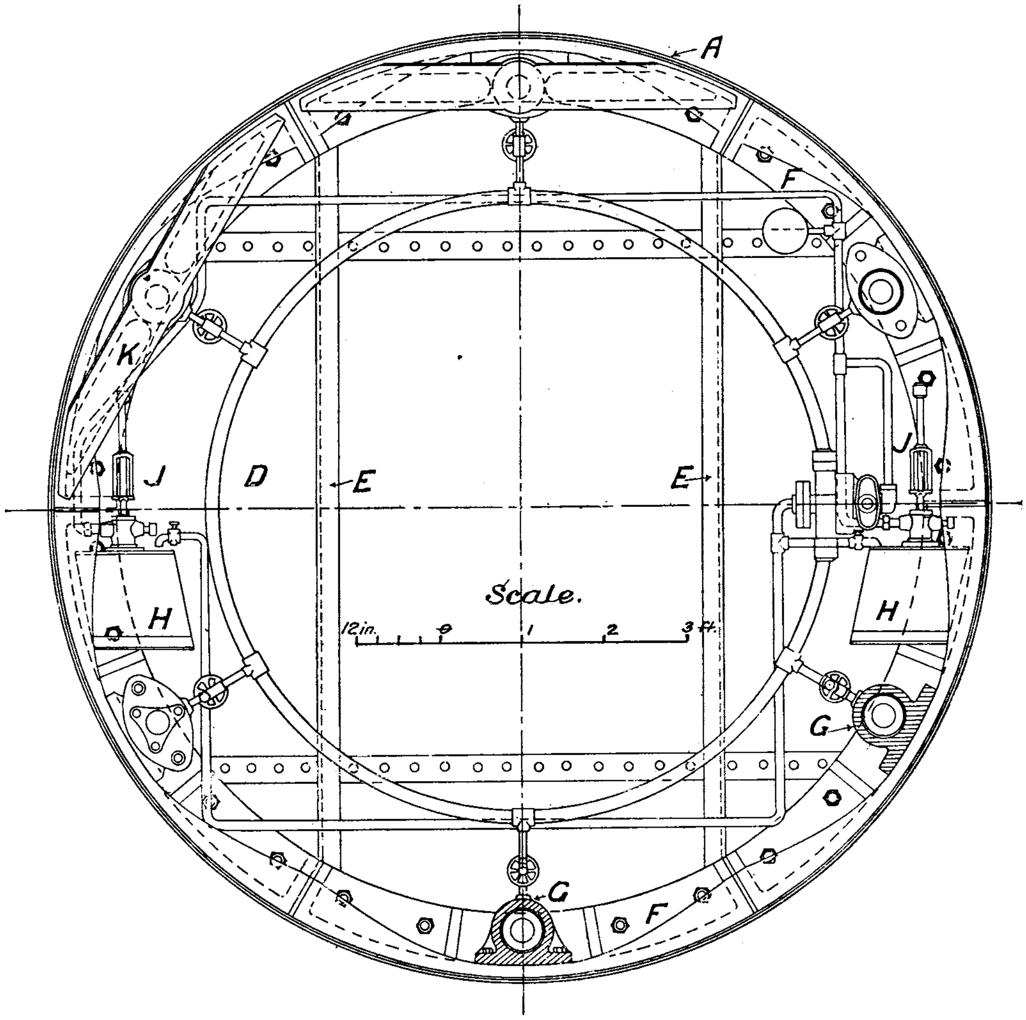


FIG. 52. CITY AND SOUTH LONDON RAILWAY.
The Greathead Shield. Back Elevation.

straps and bolts. These cills are placed in front of the ground props and level with the foot-blocks, one at each end of the break-up, 12 feet 6 inches apart. The cills are stretched apart with stretchers M, M, and the weight of the roof is then transferred to the cills by means of front props, N, N, and wedged up tight with a pair of oak wedges.

As soon as this is done the " second lift " is commenced by excavating a trench between the two centre cill stretchers for the full length of the break-up. Two back props are then put in at each end of the trench to take the weight of the cills above and wedged up off foot-blocks as before. The trench is then widened out at both sides simultaneously, and back props put in as for the first lift, together with the remaining crown bars which come below the top cill. When the second row of back props is in position the second pair of cills *O*, *O* are got in as before and stretched apart, and the weight of the top cills taken by a row of vertical props *P*, *P* as before.

The third lift, which reaches to within about 6 feet of the bottom, at the centre, is done in the same way. In the bottom lift the front props only are put in, and the clay round the lower half of the break-up is then trimmed off with the aid of a trammel to the sweep of the iron lining (see Fig. 50).

The next step is to get the iron lining fixed. The segments are brought into the break-up one at a time, and placed in position and bolted up, the rings being arranged so as to break joint. The whole of the lining for the bottom half, or up to springing-level, is got in and grouted up.

When the whole length is up to springing level, two of the rings are carried round and completed, and the space between the outside of the iron and the crown bars and polings is filled with Portland Cement Concrete, and the two rings are then thoroughly grouted up, the remaining rings being successively carried round, completed, and concreted, until the break-up has its cast-iron lining complete.

When the tunnel lining of the shield chamber, which for a 21-foot tunnel shield is usually about 25 feet in internal diameter, is complete, headwalls are built at either end of the chamber (see Fig. 51), sometimes inside the iron lining, sometimes by cutting into the clay. In these headwalls eyes are turned, in the one built round the smaller tunnel already existing, in the other made large enough to pass the shield when constructed. This latter, in such a case as Fig. 51, is usually bricked up with horizontal courses save for the small tunnel giving access to the chamber from the shaft, during the erection of the shield. Of course, as the large shield advances from the chamber the length of small tunnel lying within the latter one is gradually removed.

Figs. 42 and 43 show a station of the type constructed on the Central London Railway ; Fig. 47 is one of the earlier stations constructed on the City and South London Railway, and was the prototype on which the later ones were modelled, save that at the time it was constructed, it was considered safer to construct the station tunnels in brickwork rather than in iron, and they were consequently built in the usual way with timbered lengths. The foregoing general remarks will give some idea of the work preliminary to starting a shield in the London Clay, and the details of the shield and its working can now be considered at some length.

City and South London Railway Shield [1]

The general design of the City and South London Railway Shield is shown in Figs. 52, 53 and 54, and in the main follows the type of the one used in the Tower Subway shown in Fig. 9.

In later years modifications have been introduced to meet altered conditions, and notably the increased size of tunnels built on the Greathead system has necessitated the introduction of platforms or stages to enable the miners to attack the face in sections, but the shield used in all tunnels in London Clay of 14 feet diameter and under consists of five principal parts ; the skin or cylinder, the cutting edge,

[1] *Proc. Inst. C.E.*, vol. cxxiii. Greathead on "the City and South London Railway."

the vertical diaphragm, the cast-iron segments carrying the rams, and the hydraulic rams for propelling the shield.

In the City and South London Shield, the skin or cylinder *A* of the shield (see Fig. 53) is composed of two $\frac{1}{4}$ inch plates rivetted together. The segments composing the two plates are arranged to break joint, and of course all rivets in the skin are countersunk. Later practice has sometimes substituted one $\frac{1}{2}$ inch plate instead of two $\frac{1}{4}$ inch ones in shields of this size, the butt joints of the segments being covered by an outside plate, the front end of such cover being either bevelled off, or the casting of the cutting edge thickened to protect it, to avoid stripping when the shield is advancing.

There is little to choose between the two methods: the use of one plate only being a little cheaper than the other.

In shields of very large diameter, the cylindrical skin is perforce made up of several plates rivetted together.

The front of the cylinder is stiffened by heavy castings, forming a complete ring or cutting edge *B*.

The segments of this ring, which vary in number in different shields, are made with planed joints put together metal to metal, and are secured to the diaphragm behind them by bolts, and to the skin by tap bolts (see Fig. 55). In later shields the joints of the segments are usually provided with flanges back and front (see Fig. 62) through which the segments are bolted to each other. This is doubtless an additional strength, but if the segments are truly made, and the joints make an exact fit, there should be no need for these bolts.

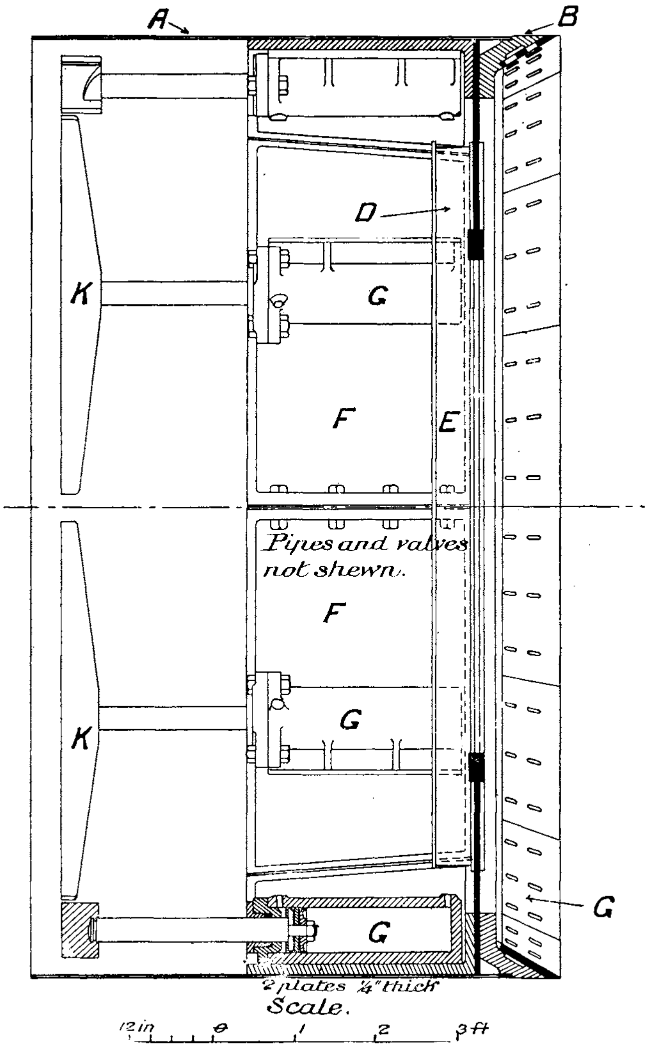


FIG 53. CITY AND SOUTH LONDON RAILWAY. The Greathead Shield. Longitudinal Section.

The actual cutters are formed of steel plates *C*, *C* (Fig. 54) an inch thick, and sixteen in number, which form a complete circular knife or chisel round the front of the cast-iron ring *B*. They are bevelled off at the outside edge (see Fig. 55), so as to make a real chiselling front to the shield. They are attached to the cast-iron ring by screws fitting into tapped holes in the latter, six screws to each plate, the holes in the steel plates being slotted so that if necessary the plates can be advanced so that thin sharp ends project outside the circumference of the cast iron.

This arrangement is devised to fill the same purpose as the skin tapered from front to back in the Tower Subway shield, namely, the avoidance of friction when the shield was in movement, particularly in the case when the shield was going round a curve.

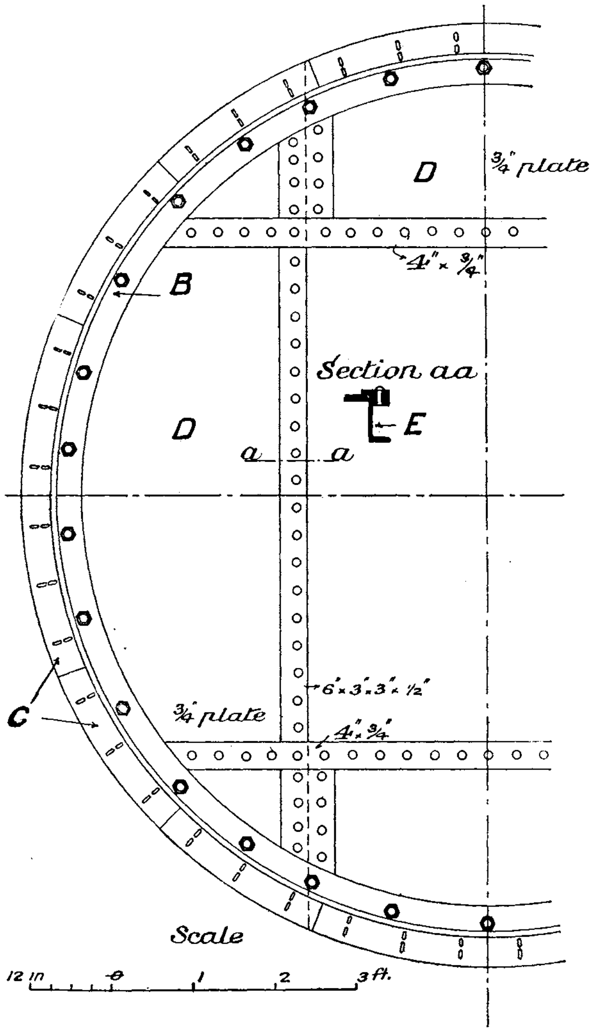


FIG. 54. CITY AND SOUTH LONDON RAILWAY.
The Greathead Shield. Half Front Elevation.

The play of ¾ inch obtainable by this means is not enough to make a clear way for a shield of the size under consideration working in clay on a curve of five chains radius, and the excavation in front of the shield has to be cut wider to allow of proper steering of the shield in such a case.

Nearly all shields for clay work are provided with these cutting plates, though they are omitted in some of those last constructed, but in the author's experience the occasions on which they can be profitably advanced are not frequent. Theoretically it should be practicable to set the cutters to trim an opening exactly large enough for the shield on any given curve; in practice the clay is taken out for each advance of the shield to suit the amount of error—to right or to left, upwards or downwards—which has to be corrected in that particular "shove." And if the miners in front have to do any extra trimming of the circumference it matters little whether that trimming amounts to 2 or to 3 inches. In the larger shields for tunnels 21, 23 and 25 feet diameter, the cast-iron or cast-steel cutting edge is never provided with these knives.

In one way these cutters are useful. Hard clay stones, and at a certain depth a hard bed of stone, are met with sometimes in London Clay, and in case of the shield encountering anything of the kind, a plate cutting edge is less likely to fracture than a cast metal one.

It is also true that, steel plates taking a sharper edge than cast metal, the cutters dress off the clay round the edges of the excavation with greater ease than would the blunter cast-iron ring.

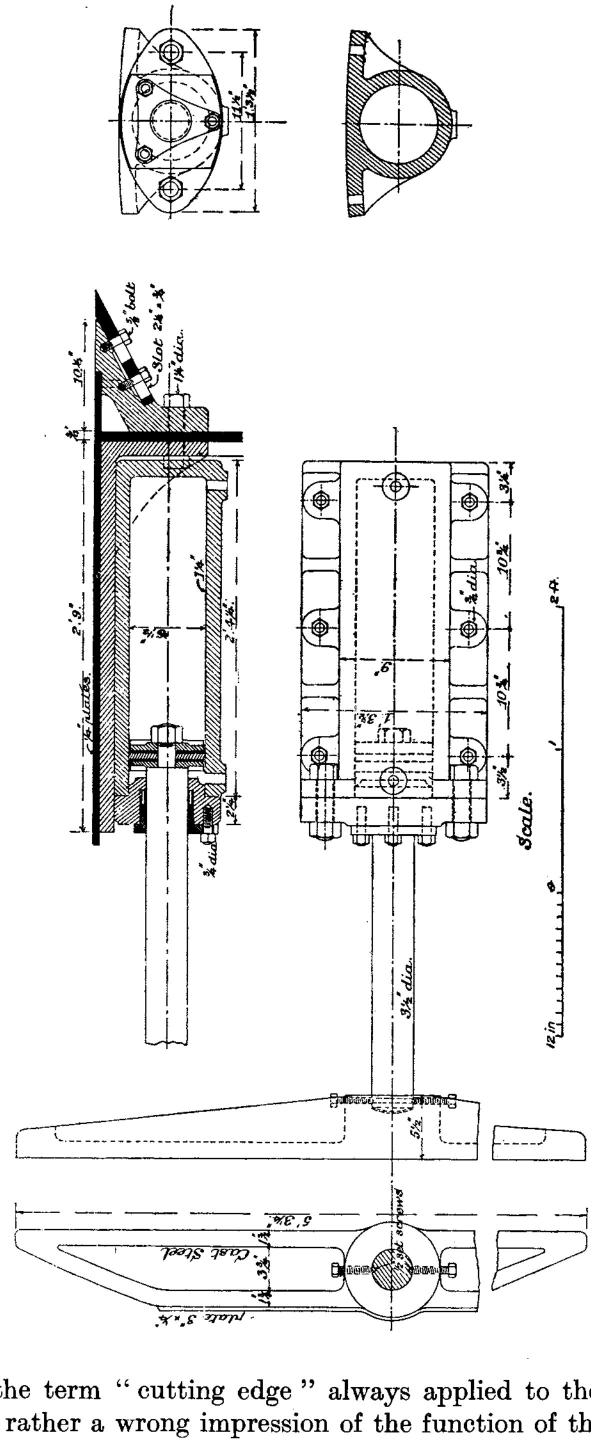


FIG. 55. CITY AND SOUTH LONDON RAILWAY.
The Greathead Shield. Details of the Hydraulic Rams.

Perhaps the term "cutting edge" always applied to the front of the shield cylinder gives rather a wrong impression of the function of the cast-iron ring; for it does very little cutting out of the clay, but is all important in stiffening the edge of the cylindrical skin (which never projects less than 1 foot in front of the diaphragm) and so preventing any buckling or deformation of it.

Immediately behind the cutting edge and between it and the cast-iron segments carrying the hydraulic rams is a vertical plate diaphragm *D*, having in its centre a rectangular door about 6 feet high and 4 feet 6 inches broad. At the side of this door are fixed channel irons *E*, *E*, into which can be dropped timbers 9 inches by 3, for the purpose of closing the opening when work for any cause is suspended.

This diaphragm performs a double service—it protects the tunnel against a sudden fall of the face, and it forms a very efficient bracing to the shield.

Behind the diaphragm, the skin of the shield is stiffened by the ram segments *F*, *F*, which, six in number, are bolted together to the skin, and also at the front end through the diaphragm to the cutting edge, and form a massive cast-iron frame. The radial joints of this frame are made with a hard wood packing between the planed ends of the segments.

These castings are about 3 feet long, and beyond them the outside cylinder or skin of the shield extends back a further 2 feet 8 inches, or sufficient to allow of space for erecting a tunnel ring within it, and at the same time to overlap the last ring of the tunnel already erected.

The dimensions of the shield for the tunnel 10 feet 6 inches in internal and 11 feet 3 inches in external diameter with 20 inch rings are : length over all, 6 feet 6 inches ; and diameter inside the skin, 11 feet 4½ inches. This last dimension allows ¾ inch play round the tunnel, which is sufficient clearance for any but the sharpest curves. In some shields, the advantage of having plenty of play in the tail of the shield and at the same time reducing to a minimum the annular space through which the grout injected behind the cast-iron lining can find its way back into the tunnel is obtained by making the skin of the shield with the usual amount of play, but putting round the back edge of it and inside a small beading or flat strip which nearly fits the tunnel. This was done in the case of the Great Northern and City, the Blackwall, and St. Clair Tunnel shields. This beading aids also in reducing the friction when the shield is in movement.

The hydraulic rams *G*, *G* (Fig. 52), six in number, for driving the shield forward are shown in detail in Fig. 55.

They are bolted to the ram castings *F*, *F* already described, and generally are fixed so that the end of each cylinder bears against the flange of the casting which in turn transmits the thrust of the ram to the cutting edge. The rams of the shield if fixed with absolute accuracy have their axis exactly parallel to the horizontal axis of the shield, but with the best workmanship this is rarely attained, and as a consequence the thrust of one or more of the rams is slightly oblique in most shields. This causes the shield to rotate, and though this movement is not a matter of much concern in the ordinary open shield for work in clay, it is of importance in certain types of shield for working in water-bearing strata (see the Greenwich Footway Shield, page 248).

Perhaps this almost universal movement of rotation might be checked by providing in the shield a means of changing the line of thrust of say two rams, opposite or nearly opposite to each other. This could be done by making the bolt holes in the bases of the ram cylinders, through which the bolts pass for fastening them to the cast-iron segments, slightly slotted instead of circular, the longer axis of the slot being at right angles to the axis of the cylinder. This would permit, when the rotary movement of the shield commenced, the adjustment of those rams to counteract the general tendency of the shield.

The cylinders of the rams are of cast steel, with an internal diameter of 6½ inches. The hydraulic working pressure obtained by the hand pumps was 1,800 pounds per square inch, or a total driving power with all the rams working of about 160 tons.

They are provided with two inlet pipes so that the rams can be drawn back as well as run out, and this arrangement has always been adopted in English practice ; but in some of the shields used in Paris, and in the St. Clair Shield, a smaller auxiliary hydraulic cylinder is used for drawing back the rams (see Fig. 109).

The water for the rams is taken from the small cisterns *H*, *H*, which are fixed on brackets on either side of the shield, and is compressed by the hand pumps *J*, *J*. These cisterns were on the City and South London shields unprovided with covers, with the result that dirt and grit got into them, and as a consequence the battens in the pumps suffered. In later shields they have been made with closed tops, and provided with a gauge glass. This was first done in some shield work in connexion with the Blackton Reservoir in Yorkshire in 1889.[1]

The hydraulic pumps may be of any pattern, the important point being that they be provided with a long removable bow or handle for pumping, so arranged that, when fixed, six or eight men can work at it effectively at one time. In later shields mechanical compressors have been introduced with great advantage. Their use sets the men free to get on with other work while the shield is going forward, and so accelerates the rate of progress.

The arrangement of the pressure pipes and valves enables the rams to be operated in groups and singly or all together, and the provision of a reversing valve made their withdrawal equally facile. (The disposition of these pipes is shown more clearly in Figs. 68 and 69, than in the plate of the South London Shield.)

The shields constructed during the last few years have, in one detail, a great advantage over this pioneer shield. They are provided with sets of reversing valves, which, often made in one casting, and always very small in bulk, can be placed on the side of the shield, nearly free from all risk of damage, and all together under the hand of the man controlling the movement of the shield (see Fig. 164), instead of each pair of valves being placed close to the rams they control.

The length of stroke of the rams of the South London Shield is 20½ inches, or a little more than the width of the tunnel rings. The piston rods are 3½ inches in diameter, and terminate in long cast steel shoes or crossheads *K*, *K*, shaped so as to bear as far as possible on the outside of the tunnel castings and not on the flanges of the last ring, against which they press when pushing the shield forward as against an abutment.

In the shield now under consideration the rams were doubtless made six in number in order that their centres might coincide with the horizontal flanges of the segments of the cast-iron tunnel lining; that is, with the point of greatest strength in the tunnel circumference.

The shoes are strengthened against unequal pressure by a ¼ inch plate fixed to them with set screws on the outside face.

In ordinary circumstances, the time necessary to force the shield forward for the length of one tunnel ring was ten minutes. This time has since been much reduced by the introduction of mechanical pumps.

[1] *Proc. Inst. C.E.*, vol. xxiii. p. 90.

In actual work a platform of planks is generally laid across the shield at the level of the bottom of the door to keep the loose clay from the face from filling the invert; and, for the erection of the upper segments of the tunnel lining a removable platform which can be fixed about the level of the axis of the tunnel is provided.

The shield as thus built has the features which are especially necessary for tunnelling in a fairly solid homogeneous material like London Clay, which takes a certain time to expand, or swell on exposure to the air, but which, if the lining of the tunnel follows promptly in the excavation, can be worked with greater security than almost any other material.

The vertical diaphragm is placed too near the front of the shield for work in any material when there is any likelihood of timber work being required in the face of the excavation, the door in the diaphragm is too high in the shield if there is any risk of an inrush of water, and the tail of the shield is too thin and flexible for work in any material less solid than the London Clay.

As will be seen later in treating of shields in water-bearing strata those features have been altered to suit the altered conditions. But regarded as a special machine designed for service under certain ascertained conditions, the shield used on the City and South London Railway is beyond all praise.

It is only when attempts were made to employ it in material for which it was not designed, that difficulties have arisen, and in such cases it is certain that its use, though less effective than in the London Clay, in which it was designed to work, has been advantageous.

The Grouting Pan

Although not a part of the shield, the Greathead grouting pan forms such an indispensable part of the tunnelling plant, and is so necessary a complement of the shield itself, that its construction and use may be described here.

In Mr. Barlow's patent of 1864 that engineer proposed to fill the annular space left outside the tunnel when the shield moved forward by injecting liquid grout, but did not indicate any method of doing it. In the Tower Subway [1] Mr. Greathead endeavoured to grout up the outside of the tunnel with lime mixed in a tub with water, and injected through holes in the cast-iron linings by means of a hand syringe. This was not satisfactory owing to the lack of pressure, and to the too great fluidity of the mixture.

Later, in 1886,[2] Mr. Greathead patented a grouting pan, which has since been in universal use.

A common pattern is shown in Fig. 56, which represents the pan used on the Central London, and on the Baker Street and Waterloo Railways.

It consists of a strong steel cylinder some 2 feet 6 inches long and 1 foot 6 inches in diameter, having through its axis a spindle passing through stuffing boxes at either end and furnished with handles. On this spindle are fixed feathers or paddles *A*, *A*. At the top of the cylinder is a circular opening *B*, capable of being closed by a lid with rubber seatings, and a valve *C*, to which can be attached a flexible pipe connected with an air compressor. At the bottom is another valve *D*, to which is fitted a flexible hose ending in a nozzle which fits the grout holes in the tunnel lining.

[1] *Proc. Inst. C.E.*, vol. xxiii. p. 62.
[2] Patent No. 5221 of 1886.

The cylinder is also provided with lugs *E*, *E*, by which it can be suspended from the tunnel roof. More frequently, however, it is placed like a barrel on a gantry.

The method of using the machine is as follows :—Through the opening *B*, the cylinder being partly filled with water, lime is introduced by one workman, another in the meantime turning the spindle with the paddles to mix the grout, until the mixture is of the consistency of thin cream. The lid is then closed, and compressed air at about 70 to 80 pounds per square inch introduced by opening the valve *C*.

One workman keeping the grout in motion with the paddles, the other applies the nozzle of the hose pipe to the grout hole in the casting when the grout is to be injected, and opens the valve *D*. The grout is then forced out of the cylinder, and passes through the hose to the outside of the tunnel, completely filling the vacant annular space. When the nozzle is withdrawn from the grout hole, a wooden plug is driven in, which after the grout has set, is removed, and subsequently the hole is pointed with cement grout, or in tunnels in water-bearing strata closed with

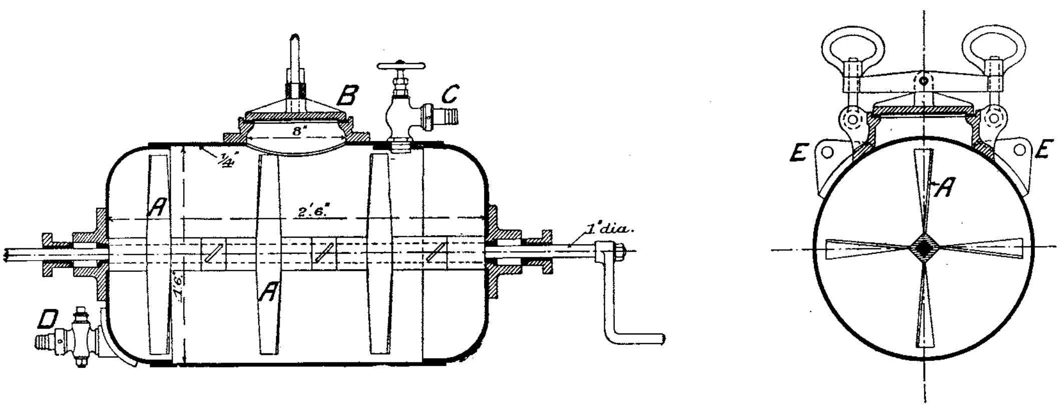


FIG. 56. THE GROUTING PAN.

a plug tapped into the hole. In a short time the lime sets hard, and forms a ring round the iron at least as strong as the clay which it replaces.

If carefully done, and done, too, immediately the shield has left the annular space exposed, this grouting effectually prevents any settlement of the surrounding clay.

Next to promptitude in carrying out the operation, the main essential is that the air pressure should be sufficient, namely about 80 pounds per square inch, not merely to force the grout into every crevice or crack in the clay, but also because only with a good pressure can the grout be mixed sufficiently thick to ensure fairly quick setting.

Lime is better than cement for use with this machine, besides being cheaper, and it has been found that a mixture of lime and sand hardly repays the economy in lime effected, the cost of the careful mixing of the two in a dry state being more than the saving in material.

A good test of the quality of the grout is its heating effect on the cast-iron lining of the tunnel. If after being grouted the cast-iron segments are warm to the touch, the grouting is probably satisfactory.

It is the usual practice to provide at least one grout hole in each segment of a tunnel ring.

In the shield as first designed for the City and South London Railway, the shoes *K*, *K* (Fig. 53) bore directly on the last ring of the tunnel already erected, and the annular space between the outside of the tunnel and the inside of the tail of the shield cylinder was left open, and consequently every time that the grouting operations were in hand, it was necessary to plug up this space with pugged clay and sacking. This was found both troublesome and ineffective, and after a time a simple arrangement of planks known as "grouting ribs" was adopted, and with little variation has been used in every shield since. The planks, 2 inches thick or thereabout, and six in number, are shaped to the curve of the shield skin, and cut long enough to form, when placed one in front of each ram shoe, a complete ring which, when held in position by the rams against the cast-iron tunnel lining, effectually prevents the escape of any quantity of grout from behind the lining into the shield (see Fig. 67).

These grouting ribs are sometimes made with india-rubber flaps on one side to make a better airtight joint, and sometimes are strengthened by making them of two planks with a flitch or iron plate between, instead of only one single plank.

When first used, they were put in place by hand as wanted, and the rams pumped out to hold them up; and when not required had to be taken down and put on one side. In later shields the shoes of the rams are provided with threaded holes, in which set pins which fasten the grouting ribs fit (see Fig. 67).

Method of Using the Shield

The actual work of iron tunnel construction with a shield[1] consists of four operations, which, however, in practice overlap each other in time as there is no necessity to suspend work on the others when one is in hand. They are the removal of the clay in the face, the pushing forward of the shield, the erection within the shield of cast-iron segments forming a new ring for the tunnel lining, and the grouting up of this ring immediately it is clear of the shield.

Starting with the shield in the position shown in Fig. 57—that is, with the hydraulic rams drawn back in the cylinders and the tail of the shield reaching over the last tunnel ring which has just been erected within it and partly enclosing the last ring but one—the first operation is to remove the clay in the face for the full area of the shield face. To accelerate progress, it is customary to drive a box heading *A*, some 6 or 8 feet ahead of the shield. This heading is timbered with head and side trees in the ordinary way, the height being about 6 feet and the width about 4 feet. Work on this heading goes on continuously.

It is usual to excavate the clay to the full size of the shield, leaving the so-called cutting edge of the shield very little to do. The adjustable cutters bolted to the cast-iron front ring were used in the early days of the City and Southwark Railway, to increase the area excavated when passing round curves, but in later work the adjustable cutters have been for the most part ignored, and in going round curves sufficient play is obtained by taking out the excavation in front of the shield some inches wider than the face of the shield.

[1] A good description of shield work in clay is to be found in Mr. Dalrymple Hay's paper on the Waterloo and City Railway (*Proc. Inst. C.E.*, vol. cxxxix.), and in a paper by Mr. Bartlett read at a students' meeting at the Institution in 1893.

When the clay is excavated for a distance of about the length of one ring of the tunnel lining, and the invert cleaned up, a platform of planks *B*, *B* is laid from the door in the diaphragm to the heading, and also across the invert of the shield, to prevent falling clay from filling up the invert when the shield is in motion, and the last settings of the box heading are knocked out.

Piles *C*,*C*, generally about 3 feet long and 4 inches square, with iron-shod points, are fixed in position in front of the shield, the iron points being placed in pockets cut for the purpose in the clay face, and the rear ends fixed against the cast-iron cutting edge. Their function is to break down the clay in front as the shield is advancing.

The shield is pushed forward by pumping water into the hydraulic cylinders and so forcing out the pistons or rather forcing the cylinders away from the pistons

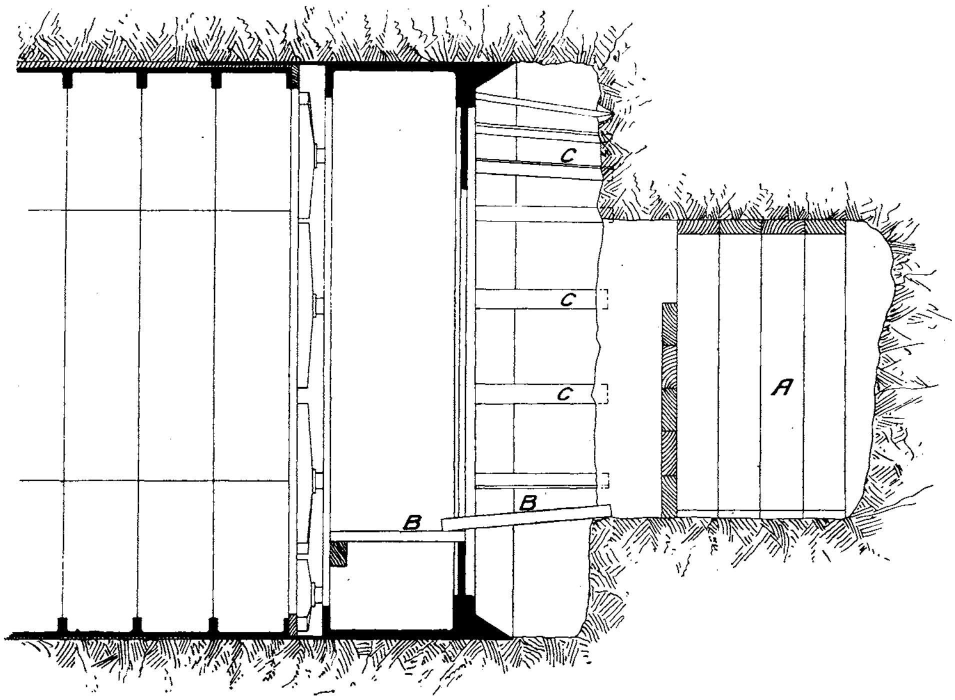


Fig. 57. The Greathead Shield in Clay.
Shield ready to Move Forward.

which, by means of the shoes *K*, *K* (Fig. 53), are bearing on the tunnel lining already erected.

The direction of the shield is controlled by manipulating the supply of pressure to the rams. If the shield is to be deflected to the right, only the rams on the left hand side are employed ; if it is found to be pointing downwards, and requires raising, the ram in the invert only is used, and so on.

As the shield advances, the piles break down the clay face, and by the time it has gone forward 20 inches into the space cleared for it, a considerable amount of the clay in front has been broken down, and is heaped on the plank platforms in front of, and in the invert of, the shield.

When the rams have driven the shield the full length of their stroke, as shown in Fig. 58, they are reversed by turning the reversing valve and passing the water through the pipe at the rear end of the rams. When the rams are withdrawn into the cylinders the tail of the skin is left clear for the erection of another ring of the permanent cast-iron tunnel, the segments for which, six and a key piece to a ring, have been brought up by trollies to the shield while the previously described operations were in hand.

The two segments forming the invert, and the two segments (one on each side) next to them, are lifted from the trolley and placed in position by the men with the aid of spanners or bars slipped through the bolt holes. They are then bolted together and to the last ring.

The two upper segments and the key piece are fixed by means of a removable platform formed of a few planks and placed usually a little below the horizontal

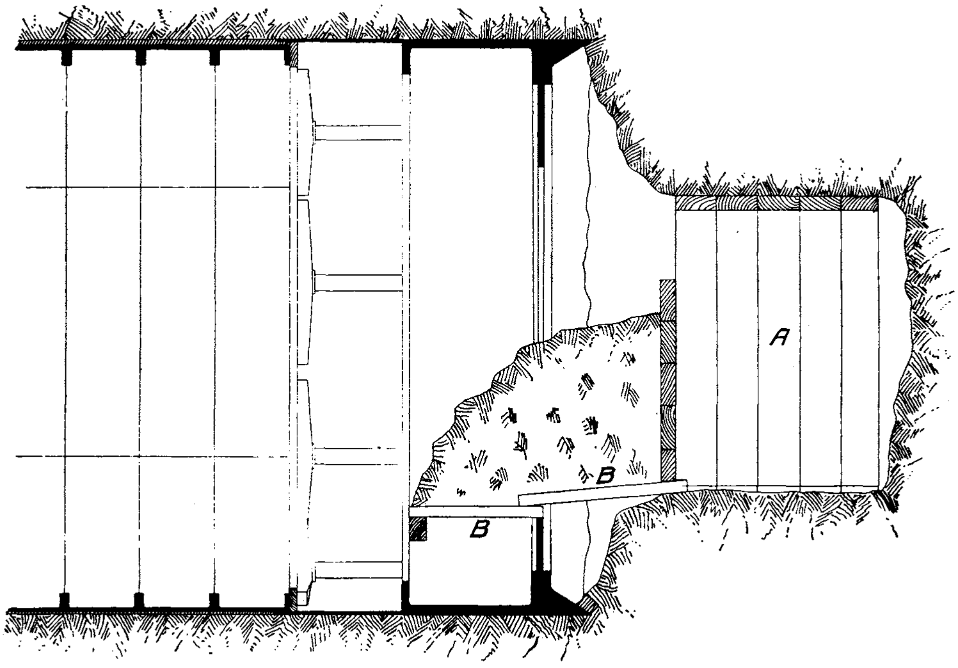


FIG. 58. THE GREATHEAD SHIELD IN CLAY.
Shield at End of Advance.

diameter of the tunnel. The two upper castings are lifted by the men on to the platform, and thence put in place, and to permit of the better adjustment of the key piece, they are frequently supported temporarily by props from the invert, and not bolted up completely until the key is in.

When the ring is completed, the grouting ribs, if loose from the ram shoes, are replaced and held in position by the shield rams, and the ring behind the shield should be at once grouted up.

The operation of erecting the segments is easily performed by six men in the case of tunnels of about 10 to 13 feet diameter in London Clay, as the segments do not, as a rule, exceed 5 cwt. in weight. The time occupied should not exceed twenty-five minutes per ring.

In the first City and South London tunnels the longitudinal or horizontal joints were made with soft wood packing $\frac{1}{4}$ inch thick, and having holes in them for the bolts. These packings were about 1 inch narrower than the flanges of the castings, to allow of the joint being pointed with Medina cement later.

The flanges were not machined.

The vertical or circumferential joints were made with chipping pieces, between which and the bolts was placed, at the time of erection, a rope of tarred hemp or oakum, the remainder of the open joint being subsequently pointed with cement.

The erection of the ring being completed, the cycle of four operations is gone through again; but of course in actual work, not only has the driving of the heading continued without interruption throughout, but the times of all the operations overlap each other. Thus by the time the ring of segments is erected, the excavation for the next advance is well in hand.

The substitution of power for hand labour in compressing the water for the pumps, and some other improvements in the conditions of work, notably the better lighting of the tunnel, now that electric light is available, have made more rapid progress possible. In the South London Tunnels, however, when once the foremen and men had become accustomed to the new conditions a very good rate of progress was maintained, the daily advance of a shield being for long periods as much as 13 feet per day of twenty-four hours.

Not the least of the advantages of the shield method of working in London Clay is that it does away with the necessity for specially skilled labour. The tunnel bricklayer disappears with the use of the iron lining, and any fairly intelligent unskilled labourer can learn the manner of working a shield in a week.

General Observations on Working the Shield in Clay

A few general observations may be added to the foregoing description of working the shield.

The first point to keep in view in working a shield in clay under London is that for the avoidance of subsidences speed is the great essential. The longer any face of clay is exposed to the air, the greater is its movement, and consequently, other things being equal, there is likely to be more surface disturbance caused by a tunnel constructed at the rate of three rings per day than by one which grows by ten rings daily.

If properly bolted up, and grouted, the iron tunnel once built does not appear to settle afterwards, and this is borne out by the fact that the comparatively small surface disturbances which are sometimes noted in connexion with this class of work are first produced not over the finished tunnel but ahead of the shield itself. The author has known some cases where small cracks in brickwork have appeared in buildings 60 or 80 feet ahead of the tunnel face.

It is true that subsidences caused by tunnelling under shield in the London Clay are in no case of a very serious character, as compared with the disturbances caused by other methods of working ; and if the work be properly carried out do not occur at all, but the importance of speed as a precaution against settlements cannot be too strongly insisted on.

In this matter of speed the use of a heading is very important. In an ordinary tunnel on London Clay of about 11 feet 6 inches diameter, seven rings of tunnel lining, or say 11 feet 8 inches in twenty-four hours, is a moderate rate of progress, with an advance heading in front of the shield ; without a heading three rings per day is the best rate of progress, unless indeed such a machine as Mr. Price's excavator be employed.[1]

In the case of a tunnel, with which the author was connected, the engineer responsible for the safety of some public buildings in the streets above refused to allow the shield to be worked with a heading on the ground that the extra excavation in front of the shield increased the risk of subsidence. It is true that the area of clay exposed at one time was larger with a heading than without, but it is difficult to believe that the increased security given by a gain of 100 per cent. in time obtained by using the heading did not enormously outweigh the possible risk of harm due to the larger area of clay exposed.

The size of the heading should not be more than sufficient for two men to work in, and care should be taken that the head and side trees are well wedged up. Its position should, for convenience of working, be rather below than above the centre of the shield.

The use of piles or wedges to break down the clay face in front of the shield is, of course, only effective when the central portion is removed by having the heading cut in it. The number of piles depends on the ram power of the shield, but a usual number is ten or twelve. They should be fixed with the bases on the solid cutting edge, and inclined towards the axis of the shield so that their effect is to break away, as it were, the sides and top of the heading in advance.

These piles are usually made of oak with iron points, but the Australian hardwood Jarrah, without iron points, has also been used on the Central London Railway with satisfactory results.

If properly applied the piles reduce the manual work required of the miners to little more than trimming the face and around the cutting edge, and preparing the invert.

The guiding of the shield during each movement forward does not offer any difficulty. As stated above it can be easily deflected to one side by employing only the rams fixed on the other side, and it is driven round a long curve by applying the rams on the outside of the circle a little in advance of those on the inside.

The important point to bear in mind in nearing the commencement of a change of direction, whether horizontal or vertical, is to commence the deflection of the shield when the cutting edge has reached the point where the change should commence and not to wait until the tunnel is built to that point.

The position of the shield is checked for direction and level in a very simple manner.[2]

On the shield are marked on the diaphragm, usually on the upper and lower edges of the opening forming the door, saw marks which indicate the vertical centre line of the shield. This centre line should, when the tunnel is straight, line up with two plumb lines fixed by the engineers on the centre line of the tunnel already completed, and which centre line is daily carried forward by theodolite as the shield advances.

When going round a curve, either a series of marks corresponding to the offsets to the tangent for short lengths of the curve are marked off to the right or left of the centre saw mark on the diaphragm, or conversely the rearmost of the

[1] For the remarkable results obtained with this machine, see page 113.

[2] For descriptions of the method of setting out the main lines of tunnels, see *Proc. Inst. C.E.*, vol. cxxxix. p. 27, and vol. cl. p. 78.

two plumb bobs in the tunnel is moved along a strip of wood fixed across the upper part of the tunnel, and similarly divided.

When working on a curve, the practical miner in charge of the shield gang generally can keep his shield correct in the daily interval between the engineer's visits for the purpose of checking the line, by measuring the advance of the shield with two slips of wood, the one used on the inside of the curve equal in length to the width of a single ring, the other used on the outside of the curve equal to the increased length of tunnel each ring must occupy there.

Mr. Dalrymple Hay has patented a system of directing the shield by means of guide rods, or graduated bars, which can be attached to the shield on either side, and which advance with it, the amount of the advance being registered by the readings of the graduated scale with reference to two zero points fixed at the side of the tunnel exactly opposite to each other.

When the tunnel is straight the readings of two equal scales so fixed should be the same.

When the shield is going round a curve, the divisions in the scale are made larger on the guide rod on the outside of the curve than on the other, the difference being proportionate to the difference of the length of the radii of the curves described by the two sides of the tunnel.

This arrangement has given satisfactory results.

The practical difficulty in keeping a shield correctly on a curve arises from the fact that however carefully each ring may be set when first erected, the repeated pressure of the rams in pushing the shield forward for subsequent rings tends to compress the tunnel more on the side where the joints are wide than where they are tight, and so to flatten the curve of the tunnel.

The amount of such compression will vary with the character of the packing employed in the circumferential joints of the tunnel linings, but some variation due to the thrust of the shield always takes place.

Another result of the continued pressure of the shield rams on the tunnel lining is that the bolts in the circumferential joints, however well tightened up they may be when a ring is first erected, always are found to be slack, when the shield has advanced ten or fifteen rings forward.

It is always advisable to have a man at about this distance behind the shield at work remedying this defect.

The rotation of the shield about its axis is a common circumstance, and is due to the fact that one or more of the hydraulic rams is not set parallel to the axis of the shield. In the London Clay as mentioned above this movement is not of any great importance, but in some other types of shield this contingency must be taken into account.[1]

The grouting round the tunnel lining must never be permitted to get in arrear, and the operation should never be allowed to be postponed until the end of a shift, or until two or three rings can be done at once.

It should be done every time the shield is moved forward, and care should be taken that the upper portion of the tunnel, as well as the lower, is properly grouted.

The cost of a Greathead shield for a tunnel in clay of from 11 feet to 13 feet diameter is about £450, and the subsequent cost of repair and keeping in working

[1] *Proc. Inst. C.E.*, vol. cl. p. 17.

order is comparatively small ; the main outlay being on the hydraulic rams and pipe connexions, which naturally are exposed to much dirt and rough usage.

The working expenses of a shield in London Clay, or in any material not requiring compressed air, or special, precautions in the front of the shield are tolerably uniform so far as labour is concerned. The supply of air pressure for grouting the tunnel and hydraulic power for driving the shield (when this is not supplied by the shield gang working hand pumps) varies of course with the local conditions, as does the first cost of the cast-iron tunnel lining. In general the cost of a cast-iron tunnel in London Clay is about £2 5*s.* to £2 10*s.* per cubic yard of excavation.

The working gang of a shield 12 feet 6 inches in diameter or thereabouts is made up as follows [1] :—

1 ganger	at 10*s.* per shift of 10 hours
4 miners	,, 9*d.* per hour
4 miners' labourers	,, 7½*d.* ,, ,,
4 general labourers	,, 7*d.* ,, ,,
1 boy	,, 4*d.* ,, ,,

These men carry out all the work in connexion with the excavation, the driving of the shield, the erection and bolting up of the tunnel lining, and grouting. They also haul the skips containing the castings from, and the skips laden with clay to, the nearest "turnout" of the contractors' line, generally about 10 yards in the rear of the shield.

The shield work is usually sublet to this gang at prices based on the foregoing wages list, with an increasing bonus per ring above a certain weekly amount.

In ordinary London Clay forty-five rings or 75 feet of tunnel per week about 12 feet in diameter is an ordinary rate of progress when the excavation is done by handwork.

The other work in connexion with the removal of the spoil, and the forwarding of cast-iron segments, lime, etc., to the shield does not vary much from similar work in ordinary tunnels.

In tunnels of the dimensions of the one under consideration it is the usual practice to make a temporary floor of the excavated clay on which the contractor's rails are laid, the clay being removed, and the tunnel cleaned up when the permanent way is put in. In larger tunnels a timber floor is laid down.

It is found that up to 300 yards of lead, one driver, if ponies are used, and one brakesman, can keep pace with the work at the shield in tunnels up to 12 feet in diameter. When the shield is more than this distance from the shaft or outlet, a double service is required.

Leaving for the present the work in the City and South London in water-bearing material, and turning to the consideration of special features in shields employed in subsequent works, we have in the first place the shields partly designed by Mr. Greathead used in the Glasgow Subway, which, although not one of the London Clay tunnels, may be considered in this place.

Glasgow District Railway

This work, which forms a circular urban line in Glasgow,[2] was commenced in 1892, and completed in 1895. Its length is about 6,500 yards, and the diameter

[1] These are Central London Railway figures.

[2] *Proc. Inst. Engineers and Shipbuilders in Scotland,* Jan. 28, 1896. Simpson on "Tunnelling in Soft Material."

of the tunnels 11 feet. The material tunnelled through varied from brick clay to silty sand, work in the latter being carried out by timbering in front of the shield.

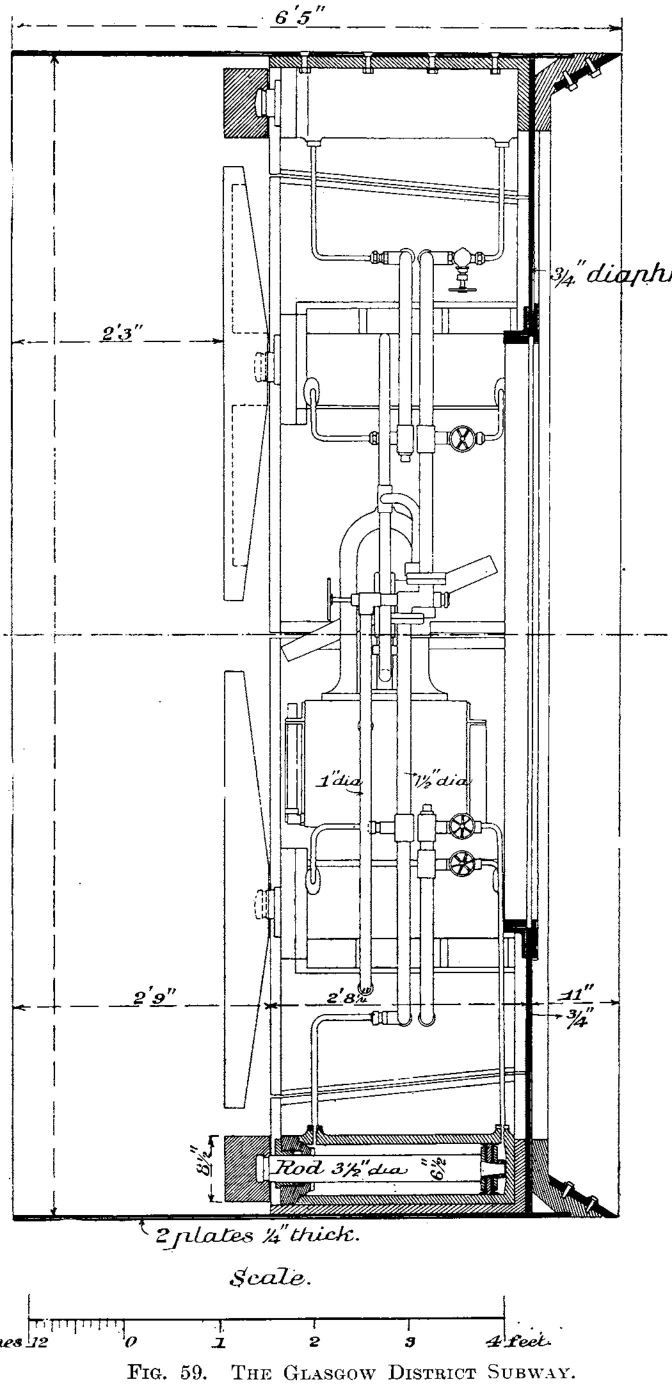


FIG. 59. THE GLASGOW DISTRICT SUBWAY.
The Greathead Shield. Longitudinal Section.

The type of shield used is shown in Figs. 59 and 60, and naturally closely resembles the City and South London shields.

Each shield was 12 feet 1½ inches in diameter, and 6 feet 6 inches in length. As in the South London shield the skin consisted of two ¼ inch plates rivetted together, the diaphragm or bulkhead was similarly placed 1 foot only from the cutting edge, and the same number of hydraulic rams, of the same design as before, were employed. The weight of the shield was about 6 tons.

A feature peculiar to this shield was the double sliding door for closing the opening in the diaphragm.

The pressure pipes are made to run vertically and horizontally, so as to leave the door in the diaphragm clear instead of forming a circle as in the City and South London shield, and this change was for the better and has been followed since.

The engineer of the line, Mr. Simpson, has put on record his opinion that the use of a shield in iron-lined tunnel work is really of little use, and further says that some of the contractors for the work actually removed the shields from the tunnel as being hindrances to the work, and broke them up.

He states that perhaps the use of the shield saved a little timbering, and was useful in paving off smooth the circumference of the excavation, and so saved a little of the manual work in excavation.

The above observations refer to work in the brick clay before mentioned, but Mr. Simpson, as will be seen in treating of the "assisted shield," can find no advantage in a shield even in bad material.

As for the shield when working in clay, Mr. Simpson is the only engineer having practical knowledge of the work who has formed the opinion that iron tunnels are better built without one, while in respect to its work in open ballast, it is true that the Greathead shield was made for work in clay, and that it requires certain modifications to adapt it for working in loose materials. It is clear, however, from the paper by Mr. Simpson, from which the above criticisms in the shield are quoted, that the slow progress made on the Glasgow Railway was in part due to the manner of conducting the work, and that a change of contractors, when the face of the tunnel was under the river, had an important effect on the rate of advance, the same shield being used by both contractors.

The Central London Railway Shields [1]

The shields used on this railway were the City and South London Railway shields with but slight modifications, the designs for them having been laid before Mr. Greathead before his death in 1896. The ordinary shield used in the section of the line between the Marble Arch and the Post Office is shown in Figs. 61 and 62, which represents, with some small modifications which were due to the fact that the numerous shields used on the railway were divided among various manufacturers, [2] the type of shield used throughout the line. [2]

The cylindrical skin is shown in Fig. 62 as being made of two ¼ inch plates, but in some of the later shields it was made of one ½ inch plate, generally in three pieces with a covering strip at the joints.

The cutting edge with the planed steel adjustable cutters was the same, save that the adjoining segments were bolted together, as that of the City and South London shield, but the bulkhead or diaphragm varied from the original model,

[1] *Engineering*, Feb. 18 and March 18, 1898; and *Engineer*, Nov. 4, 11, and 18, 1898. No complete record of this railway has been published.

[2] The shield figured is built by Markhams of Chesterfield.

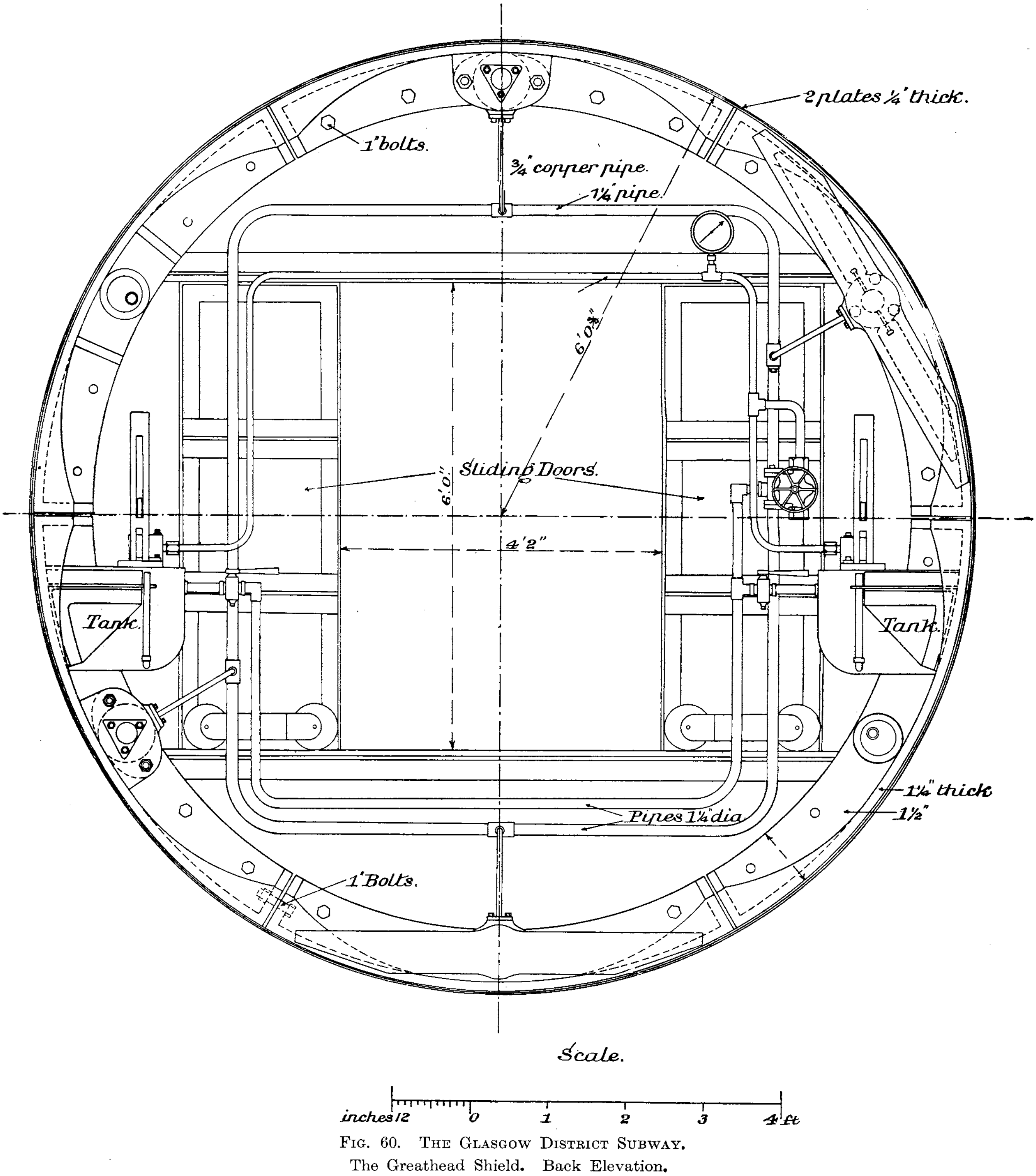


FIG. 60. THE GLASGOW DISTRICT SUBWAY.
The Greathead Shield. Back Elevation.

in that the door was larger, being 6 feet 6 inches high, and 5 feet wide. The tendency of late years has been to cut away more and more, for shields working in London Clay, the diaphragm, until in some extreme cases, notably in shields intended for use with a mechanical excavator, it disappears altogether, and the shield appears simply as a cylinder of steel plate, sufficiently stiffened by internal castings to admit of propulsion by hydraulic rams.

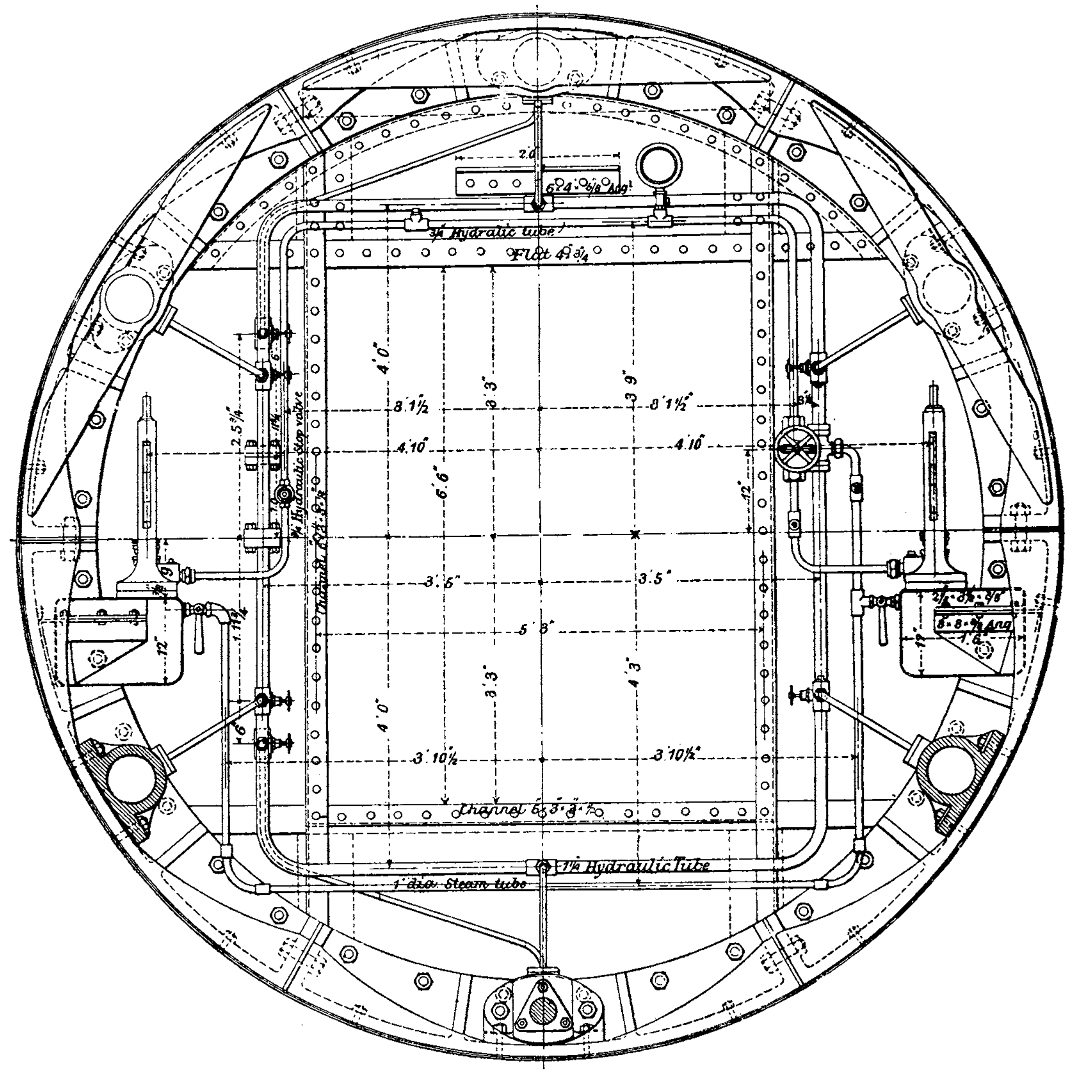


FIG. 61. THE CENTRAL LONDON RAILWAY.
The Greathead Shield. Back Elevation.

But in the ordinary Central London Railway shield this tendency was kept within limits, and as a result the shields, as a general rule, kept fairly rigid, although all to a more or less marked degree widened in the horizontal diameter with a corresponding flattening in the vertical height.

The castings carrying the rams and the rams themselves are the same as on the earlier shields, the supply pipes being arranged to follow the shape of the door in the diaphragm in order to avoid obstructing the work of the shield.

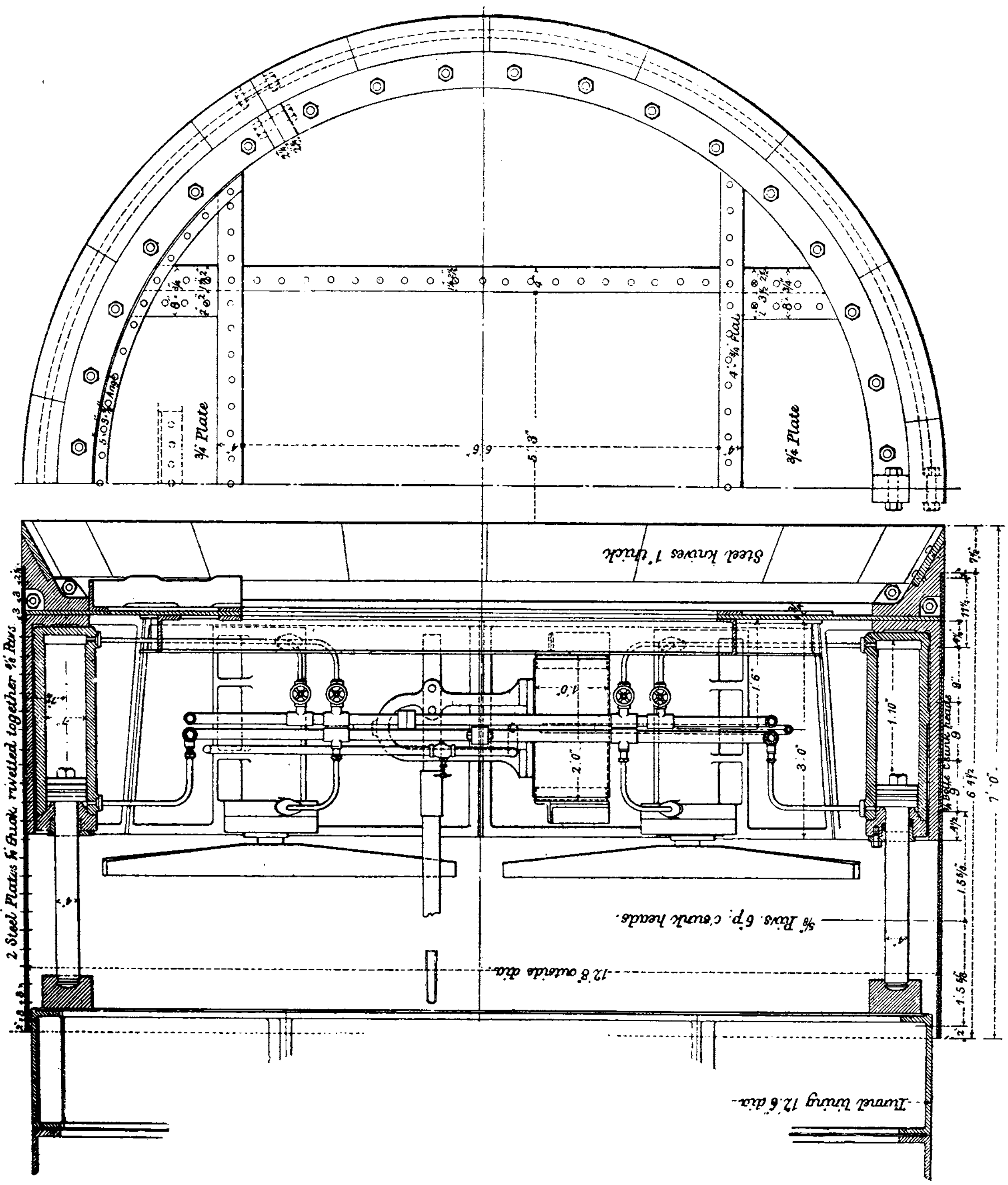


FIG. 62. CENTRAL LONDON RAILWAY.
The Greathead Shield. Longitudinal Section and Half Front Elevation.

In some of the later shields employed on the railway, the arrangement of hand pumps, with differential valves for working at high and low pressure, was abandoned in favour of a neat air engine, similar to that shown in the shield in Fig.

69,[1] which, taking water either from the tanks on the shield or from the pressure supplied by the London Hydraulic Company, in the one case compressed the water, in the other intensified the pressure in the mains, so as to supply pressure to the shield rams of the power required.

These air engines were fixed on a shelf on the diaphragm immediately above the doorway. Their use has the advantage that during the pushing forward of the

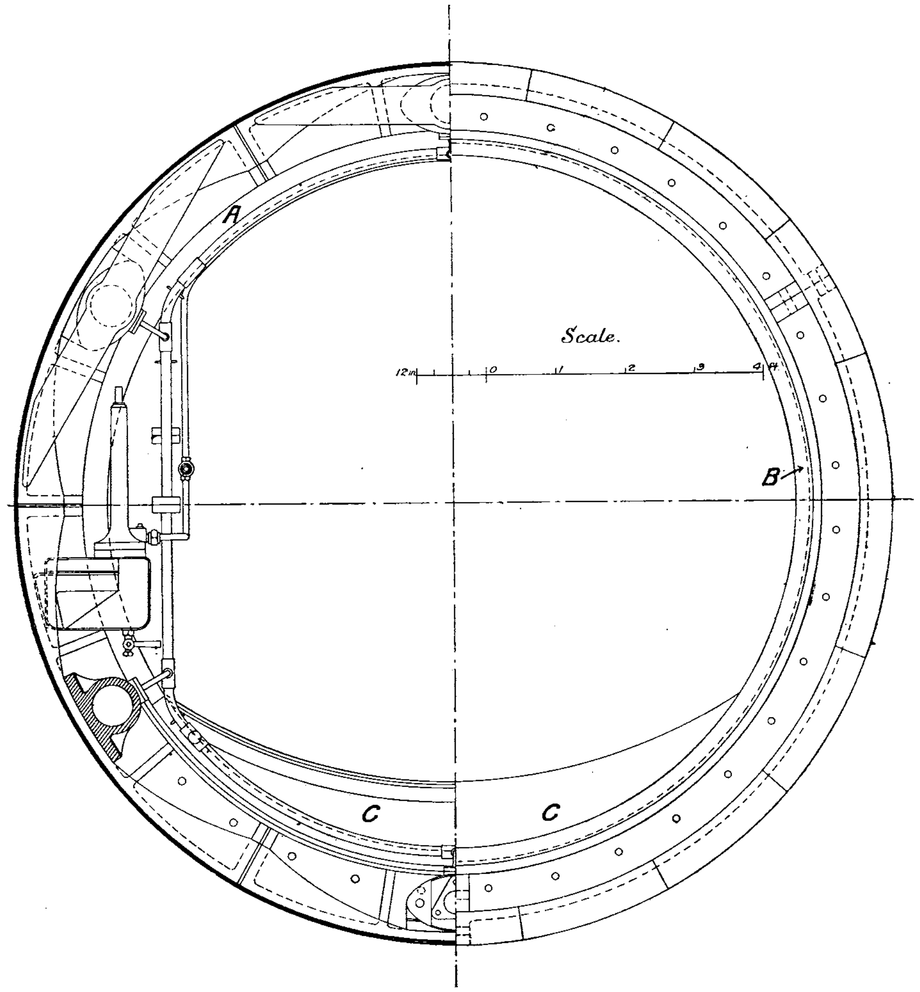


FIG. 63. CENTRAL LONDON RAILWAY.
The Greathead Shield, adapted for use with Mechanical Excavator. Half Back Elevation, and Half Front Elevation.

shield the shield gang are set free to prepare for the erection of the web ring of tunnel lining. The supply of air for the engine is easy, as air at a pressure of 80–100 pounds per square inch is required in any case at the shield for the working of the grouting pan. A minor advantage in the use of these air engines is that their use does away with the hand pumps which take up room in the shield, while the air engine, placed as it is above the door, is entirely out of the way of the workmen.

[1] The machine figured is one of Hayward Tylers manufacture.

THE GREATHEAD SHIELD IN LONDON CLAY

The shield shown in Figs. 61 and 62 is the type usually employed between 1895 and 1903 for the tunnels of from 11 feet 8 inches to 13 feet diameter in London Clay, but a modified shield made for use with a patent excavating machine [1] was also employed, and this presents one feature of interest (see Figs. 63 and 64). The whole of the diaphragm, which is an essential part of the shield as imagined by Barlow and Greathead, has here disappeared, nothing being left of it except a circular flitch, formed of two $\frac{3}{4}$ inch plates, *A A*, Fig. 64, between the cast-iron segments of the cutting edge and those carrying the rams. The shield is, in fact, merely a portable frame which holds up the roof of the excavations while the iron lining of the tunnel is being put in, but which affords no protection whatever against any coming in of the face. The plates *A*, *A*, about 1 foot 4 inches deep, which are all that is left of the diaphragm, do little more towards stiffening the shield than acting as cover-plates over the joints in the castings before and behind them. Round their inner edge is rivetted a channel iron *B*, *B*, which stiffens them in some measure, and serves as a frame in which planks can be placed for closing the face when necessary.

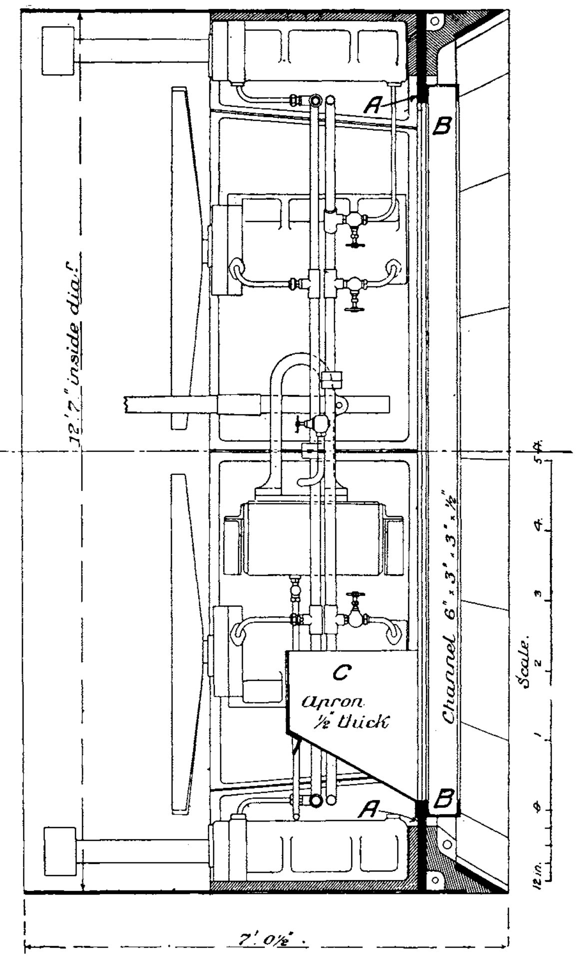


FIG. 64. CENTRAL LONDON RAILWAY.
The Greathead Shield, adapted for use with Mechanical Excavator. Longitudinal Section.

At the lower part of the opening of the shield an apron *C*, *C*, is fixed, the object of which is to keep the clay broken down by the excavator from filling up the bottom of the shield.

The excavator itself is shown in Fig. 65 (in which the shield figured varies a little from that just described, the apron being flatter and the channel iron stiffener on the tunnel side of the $\frac{3}{4}$ plate). This machine is the invention of Mr. T. Thomson, and when tried in 1897 on the Central London Railway gave fairly satisfactory results, but was only used in one tunnel, the frequent failure of the electrical motor and connexions causing the loss of so much time that the increased rate of excavation obtained when the machine was working was made of no effect.

In a larger tunnel than one of 11 feet 8 inches diameter, and with more attention paid to the motor and electrical equipment, this machine would be worth

[1] *Engineer*, Nov. 18, 1898.

further trial, in view of the fact that with it the number of men employed can b
reduced by nearly one-half.

The excavator consists of a carriage or frame on wheels, carrying on it a to

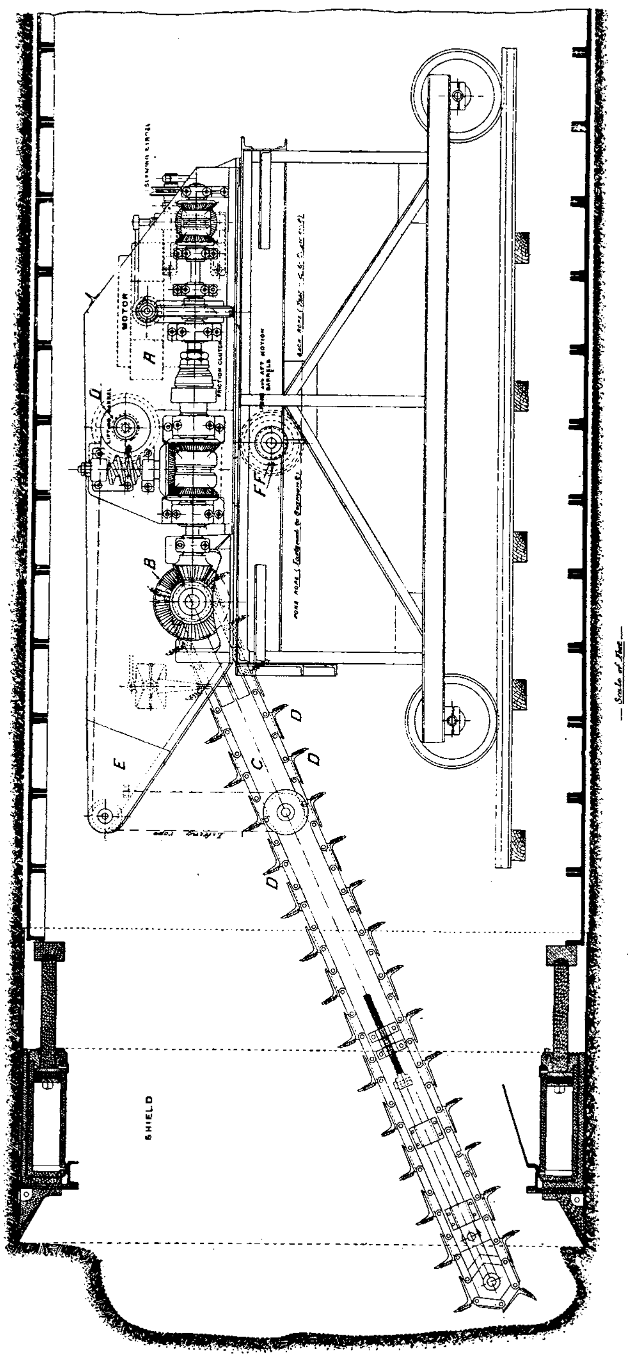


Fig. 65. Central London Railway.
Thomson's Mechanical Excavator.

platform having a certain freedom of revolution in a horizontal direction. This top platform carries an electric motor *A*, which actuates the various motions of the machine.

In the front of the platform is a shaft *B*, worked directly by the gearing shown between it and the motor. On this shaft is placed loosely an arm *C*, on which is fixed a ladder of buckets *D*, *D*, *D*, similar to that of a dredging machine.

This ladder is made to travel by the revolution of the shaft *B*. The arm *C* is raised or depressed by throwing into gear the wheel *D*, which winds or unwinds a wire rope passing over a pulley between two cantilevers or frames *E*, *E*.

To operate the machine the carriage is brought forward, so that the arm *C* carrying the excavating buckets is in the position shown in the figure, by means of the drums *F*, *F* (which can be geared at will with the motor *A*), on which are wound wire ropes fastened to the lining of the tunnel already built. The shaft *B*, carrying with it the ladder of buckets, is made to revolve at the same time that the lifting barrel *D*, which raises the arm, and makes it with the buckets go through the same operation in a vertical plane, as a dredge does in the horizontal bed of a river, is put in operation.

When one upward cut is complete the arm *C* is lowered again, and then by means of the slewing barrel at the rear of the machine moved to one side to take another cut, and then again raised with the bucket ladder working. As the bucket ladder revolves, the clay brought up by each bucket is, on the bucket turning over the shaft *B*, dropped into a truck (not shown on the drawing), the frame of the excavator being made large enough to allow of a truck passing under it.

The excavator, as can be seen from the figure, can reach all the face of the clay, save for a few inches round the circumference of the shield. This remaining material, however, was easily cut away by the shield as it advanced.

When the excavator has cut out 20 inches of clay or thereabouts, and the shield is pushed forward far enough to admit of the erection of a ring of cast-iron lining, it is run back some 10 feet to enable the miners to proceed with the erection of the ring, which being done, the excavator is set to work again, and the cycle of operations repeated.

The rate of progress with this machine was about double that attained by ordinary mining in front of the shield.

As a general rule, mechanical excavators are objectionable in small tunnels, for the reason that they form a serious obstruction in the working face, and that, should they break down, they are likely to entirely stop work for some time until they can be repaired or removed.

This fault the Thomson excavator has not ; in case of a breakdown it can be pushed back from the face, and work in the shield continued in the ordinary way, the ships or trucks for removing the clay passing through the frame of the excavator without difficulty, the working platform of the machine being made high enough to allow of this.

The motor used in driving this machine on the Central London Railway was a 100 ampère motor at 200 volts.

But in small tunnels of 11 to 13 feet in diameter a machine of this type is very expensive to work, from the fact that, owing to limitations of space, and particularly of headroom, many of the operations of the machine are carried out at a mechanical disadvantage. For instance, the lifting cable of the arm carrying the buckets, which passes over the pulley between the cantilevers *E*, *E*, is obviously attached much too near the fulcrum of the arm to lift this latter save at an expenditure of power compared with the actual pressure required to cut the clay of some three to one ; and this cannot be improved without limiting the vertical movement of the arm.

This, as said above, might be obviated in a larger tunnel, but up to the present this type of excavator has not been tried a second time.

Another mechanical excavator was tried in 1897, also on the Central London Railway, of a different character. With this machine, designed by Mr. Price, the contractor for the section of the line from Shepherd's Bush to the Marble Arch, a shield of the Greathead type, but entirely divested of any diaphragm, was used

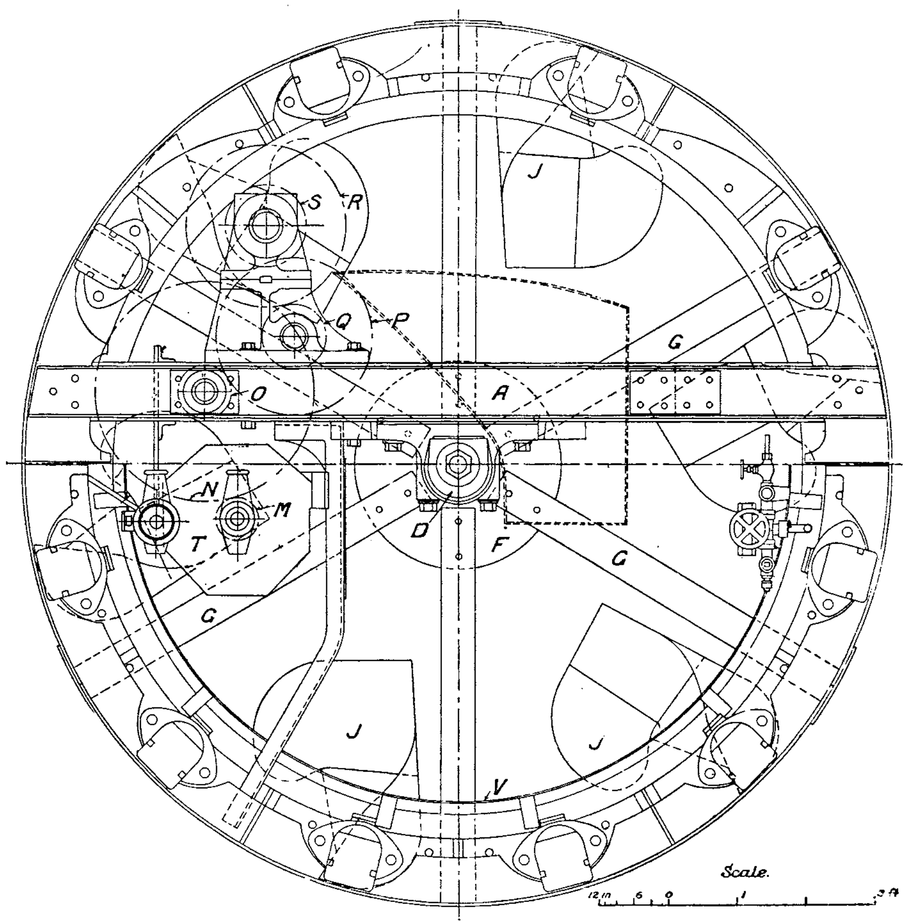


FIG. 66. CHARING CROSS AND HAMPSTEAD RAILWAY, LONDON.
Price's Combined Shield and Mechanical Excavator. Back Elevation.

(like the first described as employed with Thomson's excavator, but without the apron, which with Price's machine was not required).

The machine itself consisted of a number of arms carrying cutting chisels, which (the arms) were radial to a shaft occupying the axis of the tunnel to which the frame carrying it was attached. This shaft was rotated by electrical power, and, the arms revolving with it, the clay face was removed by the chisels.

The main defect in the design was that, when working on a curve, there was too much spring in the long axle to allow the machine to excavate more on one side than on the other, and the independence of the excavator from the shield accentuated this defect.

The driving power also was applied in the wrong place, namely at the axle instead of at the circumference of the machine.

These defects have been remedied by Mr. Price in the excavator shown in Figs. 66 and 67, which up to the present must be regarded as the best mining implement for London Clay work invented.

Charing Cross and Hampstead Shield and Excavator

It has been in regular use on the Charing Cross and Hampstead Railway for some time, and has attained in favourable circumstances the extraordinary speed of 108 rings of tunnel lining, 11 feet 8 inches diameter, or 180 feet per week, and this without many intervals of idleness due to a breakdown of the machinery.[1]

It consists of a combination, in one frame, of the shield and excavator, the latter being mounted on girders within the former, and both moving forward together.

The excavator is of the rotary type, and the clay cut from the face is, as it falls into the invert of the shield, picked up by buckets which revolve with the arms of the excavator, and discharge in turn as each reaches the soffit of the shield, the clay so gathered, by means of shoots into trucks, or as in the machine used by Mr. Price, into a mechanical conveyor. Many patents of this character are to be found in the Patent Office records, and some of them are included in the list of tunnel patents given in this volume. The two Price patents are, however, the only machines of a rotary type which have been put to the test of actual work.

In detail the machine is described below.

In an ordinary Greathead shield, which differs only from the Central London Railway type in the arrangement and number of the hydraulic rams, which are unequally spaced, six being in the lower part of the shield, and four in the upper, and in the absence of a diaphragm, save in the rudimentary form of two $\frac{3}{4}$ inch plates which form a ring round the shield hardly wider than the flanges of the cutting edge, and of the ram castings, are fixed two horizontal girders *A*, *A*, 2 feet 9 inches apart and each formed of two channel irons 9 inches by 3 inches by $\frac{5}{8}$ inch, with flanges $\frac{5}{8}$ inch thick. These are placed 8 inches above the horizontal diameter of the shield, and are bolted at the ends to the ram castings which are made of special pattern to receive them. They thus serve, in addition to their use in carrying the excavating machinery, as very effective tie bars for keeping the shield in shape.

At the centres of these girders and beneath them, so that the axis of the shaft coincides with the longitudinal axis of the shield, are fixed two journals *B*,*D*, carrying the main shaft *C* of the excavator, which is 8 inches in diameter.

The rear journal *D* is constructed to serve also as a bearing block, and against it the shaft can be adjusted by nuts accessible from the back of the shield.

In front, and bearing against a collar *E* on the shaft *C*, is fixed a cast metal hub *F*, to which are bolted six radial arms *G*, *G*, *G*. Each of these arms or spokes is formed of two channel irons 6 inches by 3 inches, which are braced together by other channel bars serving also as holders for the removable cutters or chisels *K*, *K*, *K*.

[1] 360 rings have been erected in four consecutive weeks.

These chisels are attached to the channel bars in which they lie, by plates and bolts, very much in the manner of a chisel in an ordinary planing machine.

They are arranged at varying distances from the axis of the central shaft on the different arms, so that when the arms are set in motion, the whole surface of the clay face is operated on in each complete revolution of the shaft.

The six arms are held together by circumferential plates *H, H*, which are bolted to them, and not only greatly increase their strength, but also serve as the base plates to which are attached the circular rack *L*, by which the arms are driven round, and also the buckets *J, J*, whose function is to pick up the débris thrown down by the cutters, and discharge it clear of the shield.

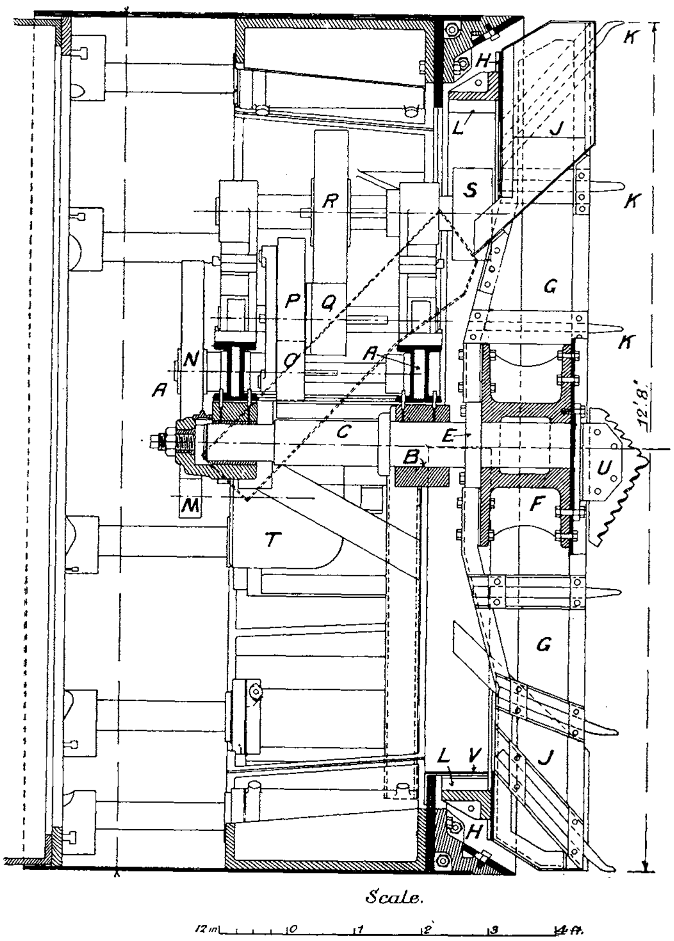


FIG. 67. CHARING CROSS AND HAMPSTEAD RAILWAY. Price's Combined Shield and Mechanical Excavator. Longitudinal Section.

It will be seen, therefore, that the excavator is, in principle, a large revolving wheel, having fixed to its spokes cutters or chisels which slice away the clay face; the wheel being mounted on a shaft concentric with the shield to which it is secured.

This wheel is made to revolve by a chain of wheels *M, N*; *O, P*; *Q, R*; *S, L*; *M* being on the axis of the electric motor *T*, and *L* the circular rack of the excavating wheel. The chain of wheels is supported on castings resting on or under the girders *A, A*, and the motor *T* is fixed in a frame carried in part by the ram casting of the shield, and in part by a channel iron between *A* and the invert of the shield. The motor is of 60 H.P., and runs at about 500 revolutions per minute, the usual speed of the excavating wheel being about one and one-half revolutions per minute.

In actual work the wheels *M* and *N* are encased in a thin metal shield, and the remaining gearing is partly protected against dirt. Round the lower half of the shield is fixed an apron plate *V*, which keeps the clay from choking the teeth of the rack *L*, this plate being secured to the shield by bent bars rivetted to the ¾ inch plates of the diaphragm.

In addition to the chisels *K, K, K*, the later shields of Mr. Price's patterns have fixed on the central hub, *F*, but placed eccentrically to its centre, a kind of toothed scraper *V*, which is intended to remove the centre of the face and also to keep the excavator steady in line.

A further improvement, which in actual work has answered very well, devised to meet the difficulty of excavating more on one side than on the other when the shield is to be driven round a curve, has been suggested by Messrs. Markham, the constructors of these machines. It consists in fixing at the ends of the arms *G*, a cutter which can by cams or eccentric arrangement be projected beyond the end of the arm and beyond the skin of the shield for a certain length of the circumference of the face, and so for that distance making a wider excavation into which the shield can be turned.

In addition to the mechanism shown in the figures there is fixed to the girders *A*, *A*, a large shoot (indicated in outline by double dotted lines) which receives the clay discharged from the buckets *J*, *J*, and delivers it to a conveyor, also worked by electricity, and somewhat of the character of the one shown in Figs. 188 and 189, but simpler, by which the clay is carried some 30 feet from the shield and discharged into skips.

The same frame or carriage which supports the conveyor carries also a small compressor for the hydraulic rams of the shield and the starting switches for controlling the mechanism of the conveyor motor and the excavator motor. This frame or carriage runs on rails temporarily fixed on either side of the tunnel.

The method of working one of these shields is as follows :—

When the erection of a tunnel ring, during which operation the shield is perforce at rest, is completed, the shield is put in motion by starting the hydraulic rams, at the same time that the excavator is made to revolve by starting the motor *T*. The full control of all the machinery is in the hands of an operator seated on the carriage of the conveyor who has within his reach the rheostats for starting the motors of the excavator and conveyor, and the valves of the hydraulic gear.

As the cutters *K*, *K*, on the arms *G*, *G*, break off the clay in the face, the buckets *J*, *J*, scoop it up, as they revolve, from the invert of the excavation, carry it round, and as one after another they reach the top, discharge it downwards into the main shoot (indicated in double dotted lines), whence the conveyor receives it.

The satisfactory working of the shield depends on the correct adjustment to each other of the two motions, the advance forward of the shield, and the revolving action of the excavator, and this requires very careful watching on the part of the man controlling the motors and rams.

As soon as he perceives by means of an ammeter that the resistance of the excavating machine is increasing, due to the fact that the shield is going forward more quickly than the excavator can remove the clay, he reduces the pressure in the rams ; if, on the other hand, he finds that the excavator is making light cuts, he increases the pressure in the hydraulic rams to keep the shield hard up to the clay face as it is excavated.

As said above, this machine has given very satisfactory results, and in material like London Clay is undoubtedly a very excellent tool. It is not, of course, suited for any material in which stones or hard rock is likely to be encountered as, even if the nature of the material in the face were discovered in time to prevent injury to the excavating tools, there is no possible means of getting to the face of the shield to work the excavation by hand except by removing the whole excavator from the shield.

The risk of meeting hard material in the London Clay is, of course, slight, except at the junction of the London Clay proper with the hard red clay of the Reading beds beneath, where bands of hard rock are sometimes found.

The manner in which the feed of the excavator is regulated by the advance of the shield is very sound, not merely because the feed is efficient, but because by making the shield advance with the excavation there is never, as in ordinary miners' work, in front of a shield an area of face and circumference unprotected and unsustained.

The shield indeed, when the machine is working well, is never at rest, except during the period—twenty minutes—necessary to erect each ring of tunnel castings, which is of itself a recommendation.

The men necessary to work the shield are :—

1 ganger,
2 miners,
6 labourers,
1 boy,

or nine men and a boy as compared with thirteen men and a boy for the ordinary Greathead shield when mining by hand.

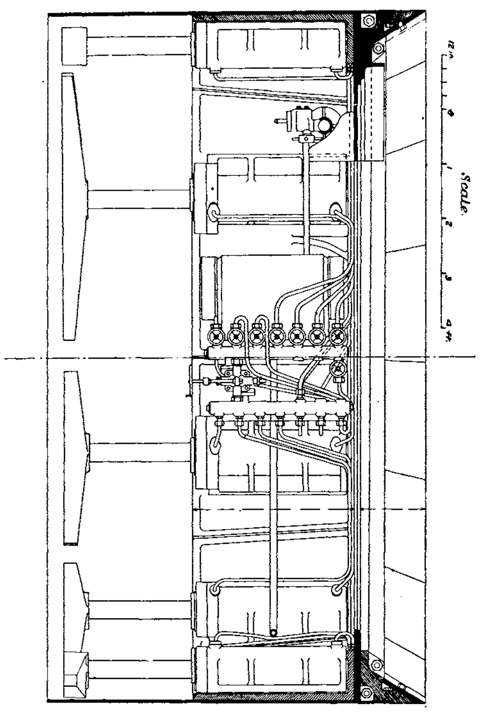


FIG. 68. GREAT NORTHERN AND STRAND RAILWAY, LONDON.
Greathead Shield. Longitudinal Section.

This gang working ten and one-half shifts of ten hours each per week has made a maximum advance of 180 feet per week, or over 17 feet per shift : a great improvement on any previous rate of progress.

The principal practical difficulty at present in the working of this machine is the tendency of the shield to get out of line, unless very carefully watched when in movement.

The Great Northern and Strand Railway

Before leaving the subject of Greathead shields as used in London Clay in iron tunnels of from 10 to 14 feet diameter, attention may be called to one of the latest patterns of shield built for Messrs. Walter Scott and Company, the contractors for the Great Northern and Strand Railway, who were also contractors for Mr. Greathead's original City and South London Railway. This shield, Figs. 68 and 69, though all its features had been adopted in one tunnel or another previously, may be usefully compared with the City and South London prototype of eighteen years before ; it is interesting both in its resemblances and in its differences.

The skin, instead of being composed of two plates $\frac{1}{4}$ inch thick, consists of one

½ inch plate in three sections, with cover-plates outside the joints. The cutting edge is unaltered, and the cutting knives also.

The diaphragm, as in the shields for use with excavating machines, has almost disappeared; and the shield is without protection from any collapse of the face, or irruption of water: experience having shown that there is so little risk of either accident in London Clay that, given reasonable care in sinking trial borings beforehand, their possibility may be neglected.

The cast-iron ring, formed of segments, which stiffens the shield is unaltered, but in the arrangement of the rams themselves there are considerable alterations.

The valves controlling the supply of water to the rams are concentrated in one cluster at the side of the tunnel, instead of being distributed, two to each ram,

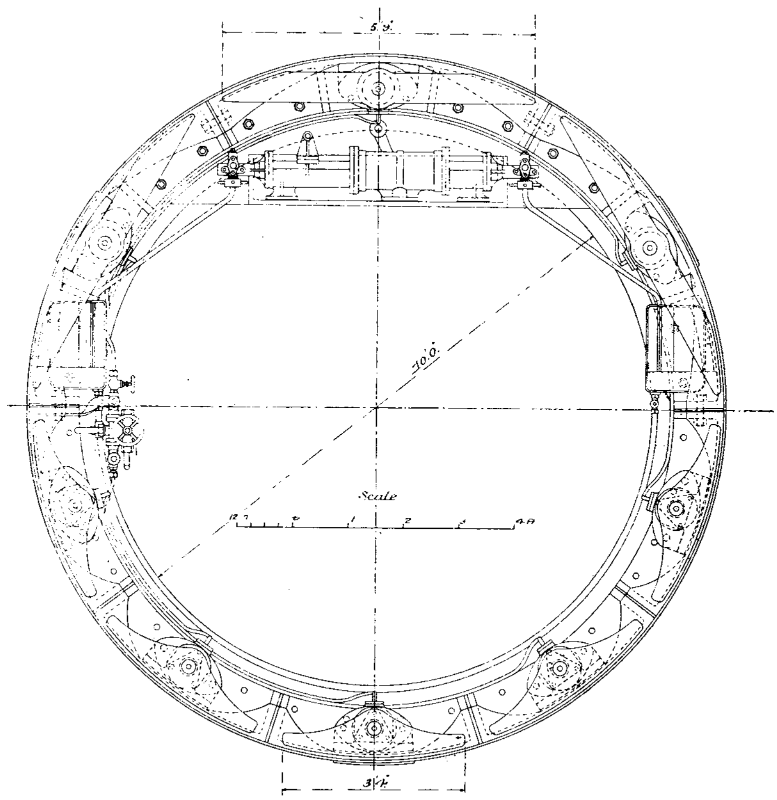


FIG. 69. GREAT NORTHERN AND STRAND RAILWAY, LONDON.
Greathead Shield. Back Elevation.

around the shield, and can be controlled by one man who can reach every valve without interfering with the other work of the shield.

The hydraulic pressure is obtained by a small air-driven compressor at the top of the shield instead of by manual labour; and the rams themselves have been increased in number (the Great Northern and Strand tunnel is only about 1 foot 6 inches larger in diameter than the earliest City and South London one) from six to eight, and instead of being symmetrically arranged in the shield they are disposed, as in the Price shield on the Charing Cross and Hampstead Railway, to exert the greatest pressure below the horizontal axis of the shield, five being in the lower half and only three in the upper.

The increase in the number of rams is an improvement : the more rams there are the more easy is the keeping of the shield in good alignment, and the less chance there is that a breakdown in one of them, if it occurs during the absence of the engineer in charge, may seriously affect the direction of the shield ; but in a solid material like London Clay the massing of the rams in the lower half of the shield hardly appears of much advantage. In loose material, where the shield has a tendency to sink, the arrangement is advantageous.

The Greathead Shield in London Clay for Tunnels of Larger Diameter

The shields so far considered are those employed in tunnels of about 14 feet diameter and under, which present a face of clay sufficiently small to be easily worked in the manner already described, without the use of scaffolding.

But in the Waterloo and City Railway[1] and the Central London Railway, both commenced under the supervision of Mr. Greathead, station tunnels of 23 and 21 feet diameter respectively were built with shields, and since that time tunnels of 30 feet diameter have been constructed in London Clay. Since then the Great Northern and City Railway has been built with tunnels throughout its entire length of 16 feet diameter, and tramway tunnels with a diameter of 17 feet are now being constructed under Holborn. These larger shields require considerable alterations from the type successfully operated in constructing smaller tunnels, and in some respects bear more resemblance to the Beach shield than to the Greathead one.

Their size compels the use of transverse platforms on which the miners may stand to work, and the employment of mechanical erectors for placing the cast-iron segments of the tunnel lining in position ; and in addition the large face of clay exposed in front requires support as it is excavated in advance of the shield. The first two requirements caused the disappearance of the solid diaphragm with a central door, which was a distinctive feature of both the Barlow and Greathead shields, and the third required the provision of rams in the front of the shield, to serve the same purpose as stretchers in an ordinary timbered tunnel face.

The Central London Railway and Waterloo and City Railway Station Shields

The shield devised to meet these special requirements, and used on the Central London, and Waterloo and City Railways is shown in Figs. 70, 71 and 72. The shields in the two undertakings are alike, and differ only in diameter, those of the former railway being 21, those of the latter 23 feet in internal diameter.

The skin of the shield, which in length over all is 6 feet 10 inches, is composed of two ½ inch plates, lap jointed with countersunk rivets. The cutting edge *A*, which is, unlike the smaller shields, not provided with cutting knives, consists of twenty-two segments as does the cast-iron ring *B* behind, carrying the rams, also twenty-two in number.

[1] *Proc. Inst. C.E.*, vol. cxxxix. p. 50. This was the first tube railway in London where the station tunnels were made with cast-iron linings: on the City and South London Railway (first contract) brick tunnels were built for the stations.

Between these two cast-iron rings is a thick steel plate diaphragm *C*, consisting of eleven segments, the joints of which break joint with those of the cast-iron rings.

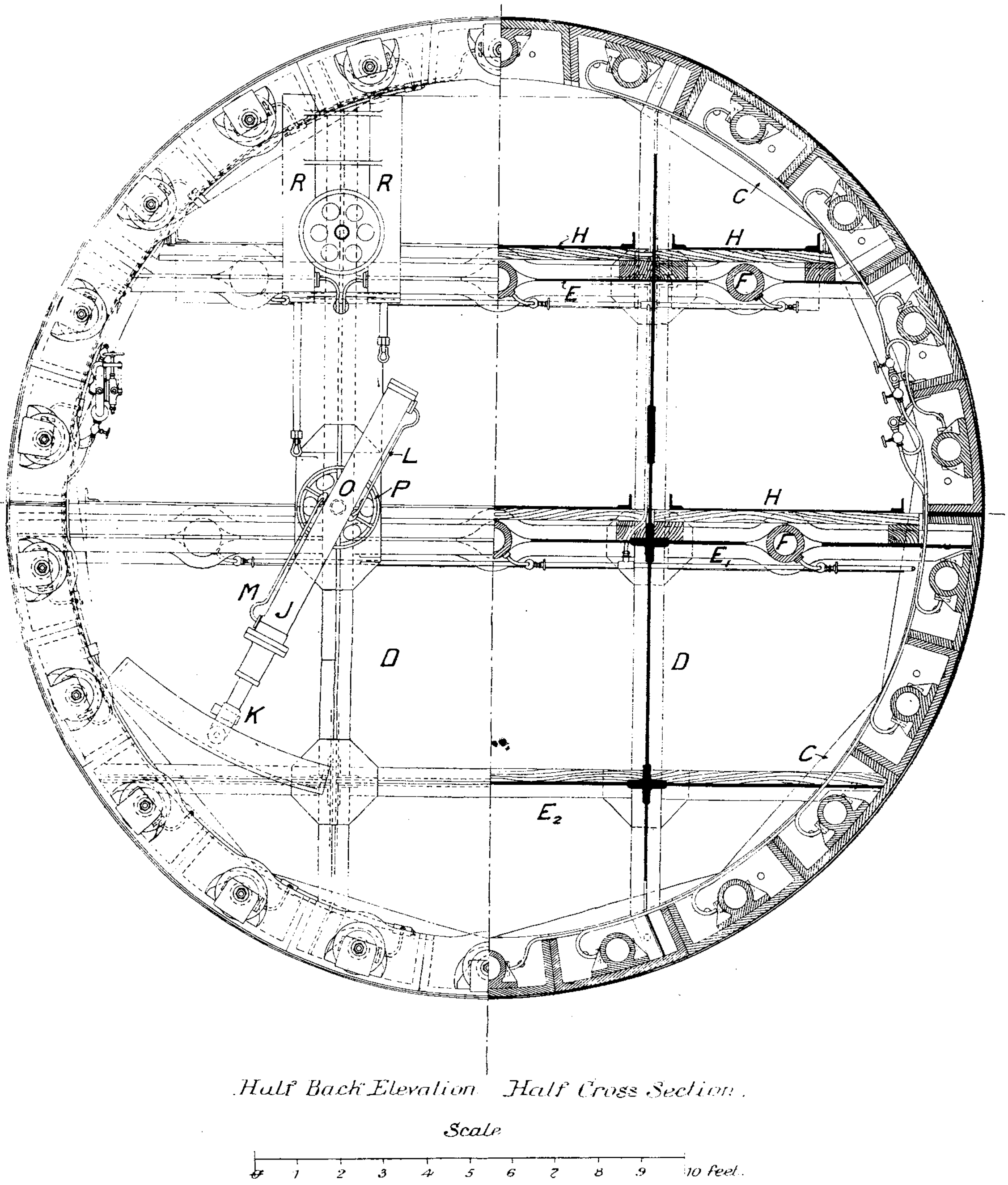
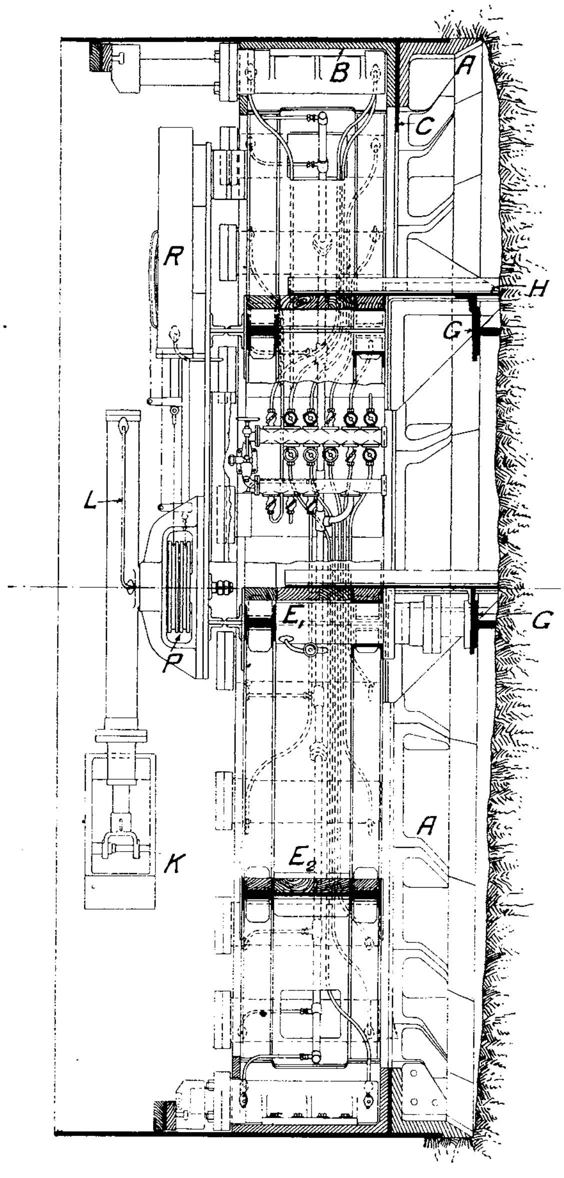


FIG. 70.—THE CENTRAL LONDON AND WATERLOO AND CITY RAILWAY.
Shield for Tunnels of 21 and 23 feet internal diameter.

This diaphragm, as is seen in Fig. 70, is little more than a cover-plate to the joints of the cast-iron segments.

The arrangement of the pressure pipes to the rams is shown in the Figures, 70 and 71, but the tanks from which the water is drawn and to which the waste is returned are not shown, and generally are not carried on the shield itself, but on a gantry behind it.



Longitudinal Section.

FIG. 71. THE CENTRAL LONDON AND WATERLOO AND CITY RAILWAYS.
Shield for Tunnels of 21 and 23 feet internal diameter.

The bracing of a shield of such large diameter is formed by two vertical girders *D*, *D*, and three horizontal girders, *E*, E_1, E_2, or tables composed of steel plates stiffened with channel irons. These girders are secured at their ends to the ram castings, and to each other at their intersections by heavy angle irons. The lowest of the three horizontal girders or tables, E_2, has the upper surface planked over, and it is at this level that the advance heading, when one is driven, is made. The rectangular framing formed by these five frames make the shield extremely rigid. The two upper tables *E*, E_1, are made so that the channel irons enclose hydraulic rams *F*, *F*, *F*, the heads of which *G*, *G*, are composed of angle irons and a plate, which are secured to a sliding table *H*, on which the miners work. As the excavation in front of the shield progresses, the rams are forced forward, and support the face.

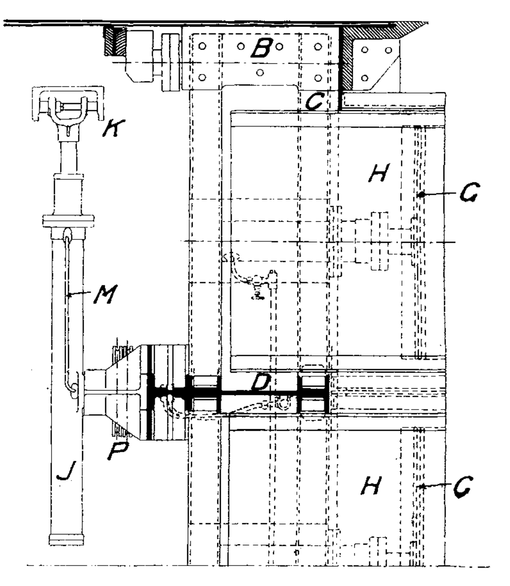
The hydraulic pressure for these "face" rams, as they are called, is arranged in the same way as that which operates the ordinary shield rams.

Behind the vertical girders *D*, *D*, are fixed two hydraulic erectors, for fixing in their places the segments of the tunnel lining. Each erector consists of an hydraulic cylinder *J*, the piston of which terminates in a fork *K*, to which the tunnel segments can be secured. The piston can be extended or withdrawn by passing the pressure through the pressure pipe *L*, or *M*, as required. The pressure is regulated in this, as in all other movements of the erector, by valves placed near one of the floors of the shield.

The cylinder J is pivotted in an axis O, which also carries a drum P, round which is passed a chain, the ends of which are attached to the pistons of two vertical cylinders R, R. By manipulating these cylinders, the drum P can be made to revolve, and with it the cylinder J.

The working of the shield is similar to that of the smaller one, except that the use of piles or wedges to break down the clay is not so effective on the large shield as in the smaller, even when a heading is used, which is not always the case. The clay is excavated from the top downwards, and held up until the shield is ready to move by a few "soldiers" wedged against the framing of the shield and the face rams, which are advanced as the excavation proceeds.

When the shield is advancing, the wedges, if any, are knocked out, and the whole pressure of the face is taken by the face rams. The ordinary shield rams, in driving forward the shield, overcome the backward pressure of the face rams which continue to support the face until the shield has advanced the full length of the excavation, when the pistons of the face rams are driven home and the face is again supported by the framing of the shield.



Half Plan of Platform.

FIG. 72. THE CENTRAL LONDON AND WATERLOO AND CITY RAILWAYS.
Shield for Tunnels of 21 and 23 feet internal diameter.

The erectors behind the shield are worked in the following manner. When the shield is pushed forward far enough to allow of the erection of a new ring of cast-iron lining, and the five or six segments forming the invert of the tunnel have been put in place by the simple method of lowering them from the level of the temporary track, usually a little above the lowest table of the shield, the first segment which requires handling is brought forward on a trolly on the temporary track which is usually carried forward on to the shield, when the erector cylinder J is swung round so that the piston ending in the fork K is directed at the segment. The piston is then extended by operating the pressure through the pipe L, and when sufficiently extended the segment is secured to the fork K with a loose-fitting bolt and nut. By reversing the pressure valves so that the water passes through the pipe M instead of L, the piston of the erector falls back, lifting with it the segment to be fixed. As soon as the casting is clear of the trolley one or other of the cylinders R, R, are put in operation and the piston of the main cylinder J pointed at the place which the segment is to occupy. This done, the valve controlling the pipe L is opened, and the piston of the cylinder J is run out until it presses the segment against the inside of the shield skin, and holds it there until it is bolted up to the segments already erected. The bolt is then taken from the fork K, and the cylinder J swung round to take the next segment.

The gang employed on a shield of this character is usually as under :—

1 ganger,
8 miners,
8 miners' labourers,
4 general labourers,
1 shield driver,
1 boy,

and the progress made is usually from eighteen to twenty-one rings per week, the rings being 18 inches wide, or say 27 to 31 feet 6 inches per week of six days.

In London Clay these shields have given very good results : they are, owing to their comparative shortness (in proportion to diameter) and number of rams on them, very easy to guide, and their construction makes the work of excavation fairly rapid ; much more so indeed if measured by the cubic yards excavated than with the ordinary Greathead shield in an 11 feet 8 inch tunnel.

The rams for driving the shields are twenty-two in number, and resemble those used on the smaller shields, except that the shoes or crossheads which bear against the cast-iron lining of the tunnel are much smaller, and have the bearing surface levelled off, so that they bear only against the outside edge of the castings, and so minimise the risk of breaking the flanges.

In working a shield of this size it is usual to provide behind it a timber staging or gantry on wheels which runs on rails fixed on either side of the tunnel. This gantry carries the auxiliary machines such as the grouting pans, pressure pumps, etc., and is fitted with stages at different levels to enable the grouting of the tunnel to be easily carried out.

The temporary or working floor of the tunnel is usually made, in the case of these large tunnels, of timber. This makes the invert below easy of access, and permits the caulking or pointing of the joints in the lining to be carried out rapidly.

The Great Northern and City Railway, and the Kingsway Subway Tunnels of the London County Council

This railway connects the City of London with the Great Northern Railway, which it joins at Finsbury Park Station, and was opened in 1904. The tunnels were designed (see Fig. 34), to permit of the passage through them of the standard gauge carriages of the Great Northern Railway, and with this object were made 16 feet in diameter instead of the usual 11 feet 6 inches to 12 feet of the London Tube Railways. This increase in the tunnel diameter necessitated an increase in the power, and additional stiffness in the framing, of the shield employed. The former was obtained by employing sixteen rams instead of the six or eight usually put in an 11 feet 6 inch shield, and making these of greater power ; the second alteration consisted in the fitting of horizontal and vertical frames in the shield similar to those employed in the station tunnel shields just described, and in doubling, for part of its length, the skin, so that the inner and outer skin, being connected together by plates and angle bracings, formed a very rigid casing to the shield. As a machine for working in London Clay, the shield proved very satisfactory ; it was very rigid, and the increased ram power enabled it to be driven without cutting the clay in front too wide of the cutting edge.

The shield figured in Figs. 73, 74, 75 is not the shield actually used in the Great Northern and City Railway, but one, almost identical in all details with it, only varying in diameter, and in which many of the fittings of the earlier one, particularly the rams and hydraulic erector, were used over again. This shield was used (1904) in driving two short tunnels, 15 feet in diameter, which are intended to carry that portion of the underground London County Council Tramway which is being constructed along the new Kingsway, where it passes under Holborn. The remaining portion, or almost all of it, of this tramway is constructed by cut and cover work; but where the tunnels pass under Holborn, the shield method of

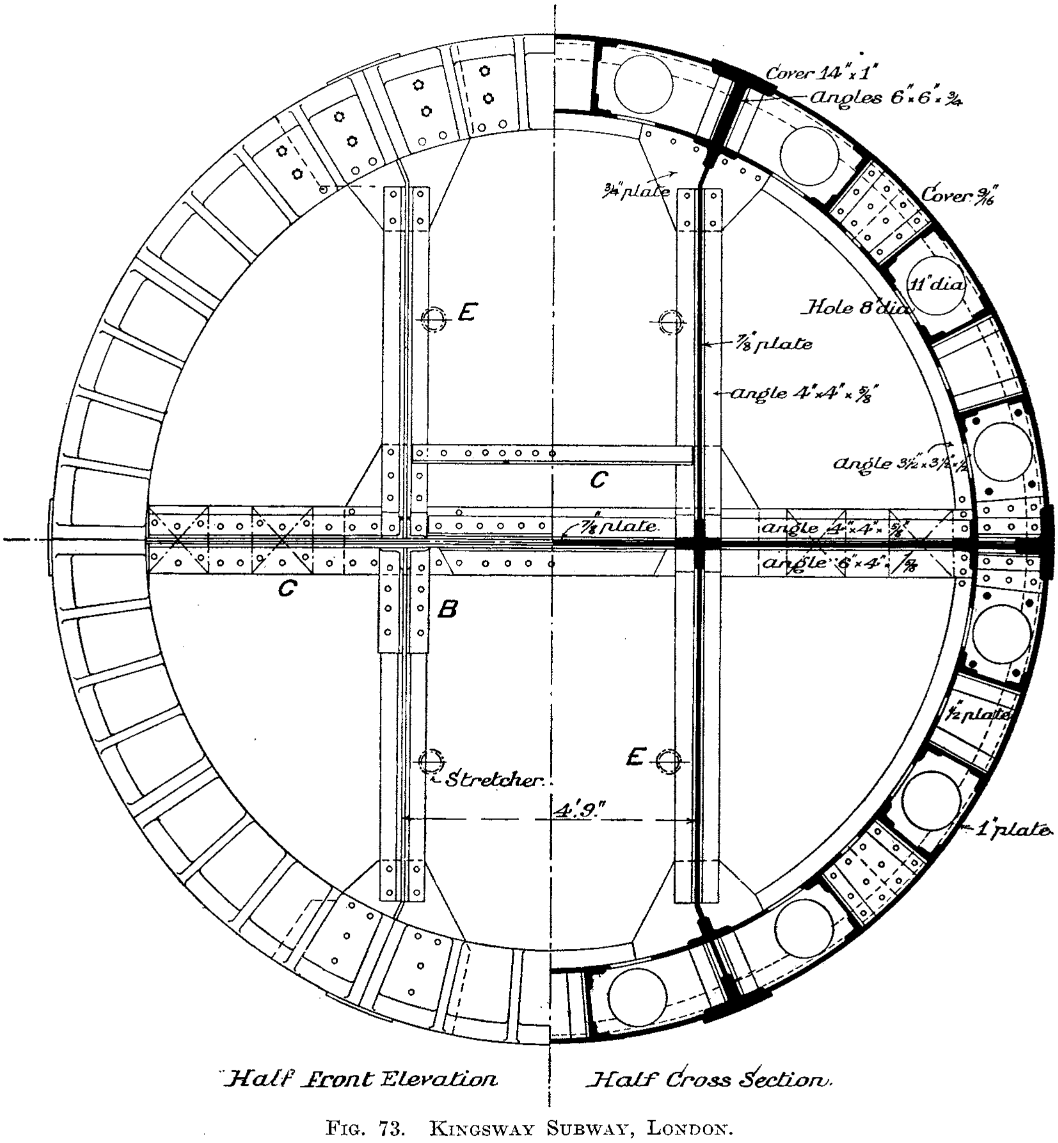


FIG. 73. KINGSWAY SUBWAY, LONDON.
Shield for Cast Iron lined Tunnel.

construction was adopted, as safer in view of the heavy and valuable buildings in the vicinity, and of the risk of damaging by settlement the sewers and numerous large gas and water mains which lie above the tunnels.

The material met with consisted of ordinary London Clay, but for some distance the top of the tunnel is in ballast overlying the clay, and there it was found necessary to timber the face in part.

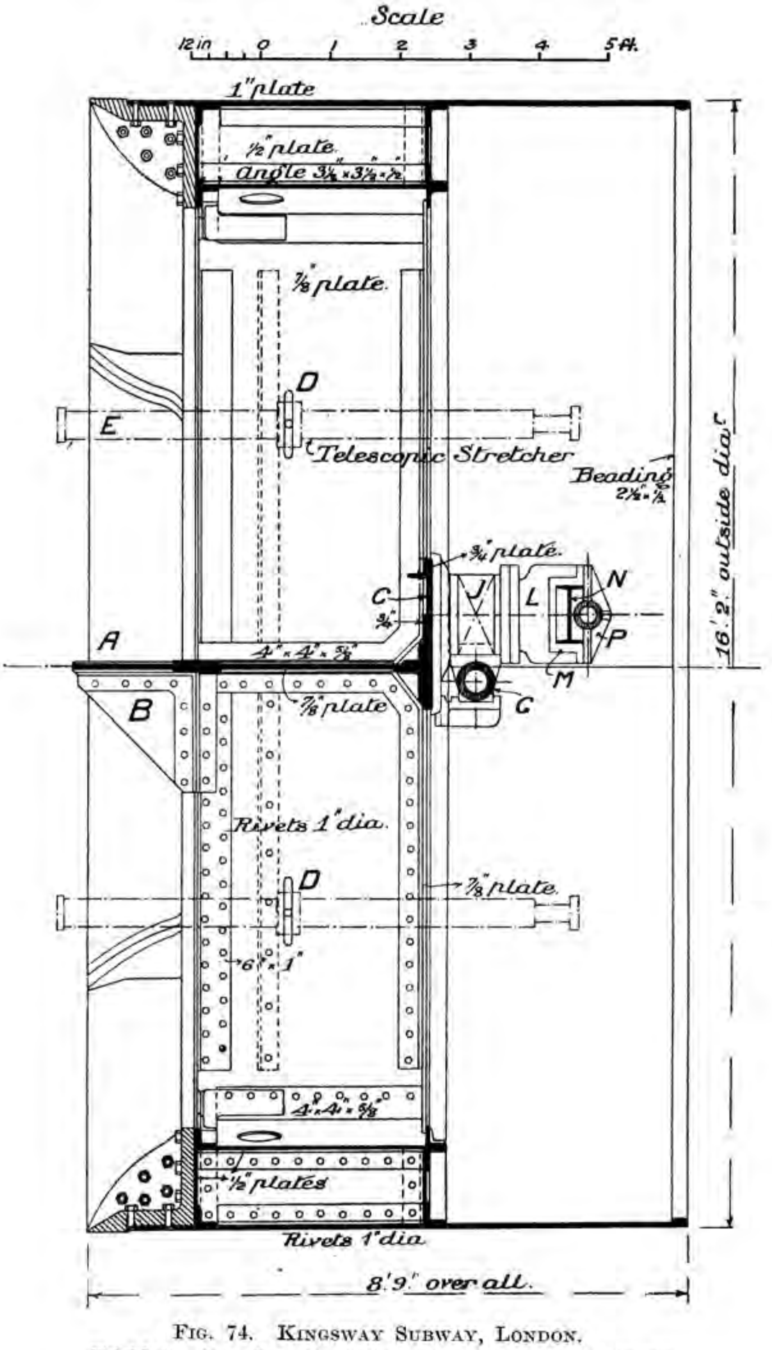


FIG. 74. KINGSWAY SUBWAY, LONDON.
Shield for Cast Iron lined Tunnel. Longitudinal Section.

The shield is 16 feet inside diameter of skin, which consists of a single thickness of 1 inch plate, 8 feet 3 inches in length and divided horizontally into six widths, the joints, which were covered with 1 inch covers, corresponding with the points of junction of the vertical and horizontal stiffeners. The cutting edge of cast iron projects 6 inches in front of the skin, making the entire length of the shield 8 feet 9 inches, and is divided into segments corresponding to the widths of plates of the skin. The outside of the cutting edge is a little proud of the outside of the skin, but not of the outside covers to the joints, the front edges of which are bevelled off to avoid stripping.

The cutting edge, the vertical flange of which is made 1 foot 5 inches deep as compared with 1 foot 1 inch on the shield from which this one was modelled, is bolted behind to the front of a circular box girder which performs the double duty of stiffening the shield and forming a series of cells or compartments in which are

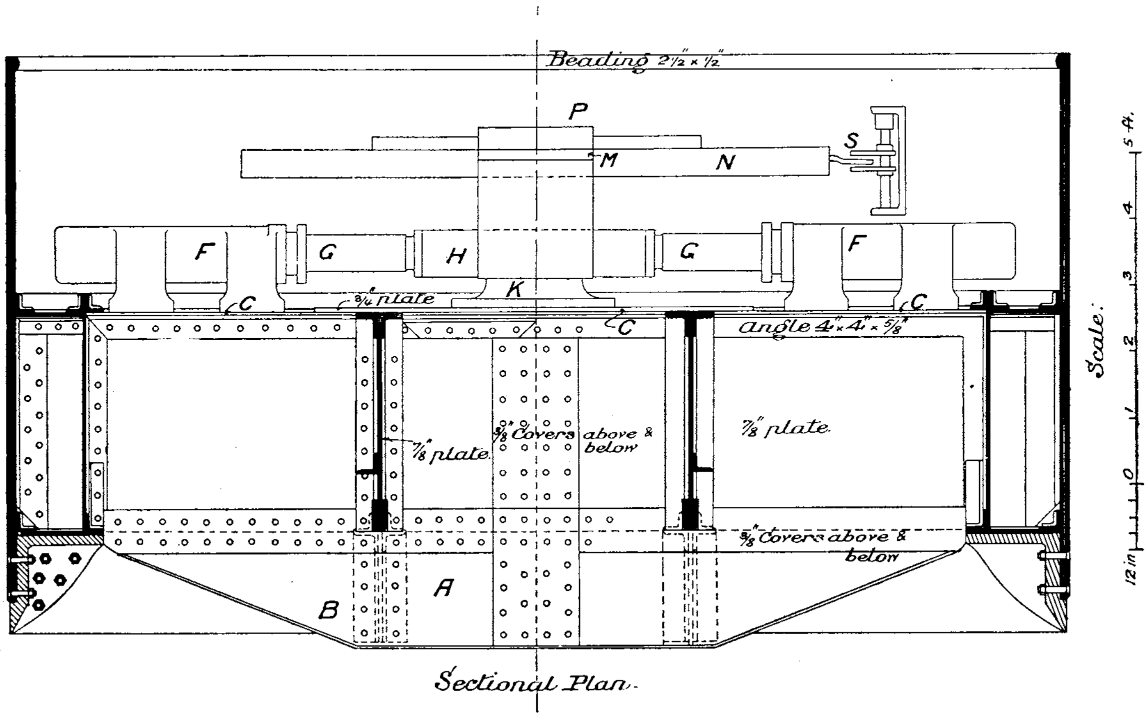


FIG. 75. KINGSWAY SUBWAY, LONDON.
Shield for Cast Iron lined Tunnel.

placed the shield rams. (These rams are not shown in the general drawings of the shield, but a section of one is given in Fig. 76.)

This circular box is 3 feet $3\frac{1}{2}$ inches long inside, and 1 foot 1 inch deep, and is composed of $\frac{1}{2}$ inch plates and $3\frac{1}{2}$ by $3\frac{1}{2}$ by $\frac{1}{2}$ inch angle irons.

The back end plates of this box are perforated by sixteen holes, 11 inches in diameter, through which pass the pistons of the hydraulic rams, and on either side of each ram is a gusset plate, $\frac{1}{2}$ inch thick with $3\frac{1}{2}$ by $3\frac{1}{2}$ by $\frac{1}{2}$ inch angles. At the junction, however, of the main vertical and horizontal frames of the shields, the webs of the frames themselves, which are continued through the box girder to the outside skin, form the gussets.

Of these frames two are vertical, and one horizontal, thus dividing the face

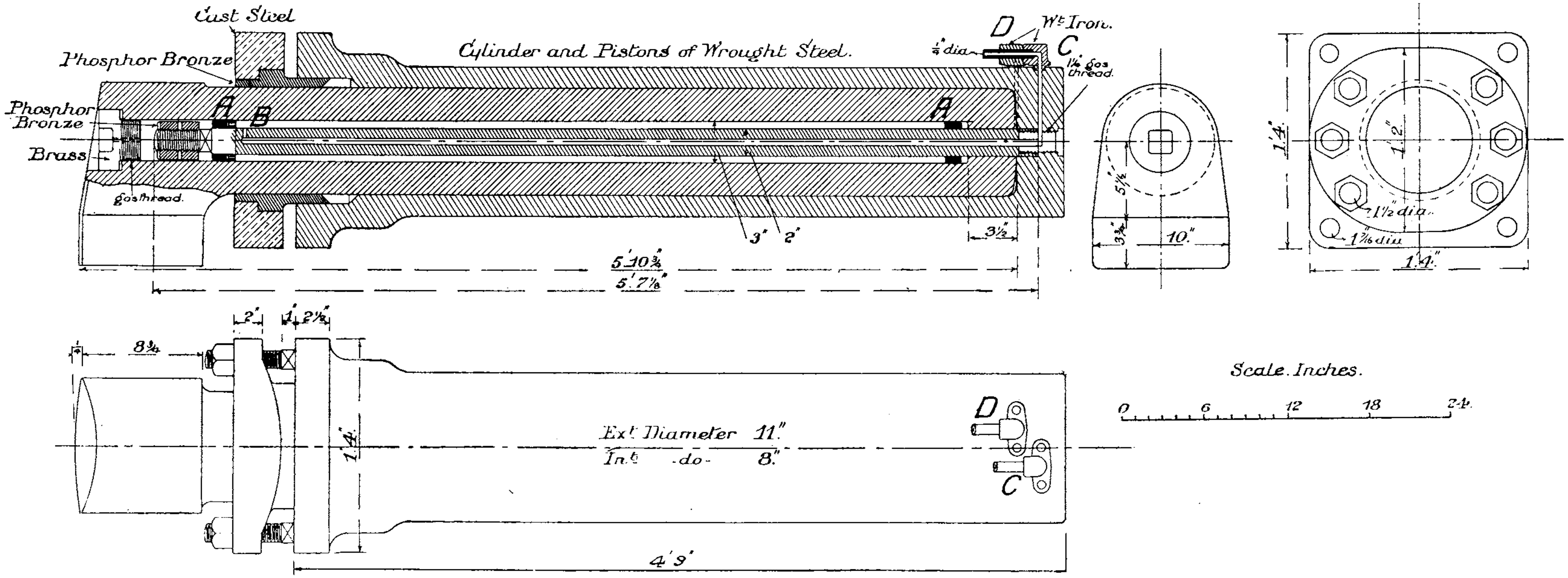


FIG. 76. KINGSWAY SUBWAY, LONDON.
Shield for Cast Iron lined Tunnel. Details of Hydraulic Ram.

into six working sections. The frames are made of ⅞ inch plates. The vertical ones, which are the same length as the circular box girder, are stiffened behind by 4 by 4 by ⅝ inch angle irons, and in front by plates 6 inches wide and 1 inch thick, having the front edges bevelled off. They are secured to the skin of the shield by 6 by 6 by ¾ inch angles, to the inner skin of the box girder by 4 by 4 by ⅝ inch angles, and to the horizontal frame, where they intersect it, by four angles of the same dimensions.

The horizontal frame which forms a table or platform for the men working in the upper part of the face consists of a plate of the same width as the vertical frames, but to it is attached by bolts, so that it can be removed, if desired, a front plate *A*, projecting at the centre 3 inches beyond the cutting edge of the shield, and supported by brackets *B* fixed on the vertical frames. The object of this projection is to afford support to the face, which, during the process of excavating a length, can be easily held up by polings supported by soldiers wedged from the front edge of the table.

The horizontal frame is stiffened at the back by 4 by 4 by ⅝ inch angles, and by vertical plates *C,C*, which also form a base of attachment for the segment erector as shown in Figs. 73 and 74.

In the vertical frames, slots *D,D*, Fig. 74, are cut to receive bolts by which the telescopic stretchers *E, E*, can be held loosely in place.

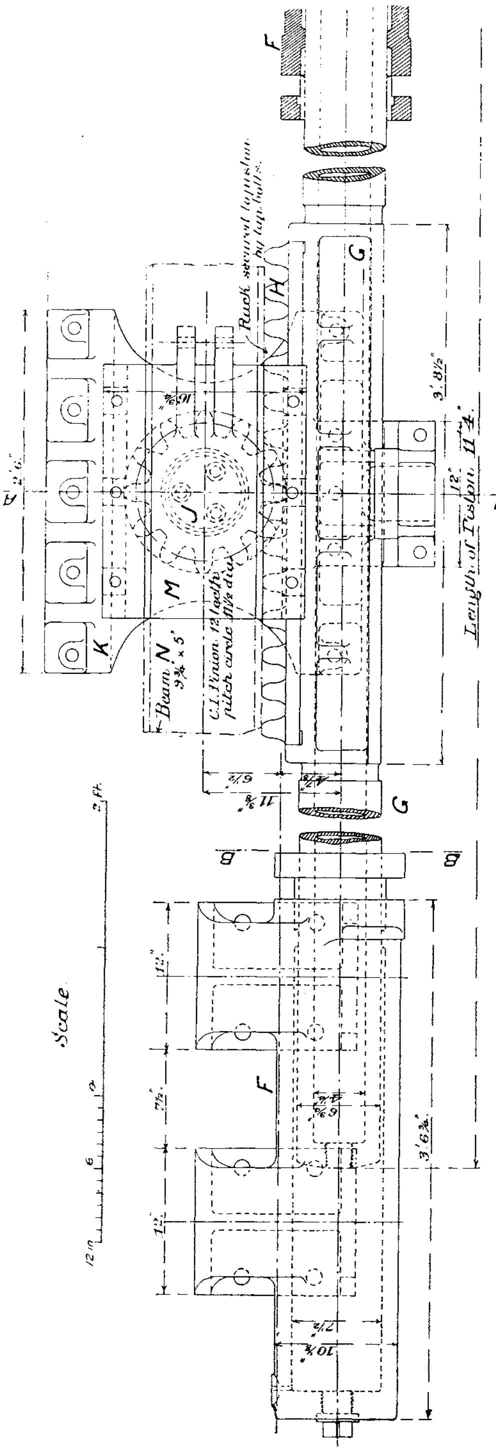


Fig. 77. Kingsway Subway, London.
Shield for Cast Iron lined Tunnel. Erector fixed on back of Shield (see Fig. 75).

Inside the tail of the shield, which is built to give 1 inch clearance round the cast-iron tunnel lining, is rivetted a beading 2½ inches by ½ inch to reduce the friction of the shield when moving forward.

A segment erector was employed with the shield in the Great Northern and City Railway work, but not in the Kingsway tunnels,and proved a very conveniently arranged appliance.

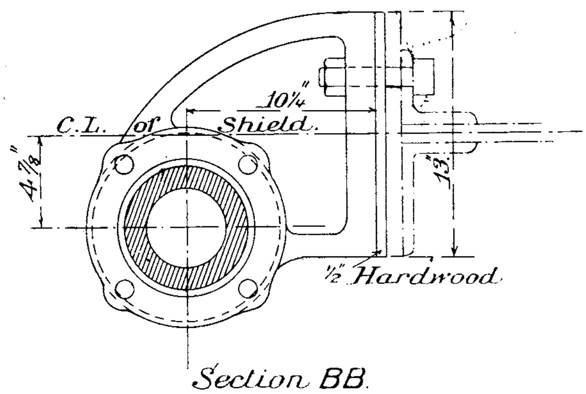


FIG. 78. KINGSWAY SUBWAY, LONDON.
Erector fixed on back of Shield. Section on line *B,B*, Fig. 77.

On the plates *C,C*, Figs. 75 and 79, are fixed two cylinders *F,F*, which have a single double-ended piston *G* carrying a rack *H* (see Figs. 77 to 81, on all of which the indicative lettering is the same). This rack gears with a pinion *J*, turning on the casting *K*, which is fixed on the central plate *C*.

To this pinion *J* is bolted the casting *L*, also turning round the axle of *K*. This casting forms a cradle in which rests the hinged casting *M*, in which slides the rolled joist *N*, forming the erecting arm of the machine. This joist is 9¾ inches by 5 inches, the flanges being planed to fit the casting *M*, also planed. To this casting is bolted the long hydraulic cylinder *P*, to the piston of which the joist *N*, free elsewhere, is secured at *R* (Fig. 80).

One end of this joist is fitted with a hand *S* for attaching the segment to be lifted. The stroke of the piston in the cylinder *P* is about 4 feet 6 inches, and the effect of working the cylinder is to move the joist *N* backwards or forwards through the castings *M* and *P*, which form a collar in which it slides freely.

Rotation is imparted to the arm by working the cylinders *F*, *F*, causing the rack *H* to turn the pinion *J*, with which revolves the cradle *L*, in which is fixed the collar formed of *M* and *P*, in which the arm slides.

A useful arrangement is the attachment to the cradle *L* of the casting *M* by a pin, and an eyebolt with an adjustable screw shank (see Fig. 80), so that when the erector is fitted to the shield, it is possible, by working the eyebolt screw, to adjust exactly the axis of the erecting arm.

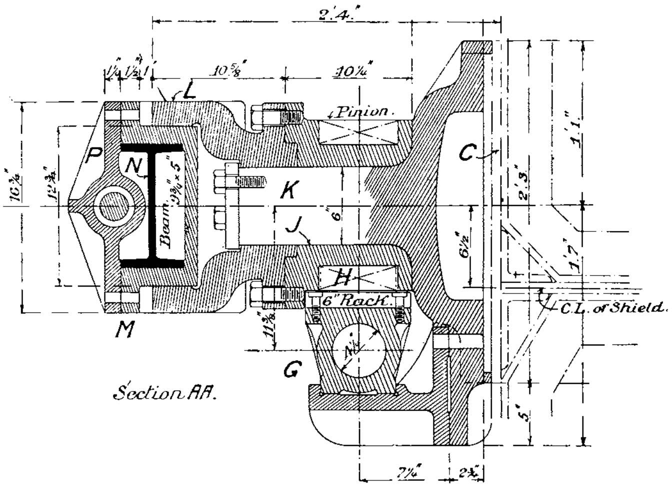


FIG. 79. KINGSWAY SUBWAY, LONDON.
Erector on back of Shield. Section on line *A*, *A*, Fig. 77.

Hydraulic power is supplied to the two cylinders *F*, *F*, by independent pipes on either side of the tunnel, and to the cylinder *P* of the revolving arm by flexible tubes connected to pressure pipes in the roof of the tunnel. This arrangement is a better one, in that in case of failure in any joint, the damage can be more easily

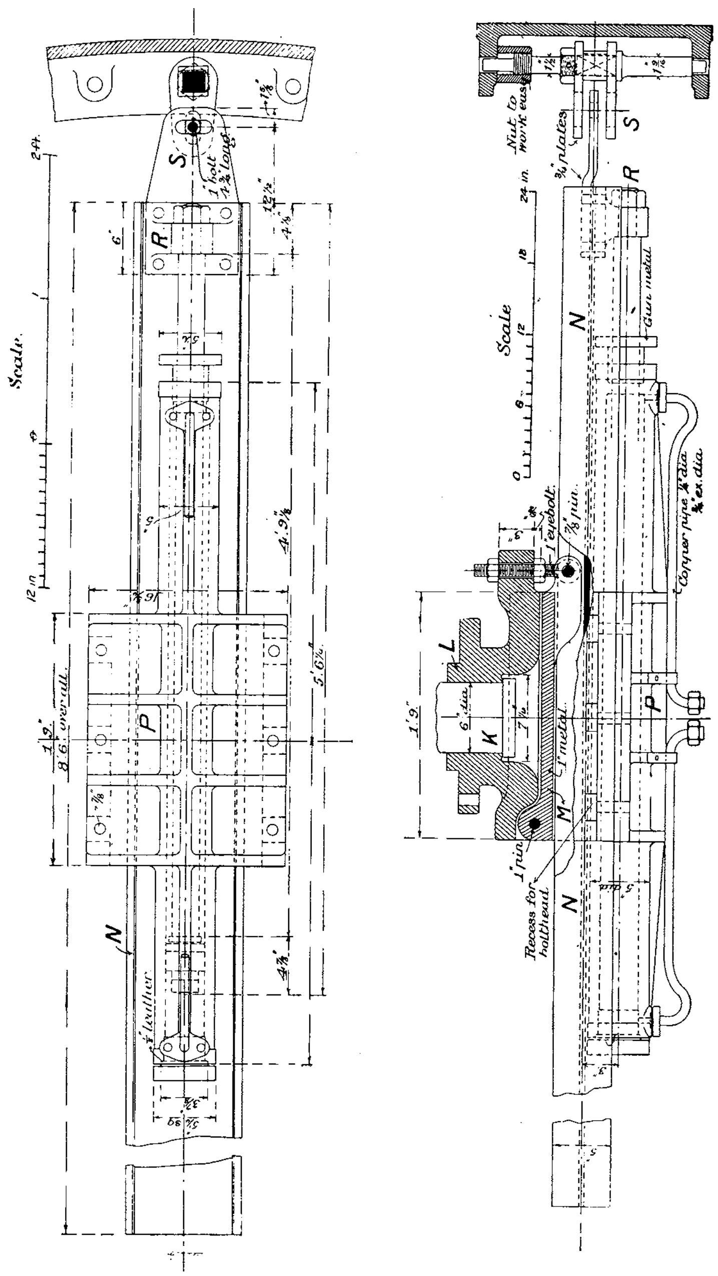


FIG. 80. KINGSWAY SUBWAY, LONDON.
Erector on back of Shield. Details of Moveable Arm.

repaired, than the more compact connexions involving the use of a swivel joint, used for the Blackwall Tunnel erectors (see Fig. 128.)

The rate of progress was very satisfactory, three rings of the tunnel lining or 5 feet per day being constructed, and the work was completed without any

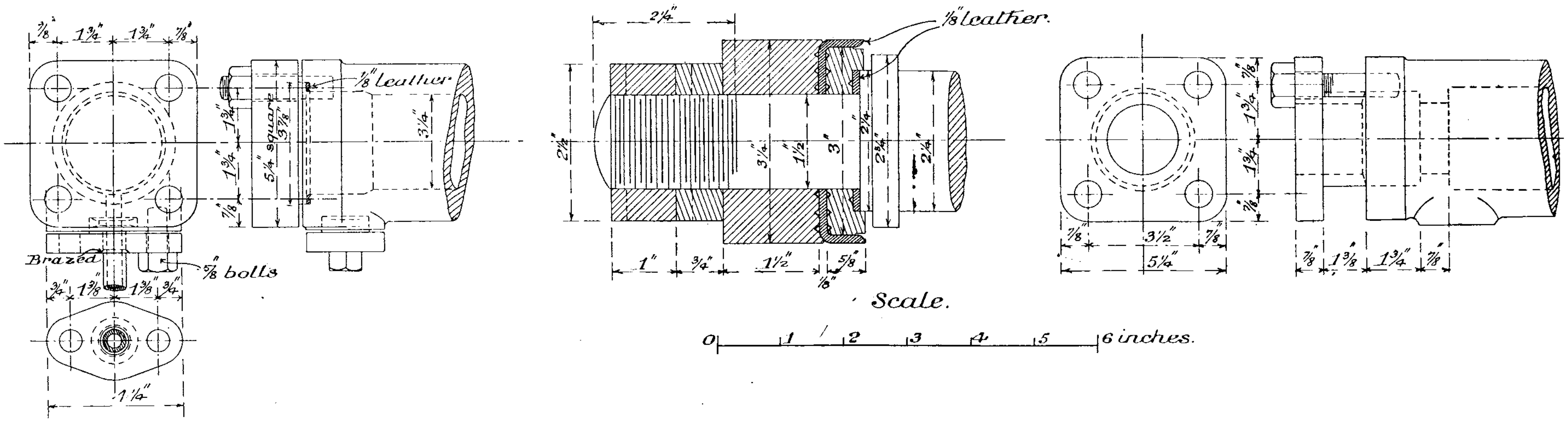


Fig. 81. Kingsway Subway, London.

Erector on back of Shield. Details of Ram Cylinder on Moveable Arm.

disturbance of the heavy buildings adjoining the line of the tunnels. As stated above, the greater portion of the tunnels are entirely in the London Clay; for some distance, however, the upper part of the tunnel cuts the gravel bed above. In this gravel water is almost entirely absent, and even when one-half of the shield was gravel, as happened at one point, compressed air was not required. The upper portion of the face was, however, timbered, Fig. 82 showing the method adopted when the top of the clay was just above the axis of the shield. The "guns" *E*, *E*, shown in Fig. 74, as hung in the slots *D*, *D*, cut in the vertical diaphragms of the shield, were not used, but instead the face was secured by three horizontal stretchers *a*, *a*, *a*, Fig. 82, which bore on byatts fixed across the tunnel behind the shield, somewhat as in the Baker Street and Waterloo shield (see Fig. 180). The crown of the face for a width of about 12 feet was close-poled with 7 inch by 1½ inch boards *b*, *b*, *b*, which rested on the cutting edge of the shield, their front ends being supported on the vertical polings *c*, *c*, *c*. Those vertical polings were set about 22 inches

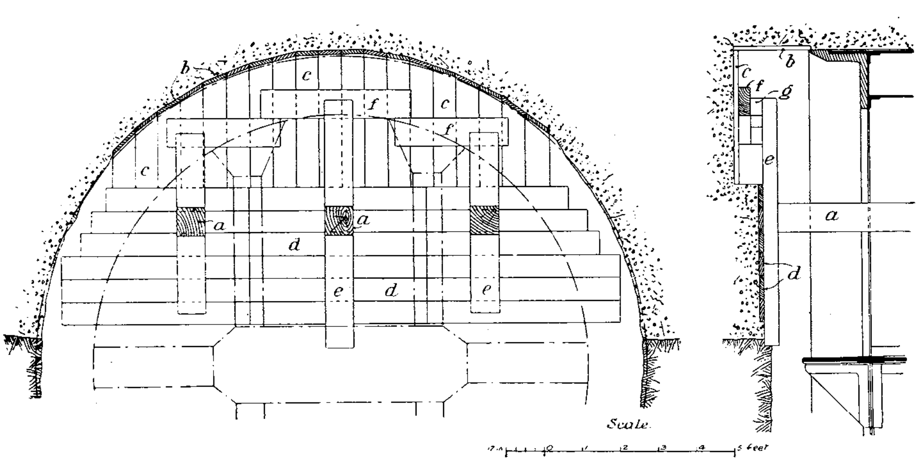


FIG. 82. KINGSWAY SUBWAY, LONDON.
Shield for Cast Iron lined Tunnel. Timbering for Ballast face.

in front of the shield (the width of a tunnel ring being 20 inches), and covered the face for a depth of 3 feet 6 inches from the crown of the shield. Below this level the face was stepped back 9 inches and the remainder of the gravel face was covered by horizontal polings *d*, *d*, *d*, of the same scantling as the upper ones, namely 7 inches by 1½ inches. These polings were held up by soldiers *e*, *e*, *e*, against which the stretchers *a*, *a*, *a*, bore, these soldiers also supporting the vertical polings by means of walings *f*, *f*, *f*, and chogs *g*, *g*, *g*.

With the face protected in this manner the shield passed beneath, and within a few feet of, a newly constructed brick subway, without damaging it.

A method of supporting a face of clay or other solid material in a tunnel of large diameter by means of adjustable iron stretchers, no shield being employed

In all tunnel work under large buildings, or wherever damage may be caused by settlement, the use of a shield combined with an iron lining minimises the risk of settlement and the cases in which the former may be dispensed with safely are few.

Cases do arise, however, where, owing to the length of tunnel required being very short, the employment of a shield would, not only on the ground of expense, but also on account of the time necessary to make a break-up for the shield, and, afterwards, to erect it, be a doubtful advantage.

It was for a short length of tunnel of 25 feet diameter that the arrangement of

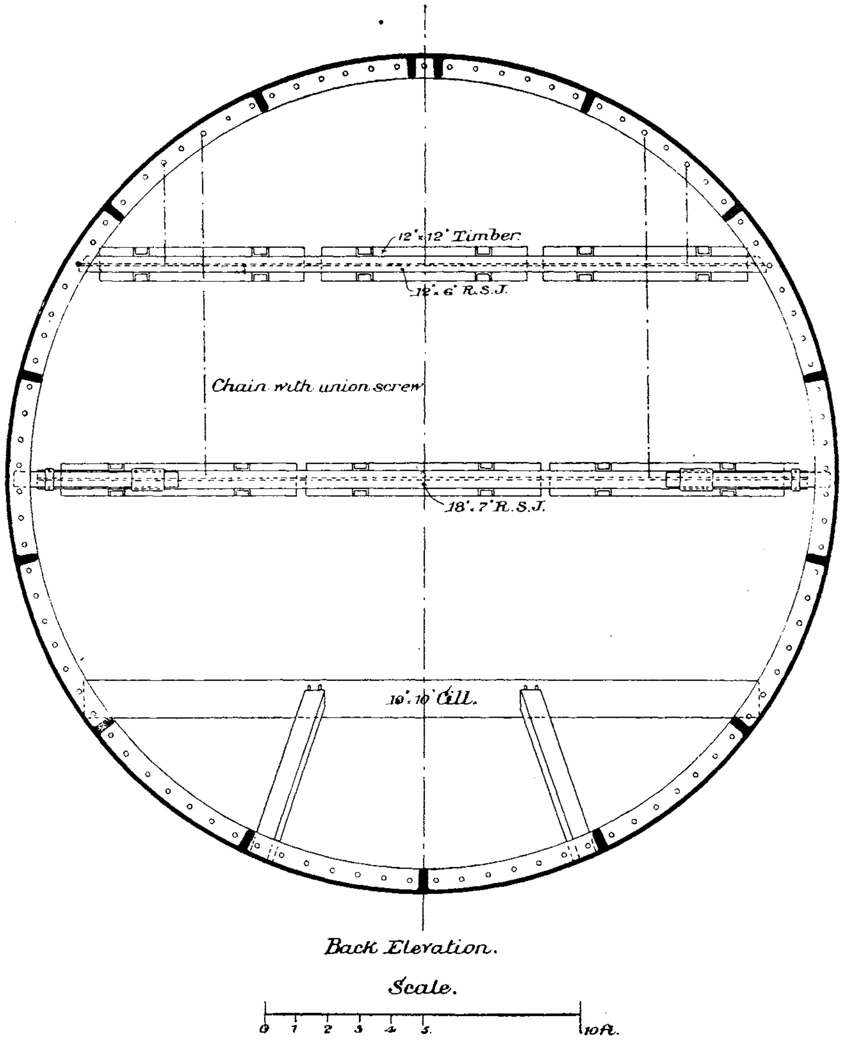


FIG. 83. CENTRAL LONDON RAILWAY.
"Shield" used in 25 foot Tunnel at Marble Arch Station.

moveable stretchers and cills shown in Figs. 83 and 83A was devised by Sir B. Baker, and gave very satisfactory results.

The lower part of the face is held up in the ordinary manner by a 10 inch by 10 inch cill, supported by two rakers, and by chogs at the ends against the last ring of iron already erected.

The upper half is supported by timbers and stretchers so arranged that, as the excavation proceeds, the supports to the face can be advanced, and the new face held up in such a way that practically there is no interval (as is the case when a cill is moved forwards), when the clay is not being sustained by the frames.

The face is held by six timbers, 12 inches by 12 inches square, and from 6 feet 6 inches to 7 feet 6 inches in length. These timbers are in two rows, the one on the horizontal diameter of the face, the other halfway between the centre and the soffit of the excavation. Each timber is stiffened behind by a channel bar 6 inches by 3 inches. To this channel bar are rivetted two pairs of channel bars, also 6 inches by 3 inches, forming stretchers, which can be secured against byatts or by square bolts fitting into the numerous holes provided for the purpose in the stretchers and driving wedges between them and the byatts.

These byatts are suspended, for convenience of handling, from the roof of the tunnel by chains with union screws. The upper ones, composed of rolled steel joists 12 inches by 6 inches, are made so long that when in position their ends bear against the flanges of the tunnel lining; the lower ones, composed of rolled joists 16 inches by 7 inches, are made a little shorter than the inside diameter of the tunnel, and take their bearings against the tunnel lining by catches or sliding bolts.

These byatts can be moved forward by, in the case of the upper ones, slackening the chains supporting them until they clear the iron lining of the tunnel, and, in the case of the lower ones, withdrawing the catches, when they can be pushed forward, one at a time, between the channel bars of the stretchers.

The method of working is to keep the upper part of the face a little in advance of the bottom (see Fig. 83A) and to commence the erection of each ring at the top instead of the bottom. As the face is worked away, the timbers are kept to it by advancing the stretchers by means of the bolts and wedges one hole at a time. The fixing of the cast-iron segments follows close on the excavation, so that there are generally three, and never less than two, rings in course of construction at once. When, by the advance of the work, the byatts require moving forward, the face is first made secure by wedging the stretchers hard against the front byatts, and

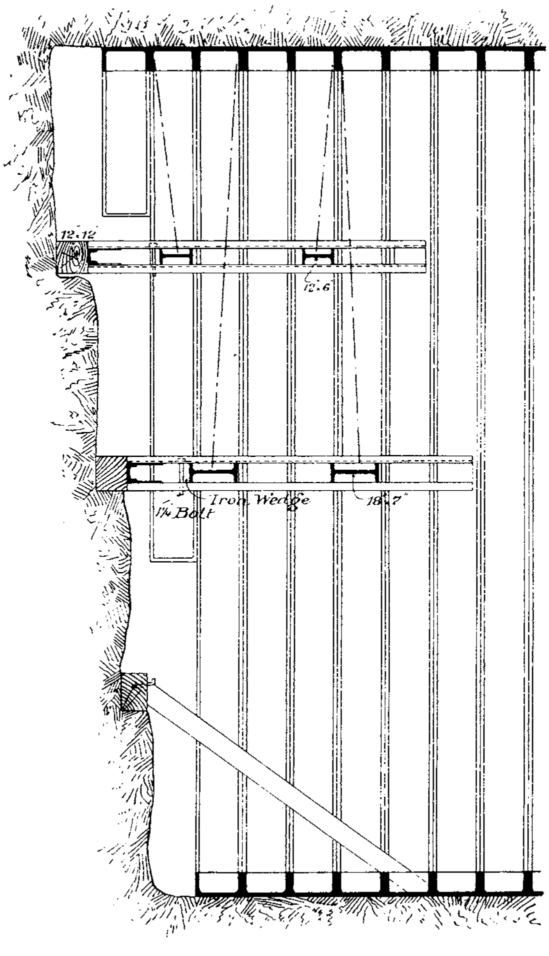


FIG. 83A. CENTRAL LONDON RAILWAY.
"Shield" used in 25 foot Tunnel at Marble Arch Station.

then the rear ones, being cleared from the segments, are slid forward between the stretcher bars, and secured in their new position.

The stretchers are then wedged against them, and the two front byatts *F* and *G* in turn released, and moved forward.

It will be seen that, by dividing up the support of the face among six independent sets of stretchers, it was possible, after working down the face over a comparatively small area, to make it safe at once instead of having to finish the full width of the tunnel as if, say, the lower row of timbers had been in one length instead of in three.

Some care was required to keep the tunnel lining correct ; the tendency being from the mode of construction for the top to come down, even more than is usually the case in iron tunnels, and it was necessary always to keep the horizontal diameter correct to dimension by means of chains and union screws.

Chapter V

THE SHIELD IN WATER-BEARING STRATA
THE ASSISTED SHIELD

The Greathead Shield Requires Additional Appliances in Water-bearing or Loose Material—The City and South London Railway Shield in Water-bearing Gravel—The Glasgow District Subway Shield—The Waterloo and City Railway Shield—Dalrymple Hay's Hooded Shield—Use of Clay Pockets on the Face in Gravel—The Glasgow Harbour Tunnels—The Mound Tunnels, Edinboro'—The Siphons de Clichy and de la Concorde

IN the previous chapter it was pointed out that the original Greathead shield, admirably adapted as it is for work in a material of the homogeneity and consistency of London Clay, is not altogether suitable for tunnelling in loose, and more especially in loose water-bearing material.

That its inventor was well aware of this is indicated in his own description of the works of the City and South London Railway,[1] as he states therein that he had prepared a special mechanism for dealing with the water-bearing beds of gravel which he anticipated might be met with, as in fact they were, near Stockwell station on that line, and only abandoned the idea of employing a new type of shield because the method of timbering in front of the shield, tried as a temporary expedient, proved satisfactory.

Unfortunately, an arrangement which was adopted on the City and South London Railway only as a makeshift was copied in other places, and proved, sometimes the reverse of satisfactory.

The very excellence of the Greathead shield in the form originally given it by its inventor, and its complete adjustment to the requirements of tunnel work in London Clay, make it an imperfect tool for work in other and looser material.

The nearness of the diaphragm or bulkhead to the cutting edge, and the entire absence of any support to the face of the excavation are both serious defects in a machine for tunnelling through loose material : while the height of the door in the diaphragm, leaving, as it does, very little solid screen above it which might, in the case of a blow retain an air space in which the miners could shelter, makes the diaphragm entirely useless, if water comes in in any quantity at the face.

To say this is not to depreciate the shield, which like most other machinery has the defects of its qualities, still less is it to say that in water-bearing material the Greathead shield is useless. It is, on the contrary, the peculiar merit of the shield as known since Greathead built the Tower Subway in 1870, that it can be adapted in any circumstances, and give, under conditions very remote from those

[1] *Proc. Inst. C.E.*, vol. cxxiii. p. 66. "Greathead on the City and South London Railway."

for working in which it was especially designed, a cheaper and more secure and incomparably more rapid method of tunnelling than any previous system, even with the drawbacks mentioned above.

When, in carrying out tunnels in the London Clay, water-bearing gravel is met with, it is the practice, if the distance to be traversed in bad material is not too great, to combine the use of a Greathead shield with timberwork, the whole operation of working the face and erecting the tunnel being carried out in compressed air.

If the distance to be driven in water justifies it, a special shield is constructed for the particular length of tunnel which requires special treatment.

The first method was adopted on the City and South London Railway, and in the Glasgow Circular Railway: the second on the Baker Street and Waterloo Railway, on which, in the section under the River Thames, a special shield was

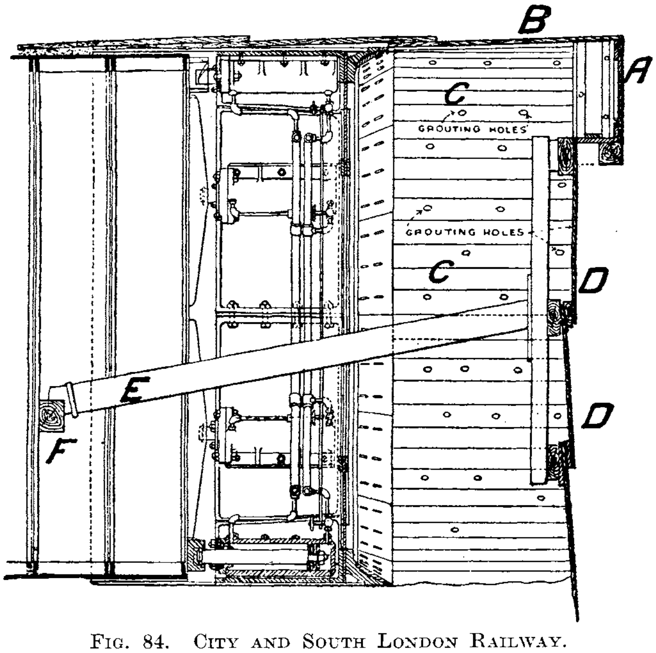


FIG. 84. CITY AND SOUTH LONDON RAILWAY.
Greathead Shield with Timbered face.

used; and both on the Waterloo and City Railway constructed at a date intermediate to those two lines.

The method of construction by means of a Greathead shield with an advance protection of timberwork is known as the "assisted shield" method: the shield, in fact, in the earlier works carried out in water-bearing strata, became little more than a portable frame in which the tunnel was erected, advancing in a timbered length of excavation, differing but little from similar work in tunnels made without shields.

In tunnels constructed recently in water-bearing strata, the shields employed have been designed especially for the work each one had to do, and in consequence each one presents special features planned to cope with the particular problems of the tunnel. In most of these shields the use of timberwork in the face, though rarely entirely discarded, and hardly ever entirely abandoned, except in special cases like the Hudson Tunnel in New York, driven through liquid mud, is a subordinate part of the scheme.

The term " assisted shield " applies only to the Greathead shield, designed for work in clay, used in conjunction with a timbered face, or an advance length of timbering. Of course, such shields as those used in the Greenwich Tunnel, and in the river portion of the Baker Street and Waterloo Railway described in Chapter VII. also require in certain conditions almost as much timbering as an ordinary Greathead shield. They have, however, in themselves certain protective appliances, and so are distinct from the simple Greathead shield.

City and South London Railway

On the City and South London Railway, for the first time in any tunnel, compressed air was employed in conjunction with a shield at various points, the greatest length of tunnel so constructed being at Stockwell, where the two tunnels were driven through open ballast under a head of water of 35 feet; the " assisted shield " method of tunnelling was employed.

The shields used were of course those employed in other parts of the line and shown in detail in Figs. 52, 53, 54 and 55, and the manner of using them in conjunction with timbering is illustrated in Fig. 84.

Under an air pressure of not more than 15 pounds, the average rate of progress per day of two shifts was nearly 5 feet, a rate which, if slower than the usual rate of shield work in other parts of the tunnel, is much in excess of that attained by any of the older methods of tunnelling.

The airlocks used were, with the exception of the first one, which consisted of an iron cylinder built with a brick bulkhead, made by building into the cast-iron tunnel, a mass of brickwork having a rectangular opening in its centre about 3 feet 9 inches square. This square was provided with doors having cast-iron frames, which were built into the brickwork, forming an airlock about 12 feet long (see Fig. 85).

Mr. Greathead claimed for this arrangement, as compared with the iron-lined lock, the advantage " of mitigating the chilling effect, due to the reduction of pressure, upon the men, hot from their exertions in the warm compressed air, in their egress. The brickwork, absorbing heat when the lock is open to the compressed air, and parting with some of it during the reduction of pressure when closed against the compressed air, is found to preserve a more equable temperature than the thin plates forming the walls of the iron locks."

The advantages claimed for this kind of lock in the passage just quoted do not appear sufficiently obvious to justify the increased amount of brickwork necessary, all of which has of course to be cut out later, if the full length of the lock is to be of this material, as against the slightly greater first cost of an iron or steel cylindrical lock which can be used again and again.[1]

The manner of working the assisted shield was, on this railway, as follows (see Fig. 84). When the shield was approaching the locality where the open ballast was known to exist, the ground in front of and above the shield was carefully probed before each advance : when the open material was actually reached, the ordinary excavation of the face was stopped, and the driving of a small box heading *A*, at the very top of the shield, started in advance. The roof of this heading was supported

[1] A brick lock was used in the Siphon de Clichy (1892).

by polings *B*, *B*, the rear ends of which rested on the cutting edge of the shield.

The roof thus made secure, the heading was gradually widened out, and the circumference and face poled by the boards *C*, *C*, *C*, *D*, *D*, as the excavation was carried down.

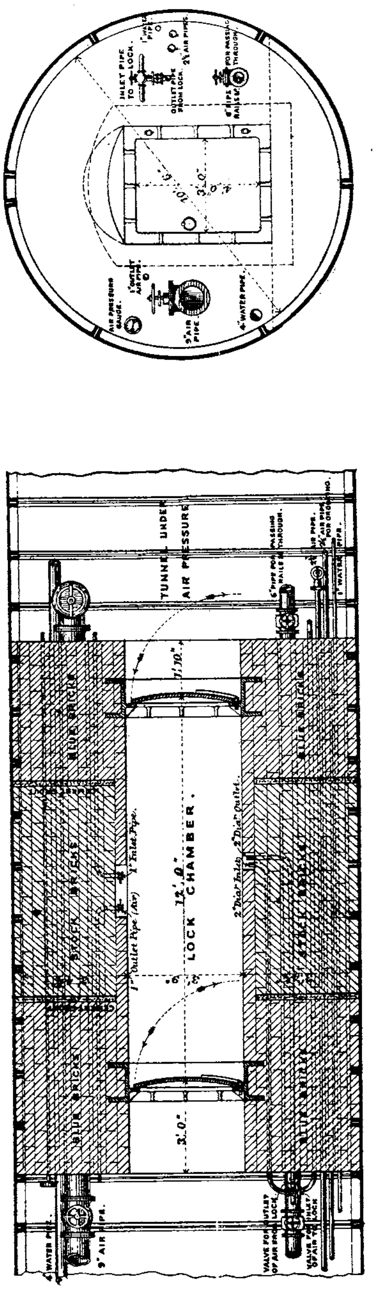


FIG. 85. CITY AND SOUTH LONDON RAILWAY. Bulkhead and Airlock.

The face was supported by means of rakers *E* bearing against a byatt *F* fixed across the tunnel, and bearing on the flanges of the cast-iron segments. It will be seen that this arrangement practically does away with the shield as a protection to the tunnel. In the case of a "blow" in the face or roof, the doorway in the diaphragm or bulkhead of the shield cannot be closed, as the rakers are in the way. This is the most serious objection to this method of working, that it exposes the miners at the face to serious risk in case of even a comparatively small failure of the face work.

The best means of diminishing the risk to life caused by a "blow" at the face, is the provision in the tunnel behind the shield of a hanging screen, made perfectly airtight at its connexions with the tunnel lining, and coming as low down in the tunnel as the necessity of leaving room for the passage below of men and materials will permit. This screen makes the upper part of the tunnel behind it a kind of diving bell, into which the men could escape in case of accident, and along which, by clinging to the tunnel lining they could make their way to an emergency airlock fixed in the bulkhead of the ordinary working lock.[1]

Mr. Greathead states[2] that such screens are not possible in small tunnels; the author however had one fitted up in a tunnel of which he was in charge, without interference with the works (see Figs. 168 and 170), the diameter of which was only a few inches greater than that of the South London one.

[1] The first suggestion, so far as the Author is aware, of the possibility of protecting the miners in a tunnel by means of such screens, is to be found in the *Scientific American* of August 21, 1880, in which a Mr. Van der Veyde, writing immediately after the disaster in the Hudson River Tunnel, by which twenty men lost their lives, suggests in a letter, accompanied by a sketch diagram, the employment of safety diaphragms exactly as they have many times been employed since.

[2] *Proc. Inst. C.E.*, vol. cxxiii. p. 108.

As the support to the face was entirely independent of the shield, it was easy, immediately the timbered chamber was complete, to push forward the shield into it, when the opening out of a new chamber was commenced. The only time when the shield supported the face polings in any way was when it was necessary to move forward the byatt F, when for a short time the front polings were wedged against the bulkhead.

Usually the poling of the face was complete down to the invert of the shield, but the circumferential ones did not extend always quite round the entire circle, the lower quarter of the excavation being left open. Holes were drilled in alternate polings through which lime grout under pressure was injected, and this had the effect of very materially reducing the escape of air from the face: in fact, without this grouting the air compressors employed would not have been equal to the task of keeping out the water over the large area of poling required by this method of working.

In this way the tunnels were driven in ballast beneath sewers and large water mains, also in ballast, without causing any disturbance to them or to the street traffic above: the general level of the water in the ground being about 35 feet above the invert of the tunnels.

The shield, when working with a full face of ballast, and with the same material below the invert, had always a tendency to sink. This was checked by using skids of rails, and by manipulating the rams. In later shields an increased number of rams, and their concentration in the lower half of the shield, has obviated much of this difficulty.

The quantity of air to be provided for work of this class was, at the time these tunnels were made, a matter of conjecture only, the experience gained in tunnelling with compressed air at Antwerp and New York not presenting any analogy to tunnelling in open ballast, and it was ultimately settled that a machine capable of supplying 1,500 cubic feet of free air per minute would be necessary, one tunnel only being driven at one time.

The compressor laid down had cylinders 18 inches in diameter, with 36 inches stroke working at 90 pounds; the air cylinders, which were tandem coupled, having a diameter of 26 inches. These, when run at fifty revolutions of the fly-wheel per minute, actually delivered 1,660 cubic feet of free air, an inlet pipe 9 inches in diameter being used.

This quantity was required until the effect of grouting behind the poling boards was tested, with the result that while the rate of progress was doubled, the rate at which the compressor was run dropped to from thirty to forty revolutions per minute, thus conclusively proving the efficacy of the grouting.

The Glasgow District Subway[1]

The tunnels for this work (1892–5) were driven partly in brick clay, impervious to water, and partly in water-bearing material, mostly sand and gravel, and in two places actually passing under the River Clyde.

The work in clay was carried out in the same way as on the City and South London Railway, and, judging by the results, it would have been better, apparently, had the "assisted shield" work also followed the earlier model more closely.

The engineer of this railway was not however favourably impressed with the

[1] *Proceed. Inst. of Engineers and Shipbuilders in Scotland,* Jan. 28, 1896. Simpson "On Tunnelling in Soft Material."

Greathead shield as a tunnelling machine in clay, and in water-bearing strata he had put on record his opinion that it was of very little use.

While some of his criticisms are entirely just and reasonable, there is ground for thinking that the difficulties met with in driving the tunnels for this railway under the River Clyde were in part owing to the method of timbering adopted in front of the shield.

In Figs. 86, 87, 88 the details of the timbering are shown. An advance heading *A*, 6 feet high by 4 feet wide, was driven in advance. The top polings of this heading were just high enough to take under them the 3 inch polings of the chamber which was subsequently opened out. The head and side trees of the heading, cross-sections of which are shown at *B* and *C*, Fig. 88, were of 7½ inches by 3 inch timbers, with 1½ inch poling.

When approaching the river this heading was kept 9 feet in advance of the main excavation, which also at that place was made 9 feet long, or sufficient for six rings of tunnel lining.

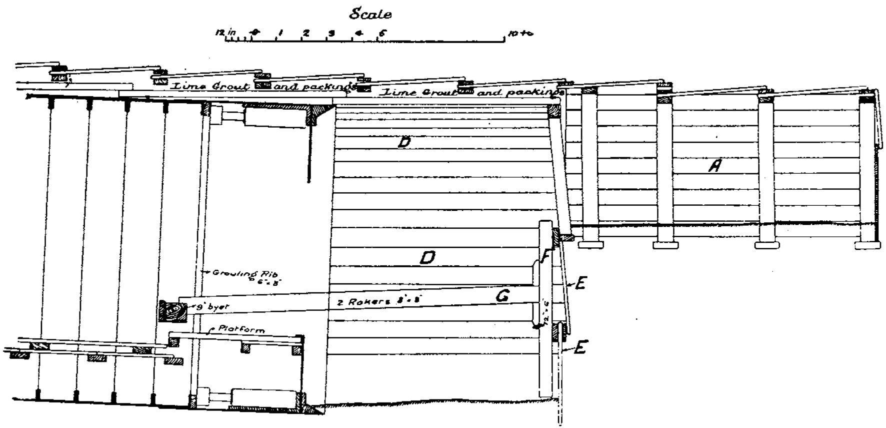


FIG. 86. GLASGOW DISTRICT RAILWAY.
Greathead Shield and Timbered Heading.

This length in front of the shield was close polled from the top to near the bottom, the polings *D*, *D*, being 3 inches thick : and the face, with similar polings, *E*, *E*, was held up by 9 inch by 3 inch horizontal timbers, with two 12 inch by 6 inch soldiers, *F*, *F*, stretched back to a byatt in the tunnel by two 8 inch by 8 inch rakers, *G*, *G*.

All the timber work was well grouted, and when the length was completed it formed an almost air-tight barrel 12 feet 3 inches in diameter, into which the shield could be propelled and the rings behind erected one by one.

This arrangement is certainly open to criticism, if only in regard to the length of excavation supported on timber.

In making a brick tunnel a 9 foot length is reasonable enough, as heavy crown bars are employed and all the other framing is solid in proportion ; but in an iron tunnel, the permanent lining of which can be built, as in the case under consideration, in successive lengths of 18 inches, it certainly appears to be taking an unnecessary risk to open up the ground for a six-ring length, with another equal length of heading in front of it.

Of course, the shorter the chamber, the more face timbering there is to do; on the other hand, it is much easier and safer to maintain a small area of face water tight than a large one, and in all subaqueous tunnel work, safety is more important than speed. When actually working under the River Clyde, the length of the timbered chamber was reduced to 6 feet, and then to 4 feet 6 inches, and the advance heading done away with, but even the shorter length was found too long for safety by the experienced contractor who ultimately completed the work; and the engineer, Mr. Simpson himself, records the serious difficulties encountered under the river near St. Enoch's when working in the manner described, and the improvement which followed a change of system.

The first tunnel driven from St. Enoch's under the River Clyde had ten " blows " at the face during the construction of 80 feet of tunnel, culminating in one which blew the whole timbering in front of the shield up into the river, and formed a hole in the bed 24 feet square and 16 feet deep.

The cover over the tunnel varied from 14 to 29 feet of open material, and the

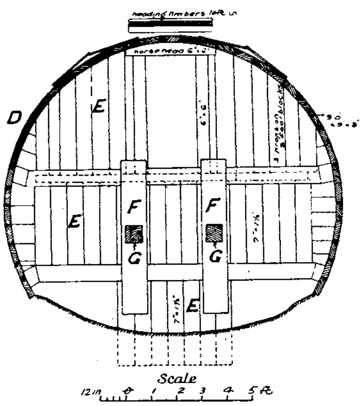


FIG. 87. GLASGOW DISTRICT RAILWAY. Timbered Face. (The Section is taken in front of the Shield in Fig. 86.)

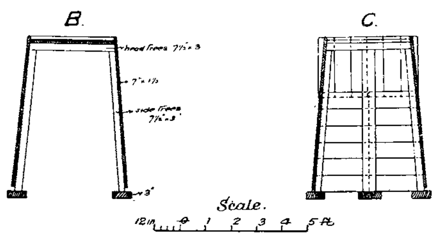


FIG. 88. GLASGOW DISTRICT RAILWAY. Details of heading.

depth from high-water level to the tunnel invert was from 47 to 55 feet, which latter is equivalent to a pressure of 26·25 pounds per square inch.

The actual pressure required was at most 23 pounds, so that the amount of sand, etc., of cover made very little difference in the pressure.

No clay cover or blanket, such as has proved so useful in similar cases elsewhere, could be used, owing to the impossibility of reducing the depth of the waterway: and, in consequence, very great difficulty was experienced in maintaining the invert of the tunnel fairly dry (which necessitated a pressure greater than was required to dry the face at the crown) and avoiding at the same time the blowing out of the roof of the timbered chamber in front of the shield.

The adjustment of the pressure so that the water may not enter the face, nor the face blow out, is difficult at any time, but the difficulty becomes almost insuperable in tunnels of large diameter when working in open ballast containing very little sand and under a varying pressure due to the movement of the tides, if clay is not available as a cover or rather as a load for holding down the loose ballast.

After 80 feet of the first of the two tunnels had been driven in the gravel under the river, and five months had been spent in this short length, the contractors engaged retired from the work, and another firm undertook to complete the section.

A considerable change was made in the system of timbering : the new contractor at once reduced the length of the timbered chamber to about 20 inches, or sufficient for one ring only of the tunnel lining ; the heading in advance was abolished, but the reduction in the size of the chamber was not accompanied by any reduction in the sizes of the timber used ; and perhaps as important a change as any other, work was carried on day and night, Sundays and weekdays, thus giving less time for any weakness in the timbering to develop.

To keep the roof secure, one very useful modification was introduced. Besides fastening the roof polings together with iron dogs, and of course grouting well behind them, the new Contractor introduced a variation in the manner of holding

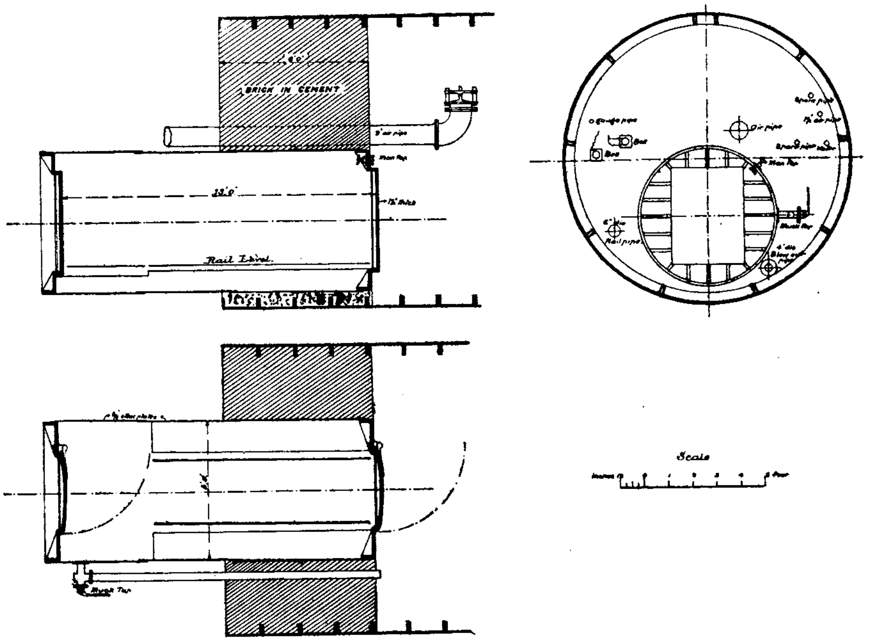


Fig. 89. Glasgow District Railway.
Bulkhead and Airlock.

the front ends of the polings.[1] These, instead of being carried on the ends of the vertical polings of the face, as is usual, were supported, and at the same time held down, by a circular iron plate, $\frac{1}{2}$ inch thick, bent to the radius of the shield. To this iron plate they were secured by coach screws, and the plate in turn rested on a rib or centering which at its springing was securely fastened to a sill 10 inches square fixed across the centre of the face.

The same arrangement, without the iron plate, was used at the Glasgow Harbour Tunnels about the same time.

It proved very effective, and was easier to set up and take down than the ordinary poled supports had been.

For a time, when working with little cover, one ring per day was done, but with

[1] Patent No. 717 of 1893.

more cover, the timbered length was made long enough to admit of two rings being erected at a time, and these lengths were also done in twenty-four hours, three eight-hour shifts being worked.

The average rate of progress with this poling work in front of the shield was about 100 feet per month : and the cost of the tunnel about £40 per yard forward.

The Waterloo and City Railway[1]

This deep level railway, commenced in 1894 and completed in 1898, connects Waterloo Station, the London terminus of the South-Western Railway, with the

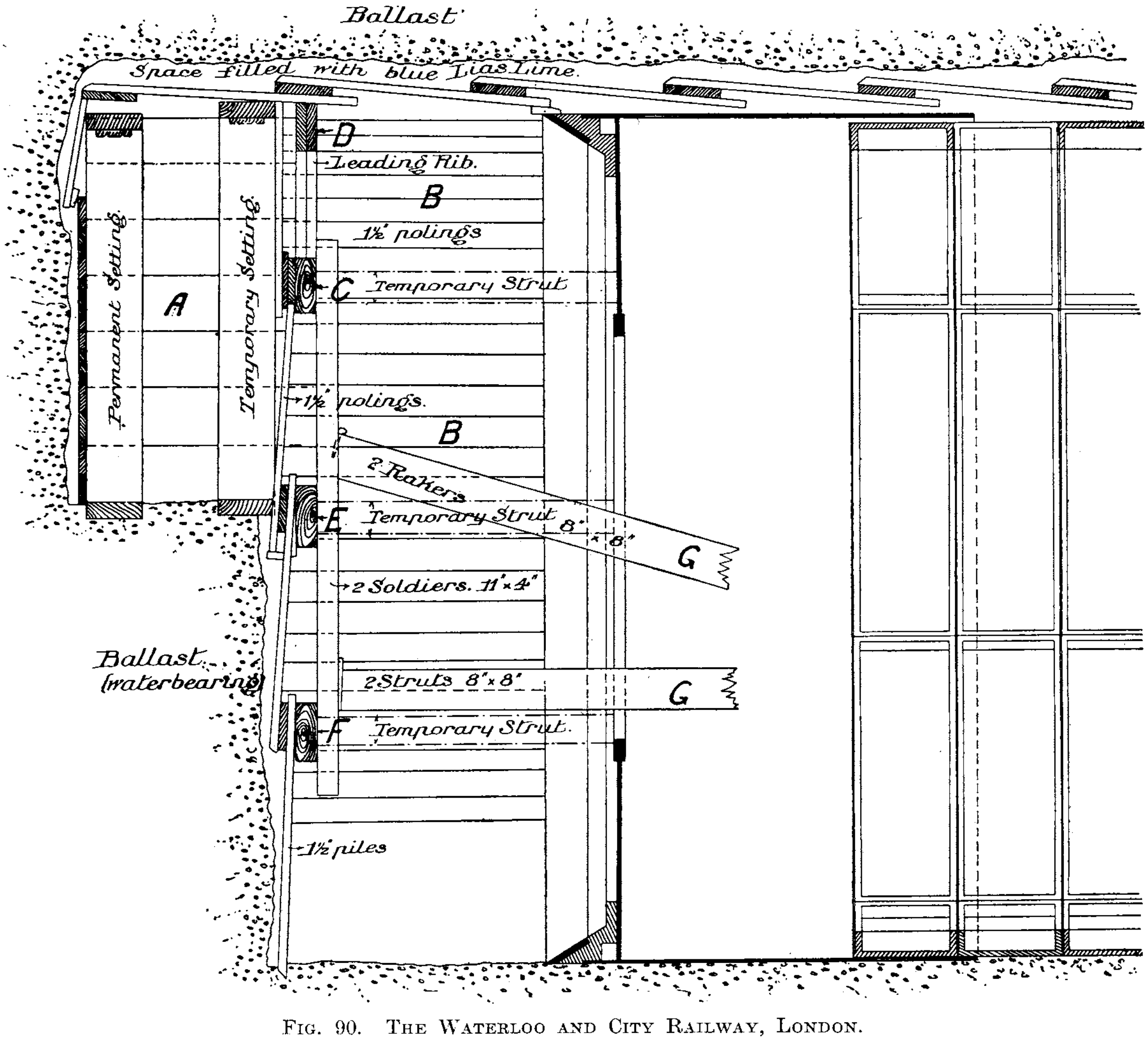


FIG. 90. THE WATERLOO AND CITY RAILWAY, LONDON.
The Greathead Shield and Timbered Face.

City of London, its eastern stations being situated under Queen Victoria Street, in close proximity to the Mansion House. For the greater part of their length, the tunnels, which are of the iron lined type, are excavated in the London Clay,

[1] *Proc. Inst. C.E.*, vol. cxxxix. Dalrymple Hay on "The Waterloo and City Railway."

and their construction was, for the most part, carried on on similar lines to the tunnels of the City and South London Railway in the same material.

For a considerable length, however, compressed air was employed, the engineers of the Metropolitan District Railway, under which the new tunnels passed near Blackfriars Bridge, requiring that precaution to be taken, although the work was at that point entirely in the London Clay ; and the gravelly nature of the material passed through between the Thames and the Waterloo terminus, and the head of water met with (about 20 feet) made it necessary to employ compressed air for a considerable distance on the south side of the river also. In the first case compressed air was employed solely as a means of giving support to the superincumbent material ; in the latter it was necessary in order to enable the work to be carried on at all.

The tunnels under the River Thames were driven through the London Clay, there being always a sufficient cover of this material above to render the use of compressed air unnecessary.

It was in driving the tunnels through the water-bearing gravel near to Waterloo Station that the engineers in charge of the work introduced early in 1896 an improvement in the cutting edge of the shield and in the method of working the face, which has there and elsewhere since given very satisfactory results.

On commencing work with compressed air in water-bearing material, the system of timbering employed in similar conditions in the City and South London Railway by Mr. Greathead, who was also one of the engineers of the Waterloo and City Railway, was used with slight variations.

Figs. 91 and 92 show the method of timbering the face. A heading *A*, about 6 feet high by 2 feet wide, and built in the ordinary way with head and side trees, was always driven about two rings length, or 3 feet 4 inches in advance of the chamber into which the shield was ready to move.

Each time the shield had moved forward the heading was opened out to form the roof of the next length, 3 feet 4 inches long, the polings *B*, *B* were put in, being supported temporarily on face props, and at the rear on the cutting edge of the shield, and carefully grouted up, holes being drilled in them for that purpose, and all joints and openings being filled with pugged clay.

When the roof was poled, and the excavation of the length brought down far enough, the first or upper waling *C* was put in position, and provisionally strutted against the diaphragm of the shield. On this waling was erected a leading rib or centre *D* to support the roof polings. The opening out of the length was then continued downwards until the second waling *E* could be got in, and also strutted against the shield. The face and sides of the length below the level of the upper waling *C* were then poled and grouted as before, before going down with the excavation to the third waling *F*, which when put in served also to support the piles, $1\frac{1}{2}$ inches thick, which completed the closing of the face.

The pressure of the face, which had so far been taken by the struts between the walings *C*, *E*, *F*, and the diaphragm of the shield, was on the completion of the length taken by two rakers and two struts *G*, *G*, which bore on a byatt *J* fixed across the tunnel behind the shield, when the temporary props were removed.

The face of the timbered length or chamber having thus been secured independently of the shield, this latter was pushed forward for the length of two rings, and in so advancing naturally disturbed considerably the polings protecting the roof and sides of the chamber, which rested on it, and so caused a considerable escape of air.

After some months' experience of this method of working, Mr. Dalrymple Hay, the resident engineer of the railway, hit on the idea of excavating by means of a series of pockets made in the ballast, and immediately filled with clay, a ring of soft, airtight material into which the cutting edge of the shield could be driven, and by the use of which the extensive timber work in front of the shield necessary for working the Greathead shield in ballast could be done away with. He proposed

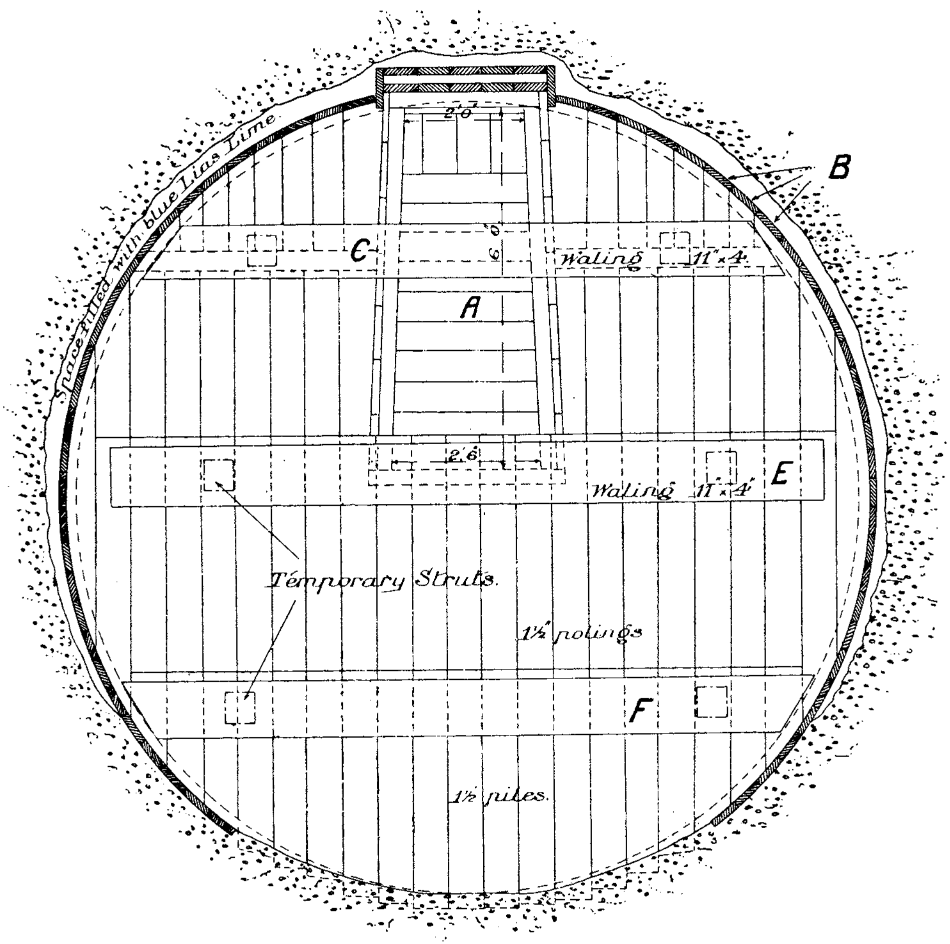


FIG. 91. THE WATERLOO AND CITY RAILWAY, LONDON.
Timbered Face. (The Section is taken in front of the Shield—see Fig. 90.)

to combine this method with a modification in the shape of the cutting edge of the shield, which he proposed to make longer at the top than at the bottom, or, to use the name which custom has now given to the pattern, he proposed a "hooded" shield. (The French word *vizière* or vizor is a better one than "hood" to describe the new feature.)

This arrangement, while it can hardly claim to be an absolutely novel idea, was undoubtedly an entirely new departure in shield work of the modern kind.

The clay pockets were a feature of Brunel's shield work [1] and only a few months previously in the tunnel under the Seine of the Siphon de la Concorde at Paris, a Greathead shield was employed which the French engineer in charge of the works had fitted with a sliding roof or "parapluie," which could be advanced about 1 foot 6 inches in front of the cutting edge of the shield,[2] and appears to have given satisfactory results. This tunnel also was driven through sand and gravel for the greater part of its length, and through a chalk bed broken up by many fissures.

The first attempt made by Mr. Hay to extend the front of the shield was on similar lines and is shown in Fig. 92. It consisted simply of two plates, 2 feet 9½ inches wide and ½ inch thick, curved to the radius of the cutting edge of an ordinary Greathead shield, and extending round it for a length equal to about one-third of its circumference. The plates were secured in front of the shield by six gussets which were rivetted to the plates, and bolted to the cast-iron cutting edge and the vertical diaphragm of the shield as shown in the figure. Grout holes were provided in the plates forming the hood.

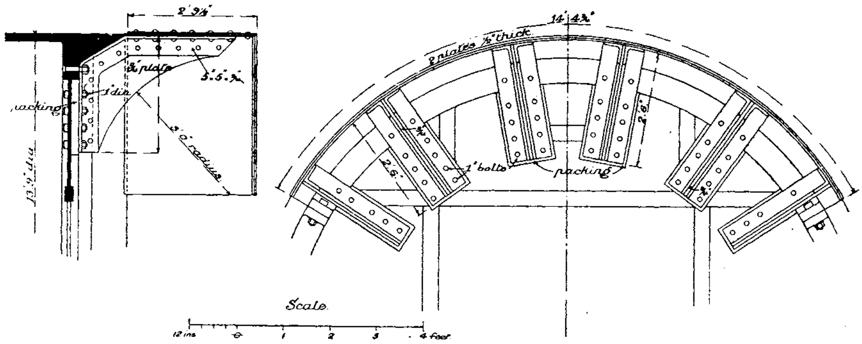


FIG. 92. THE WATERLOO AND CITY RAILWAY, LONDON.
Dalrymple-Hay's Hood on a Greathead Shield.

At first it was proposed to loosen the ballast in front of the cutting edge of the hood by the miners working it with timber dogs, but a very short trial showed that this was impossible, and Mr. Hay determined to try the effect of removing an annular space in front of the cutting edge by making a succession of pockets, each pocket when made being filled with well-pugged clay. The ring so made was got out a little larger than the outside of the hood, so that when the latter advanced into it, a skin of clay from 1 to 2 inches thick remained outside the skin of the shield, and served, as the shield advanced, in some measure as an airtight coating outside the tunnel lining.

A more detailed description of the process is given in dealing with the first hooded shield employed later by Mr. Hay (p. 148).

This, in being tried, was found quite feasible, and the amount of air to be pumped was considerably diminished, while the cost of the tunnel gang was reduced and the rate of progress increased. But the system had hardly got into working order when the shield showed signs of failure due to the extra pressure on the extended front, and the fear of the shield collapsing altogether caused the contractors

1 Weale's *Quarterly of Engineering,* 1846, vol. v.
2 Legouez, *Emploi du Bouchier,* pp. 278, 280.

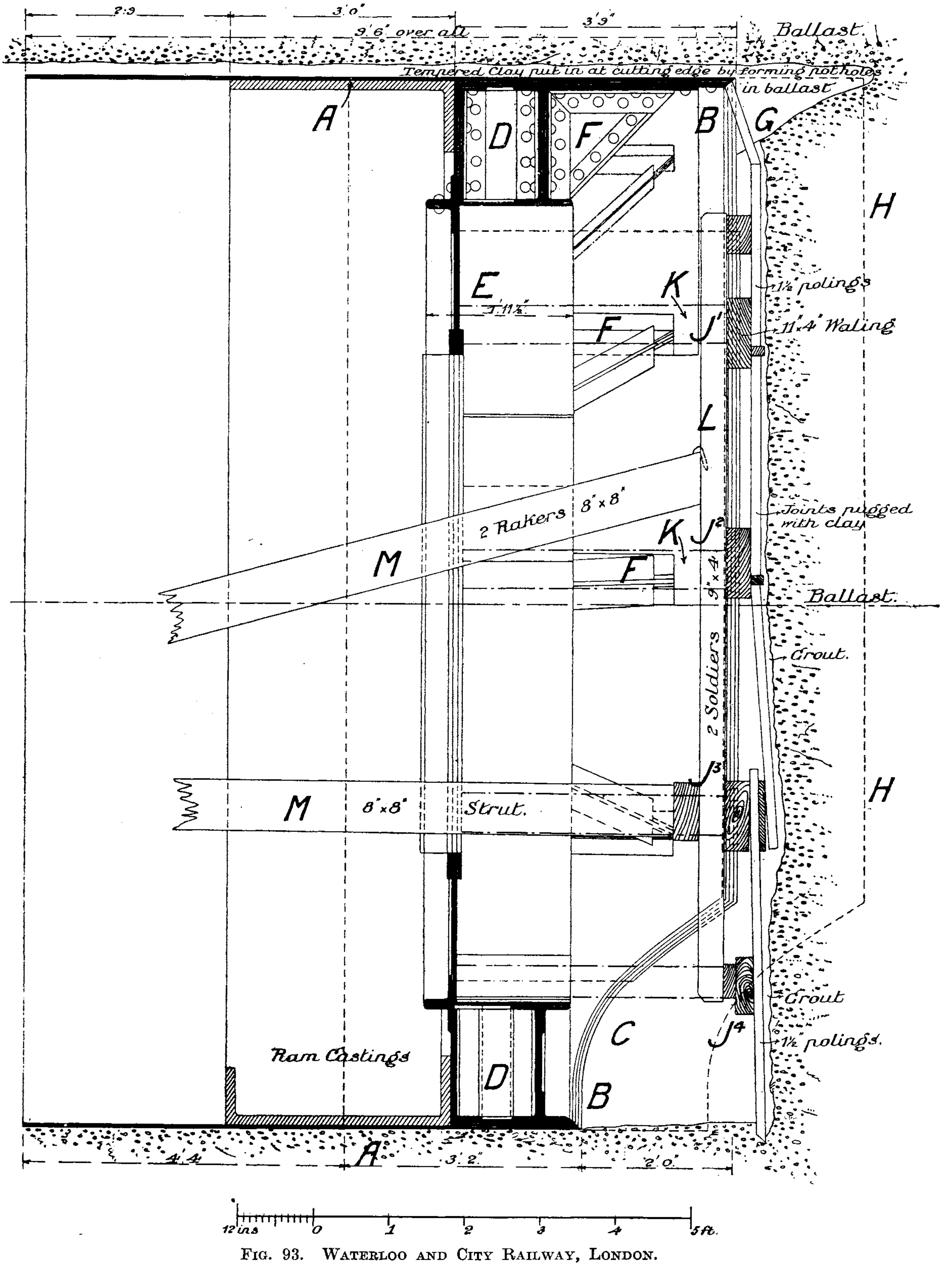


FIG. 93. WATERLOO AND CITY RAILWAY, LONDON.
Dalrymple-Hay's Hooded Shield. Longitudinal Section.

to remove the hood, and revert to the older system of timbering in advance. The great economy effected, particularly in the supply of air required, by the use of the hood and the clay pockets, was, however, so obvious, that a little later they employed, in another part of the railway, a specially made shield embodying Mr. Hay's ideas, in place of the provisional one previously used. This shield is shown in Figs 93, 94, 95. It consists of a cylindrical skin formed of $\frac{5}{8}$ inch plates, which, contrary to the usual practice in shields of this size, was not in one piece from front to back of the shield, but there was a circumferential butt joint at *A*, 4 feet 4 inches from the tail of the shield, and 5 feet 2 inches from the front of the hood. This skin extended to the cutting edge *B*, there being no cast-iron cutting edge, but one composed of plates making a total thickness of $2\frac{1}{2}$ inches for the greater part of the circumference, and of $1\frac{7}{8}$ inches at the invert. This cutting edge extends 3 feet 9 inches in front of the vertical diaphragm *E* of the shield, except at the bottom, where it is cut away (at *C*) so that it is only 1 foot 9 inches long. A projecting edge of this length would not, of course, be sufficiently stiff in itself to resist the pressure of the ground above, but it and the shield generally is stiffened by a circular box girder *D* immediately in front of the diaphragm, to which and to the cutting edge plates it is rivetted.

The overhang of the cutting edge beyond the box is further supported by nine gussets *F*, *F*, formed of plates and angle irons.

The arrangement of the hydraulic rams (not shown in the figures) and of the ram castings is of the usual type. They were, in fact, taken from the Greathead shield on which the experimental hood was tried.

The shield measured over all 9 feet 6 inches in length, and 13 feet 9 inches in outside diameter. It was thus about 2 feet 6 inches longer than the ordinary Greathead shield, the cost being about the same.

It will be seen that the overhanging cutting edge formed a comparatively roomy chamber in which the miners could work in safety, and it is further claimed for the hood that it admits of the ballast in the face being entirely removed in front of the cutting edge at the invert, and so facilitating the advance, and removing for that part of the face the risk of the cutting edge being deformed by meeting boulders or large stones.

The other innovation made in combination with the hooded shield was the employment of tempered clay in front of and around the cutting edge for the double purpose of limiting the escape of air at the same time that the amount of timbering in front was reduced, and of preventing in some measure the settlement of the ground above. In both directions the arrangement was satisfactory ; the amount of air required to dry the face and the cost of labour were reduced ; there was very little settlement in the buildings above, and further, the rate of progress was about 24 per cent. quicker than with the timbered heading method of work.

The method of employing the clay was as follows :—Commencing at the crown of the shield, a hole about 15 inches wide and 22 inches long was formed in the ballast in front of the cutting edge, by raking it out with a timber dog, or a short bar, and at once filled up with tempered clay, the outside of the hole being about 2 inches above the cutting edge (see *G*, Fig. 93). Another hole of like dimensions was then commenced at the side of the first and clayed up, and the process repeated until finally a ring of tempered clay was formed in front of and extending some 2 inches outside of the cutting edge of the hood. The clay ring was not carried below the hood.

Care was required in making those pot holes, and it was necessary to clay them up immediately they were made, but the operations were simple enough in themselves.

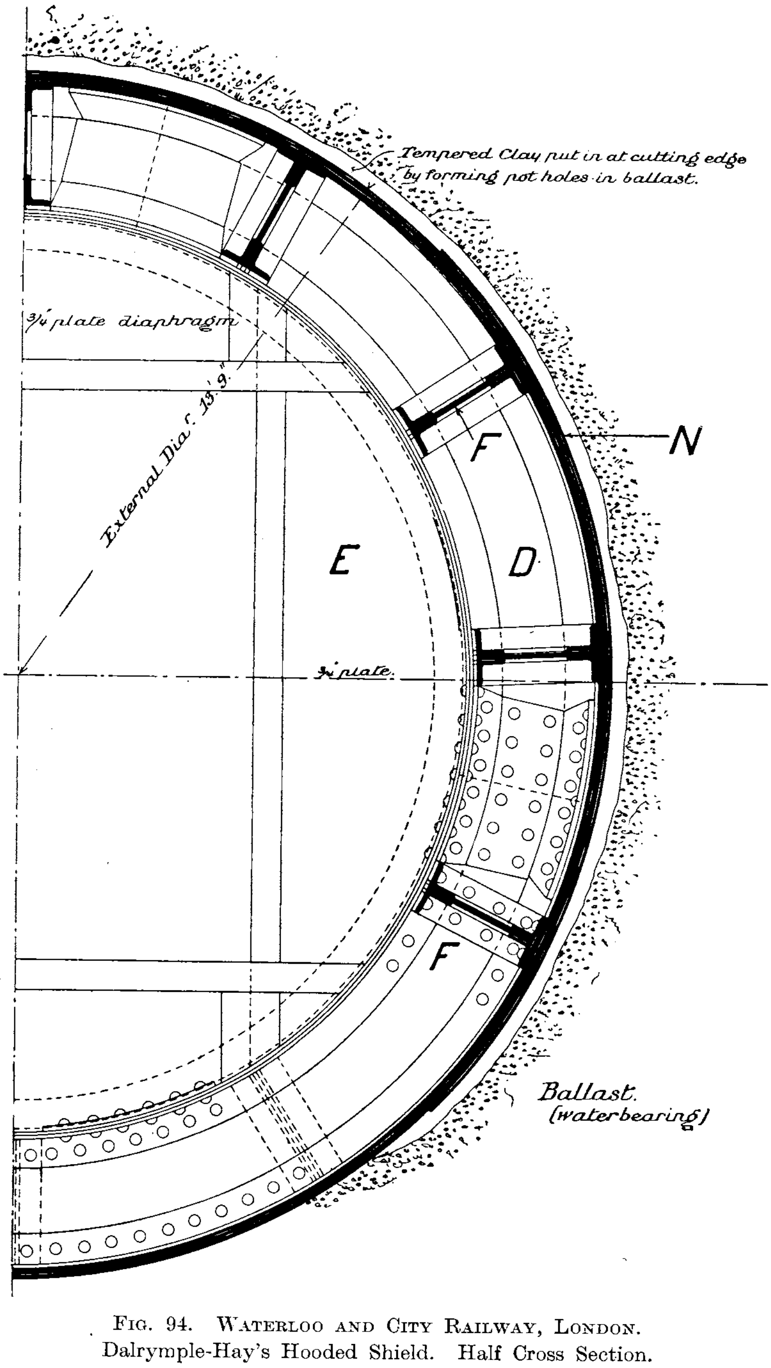


FIG. 94. WATERLOO AND CITY RAILWAY, LONDON.
Dalrymple-Hay's Hooded Shield. Half Cross Section.

In Fig. 93, the clay ring G is shown as complete, and the shield ready to be pushed forward. As the shield advanced to the position shown by the dotted line

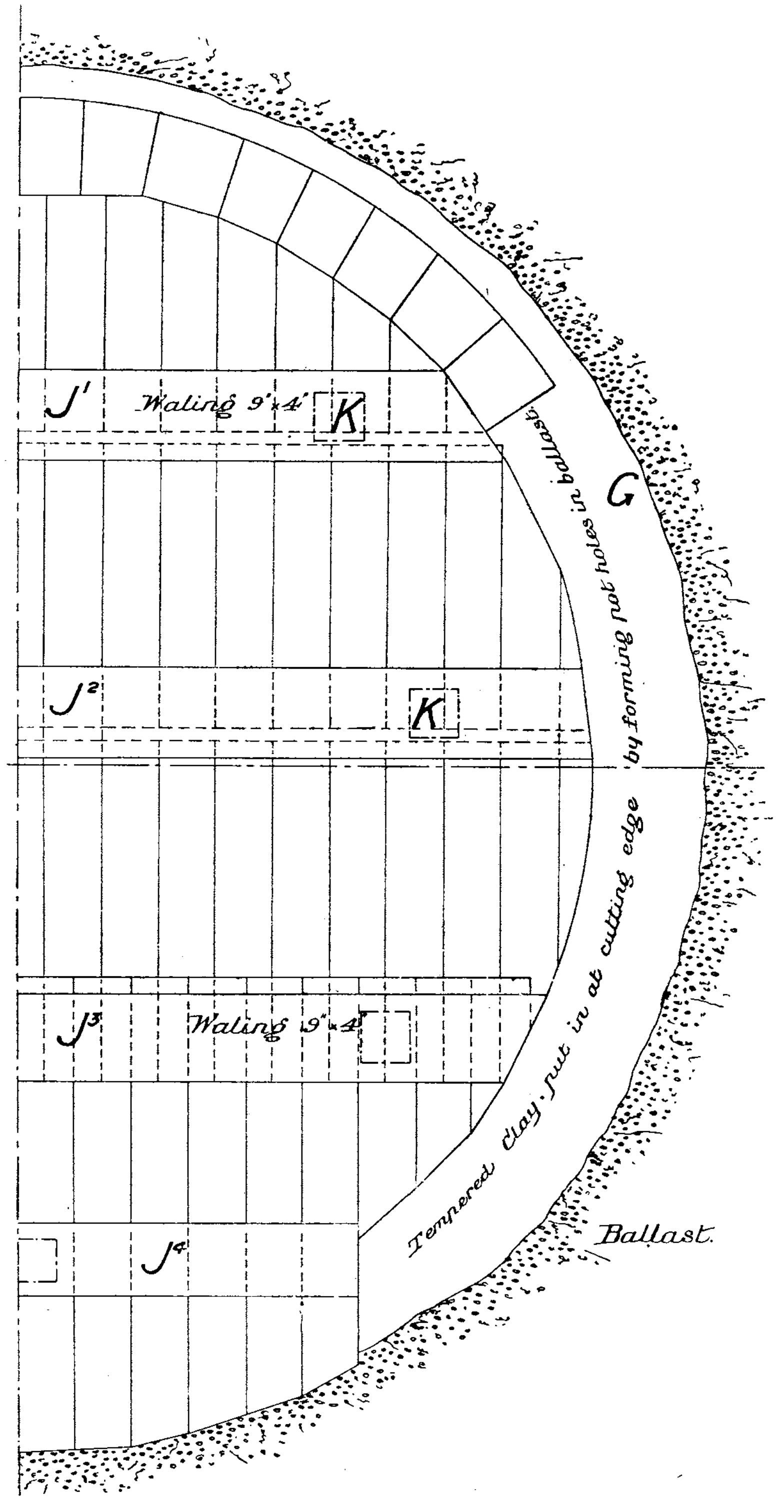


FIG. 95. WATERLOO AND CITY RAILWAY, LONDON.
Dalrymple-Hay's Hooded Shield. Timbered Face.

H, H, the cutting edge of the hood buried itself in the tempered clay. The clay ring being got out some inches outside the cutting edge, a layer of clay was left behind as the shield advanced, and is said to have remained in a comparatively continuous layer, not only on the shield but outside of the tunnel. This of course had the effect of greatly reducing the usual loss of air between the tail of the shield and the last tunnel ring, and also at the joints and grout holes of the tunnel.

This, and the fact that the method of working did away entirely with the advance top heading, doubtless reduced the escape of air by 50 per cent. as compared with the earlier system.

The timber work of the face is all done under the shelter of the hood, and, there being no heading, the amount of work to be done is comparatively small.

Each time the shield was pumped forward and a new ring of the tunnel lining erected, the setting forward of the timbered face was proceeded with before the making of the clay ring already described was put in hand. The poling boards at the upper part of the face were advanced to the line of the cutting edge and the walings J^1 J^2 J^3 J^3 successively put in as the face was worked down in the same manner as in the timbered lengths already described. The walings were stretched temporarily to the diaphragm of the shield by the struts *K, K* indicated in dotted lines in Figs. 93 and 95. When the face was secured in this manner, and well grouted up, the clay ring was formed as already described, and the length bottomed up.

On the completion of the timbering and excavating of the face, the walings, which until then were stretched back to the shield, were supported by soldiers *L*, and struts and rakers *M, M* bearing on a byatt fixed across the tunnel, thus leaving the shield free to move forward again, without disturbing the timbered face.

It will be noted that this system, although a great improvement on that previously employed, was still open to the objection that by the use of struts and rakers passing through the door of the shield, when it was advancing—that is, when collapse of the face was most likely to occur—no possibility existed of closing up the front of the shield in case of accident.

Owing, too, to the "overhang" of the hood of the shield, the tendency which every shield has when going through water-bearing ballast, to sink as it advances, was perhaps increased, and no doubt Mr. Hay's use of a clay lining outside of the shield, by its tendency to yield, assisted in the movement. This was counteracted by the use of timber skids and iron plates in the bottom of the invert.

Another advantage which the use of the clay ring possesses when it is made, as was the case in the Waterloo and City Railway work, sufficiently large to leave a clay ring some 2 inches thick round the shield, is to increase the facility of handling the shield on a curve. This in Mr. Hay's shield was further made easier by fixing on the outside of the skin, and on either side of the shield, a ⅝-inch plate *N* (Fig. 94) extending backwards from the cutting edge a distance of 3 feet 9 inches, and reaching above and below the horizontal diameter of the shield about 5 feet 9 inches. The effect of the extra thickness thus provided in the front part of the skin of the shield was to make a wider cut as the shield advanced in which the tail could turn; and as a matter of fact the shield was so driven round a curve of 320 feet radius without difficulty.

The Glasgow Harbour Tunnels (1890–93)

The Glasgow Harbour Tunnels [1] were constructed under the River Clyde, and are peculiar in that they are all connected to single shafts on either side of the river and are so close together that there is in places barely 2 feet of intervening material between them. The three tunnels were provided to afford the required traffic facilities and at the same time keep the diameter of the tunnels as small as possible.

The vehicular traffic going south has a separate subterranean passage, and there is also one for the traffic going north, while the central tunnel is for passengers only (see Fig. 96).

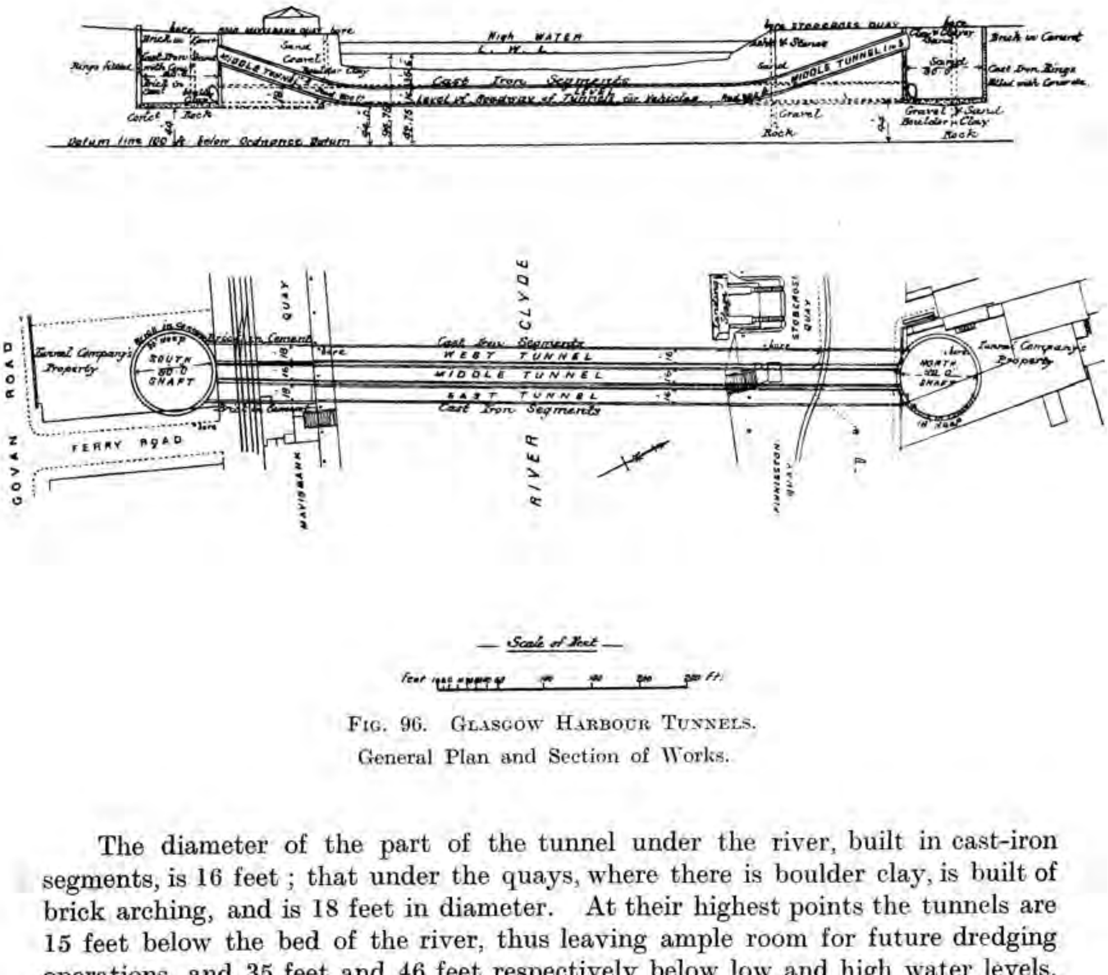


Fig. 96. Glasgow Harbour Tunnels.
General Plan and Section of Works.

The diameter of the part of the tunnel under the river, built in cast-iron segments, is 16 feet; that under the quays, where there is boulder clay, is built of brick arching, and is 18 feet in diameter. At their highest points the tunnels are 15 feet below the bed of the river, thus leaving ample room for future dredging operations, and 35 feet and 46 feet respectively below low and high water levels. The shaft on the north side is about 400 feet west of Finnieston Street and 170 feet from the quay wall, while the shaft on the south side adjoins the Govan Road,

[1] *Engineering*, May 10 and 31, and June 14 and 28, 1895, from which, by the courtesy of the Editor, the illustrations are reproduced.

and is 120 feet from the quay wall. As the river is 415 feet wide, the length of tunnel from shaft to shaft is just over 700 feet. Both shafts are round, and 76 feet in diameter. The shaft on the north side of the river is 72 feet 6 inches deep, and that on the south side 75 feet 6 inches deep. In each shaft there are six elevators, three for lifting and three for lowering, but any and all can be used either for lifting or lowering when required. They are for vehicles. The passenger tunnel pierces the shaft 34 feet from quay level, with flights of stairs. From the shaft it is on a decline of 1 in 3.

The work of constructing the shafts was started on February 3, 1890, and the south shaft was first taken in hand. The walls of the shaft consist for the greater part of their depth of an inner and an outer lining of ½-inch cast-iron segments braced together with wrought iron T bars 3 inches deep by ½ inch thick, the intervening space being filled with concrete consisting of five parts of sand and broken stones to two of cement. The total thickness is 4 feet. The upper and lower parts of the completed shaft are entirely of brickwork. The upper soil of sand was removed to a depth of 14 feet, when water was reached. A double ring of segments, each of 2 feet depth, was then built on a cutting edge. Other rings were built and filled with concrete as the excavation proceeded, pumping arrangements being meanwhile introduced to deal with the water. With about thirty miners employed the shaft was carried down at about the rate of 8 feet per month so long as the material met with was sand only. At a depth of 48 feet, however, boulder clay, the surface of which was much higher on one side of the shaft than on the other, was found.

Considerable trouble was experienced in consequence in keeping the shaft level and true, but by employing pig iron as kentledge in the side where the clay was highest, and by lubricating the outside at the same place with water by means of a trench dug round the caisson, it was sunk into the clay without deformation.

When the shaft was well into the clay, all round the cutting edge and the remaining 21 feet of depth was built by underpinning in brickwork 4 feet thick. This was done without difficulty except on the south side, where sand was found. This was dealt with by driving piles inside the caisson to a depth of in some cases 40 feet, and when it was dry, excavating the sand behind them and underpinning in short lengths.

The bottom being mainly clay, a concrete invert 2 feet in thickness was considered sufficient.

The north shaft was sunk under more difficult conditions, the material being fine sand, which at a very small depth beneath the surface was waterlogged. The rate of progress was about 6 feet per month, and the sinking of the caisson was easy, but of course expensive pumping plant was required, the amount raised reaching 1,500 cubic feet per minute. When sinking in this loose material, however, the cast-iron segments of the lining showed indications of parting, and ultimately a second or inner lining also of cast iron and secured to the original caisson, the spaces between them being filled with concrete, was constructed.

The use of cast iron in a double-skinned caisson does not appear to have been satisfactory. In part this may have been due to imperfect bracing, but the main objection to the use of a caisson with two skins formed of cast-iron segments is that in the event of irregular sinking in bad material the stresses set up in the caisson may be tensional and not merely compressional, as they are in shafts sunk in good material. In such conditions a frame of cast-iron segments bolted each to its neighbours is the worst kind of lining to a caisson.

The invert of this shaft was covered with concrete 10 feet thick, the cast-iron lining being carried down to the bottom and no brickwork used.

Of the three tunnels which connect the two shafts, the two outer ones were made level from shaft to shaft, being reached by lifts which are large enough to take vehicles of any size, these two tunnels being reserved for wheeled traffic.

The central tunnel leaves each shaft about 35 feet from the top, and descends to below the river bed on gradients of 1 in 3, stairways being provided for foot passengers both in the shafts and in the inclines of the tunnels.

Owing to the fact that the boulder clay met with in the south shaft extended for a considerable distance under the river, it was possible to construct the first portion of the tunnels, starting from that shaft, in the ordinary manner in timbered lengths, the tunnel being lined with brick, the internal diameter being 18 feet. This size enabled the shield for driving the cast-iron lined tunnels 16 feet in diameter under the river to be taken through it with ease.

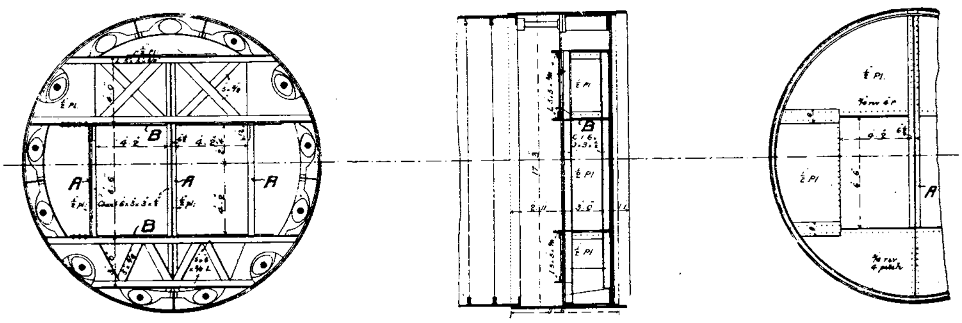


FIG. 97. GLASGOW HARBOUR TUNNELS.
Shield.

Compressed air was employed in all three tunnels under the river, and shields also, these latter being Greathead shields, resembling in some respects the Glasgow Subway shield, but of greater strength. Two types of shield were used, the second of which is shown in Fig. 97.

In was 17 feet 3 inches in diameter and 8 feet 6 inches in length over all. The skin was composed of two plates ½ inch in thickness, and there was no cast-iron cutting edge, as was usual with all the Greathead shields of that date.

The plate diaphragm placed 1 foot 1 inch back from the front edge was of ½ inch plates, and was pierced by two doors 6 feet 6 inches high and 4 feet 2 inches wide. These doors could be closed by sliding doors, like the ones on the Glasgow Subway shields (see Fig. 60). These, however, were never used. The special feature of this diaphragm, however, was the manner in which it was stiffened by horizontal and vertical girders behind it. These girders, formed of ½-inch plates, stiffened in the case of the vertical ones *A*, *A*, *A*, Fig. 97, by channels 6 inches by 3 inches by 3 inches by ½ inch, and in the horizontal ones *B*, *B*, by angles 5 inches by 5 inches by ⅝ inch, gave great rigidity both to the diaphragm and to the skin of the shield.

The rams were thirteen in number and 7 inches in diameter, fitted in a cast-iron ring of the same length as the diaphragm girders were wide. The tail of the shield was 2 feet 11 inches long.

The greatest pressure employed in the tunnel never exceeded 18 pounds, and was usually much less. The compressed air plant was therefore of comparatively limited capacity.

The bulkheads and airlocks employed were of two types. In the first the bulkheads were of brickwork, the total thickness being 19 feet, and the lock being simply an opening 5 feet by 3 feet 6 inches left in the wall, and closed by cast metal doors fitted to frames similar to those employed in the Mersey Tunnel lock (see Fig. 149).

In the second the bulkhead consisted solely of a curved diaphragm *A* fitted to the cast-iron lining of the tunnel (see Fig. 98), with the convex side towards the pressure chamber, and stiffened by seven vertical gussets *B*, *B*. Secured to this diaphragm on the outside—that is, in the ordinary atmosphere—was a lock about 13 feet long, 5 feet 7 inches high and 4 feet 3 inches wide, rectangular in shape, the casing being made of buckled plates, with the convex side inwards.

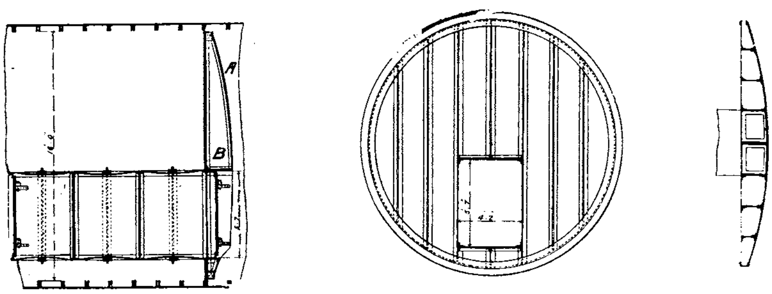


FIG. 98. GLASGOW HARBOUR TUNNELS.
Built from Bulkhead and Airlock.

This arrangement proved very satisfactory, and its removal, when done with, was easy.

The work of driving the tunnels was carried out successfully, though, compared with some later works, the rate of progress appears somewhat slow.

The first start was made with the down-stream tunnel, and as this was for some distance entirely in clay, the tunnel was for some distance constructed without shield or air pressure, and indeed without iron lining, brick being employed.

This brick-lined tunnel was made, as stated, about 18 feet in diameter, thus enabling the shield for the 16 feet tunnel to pass through it. A length of 60 feet was driven without air.

The compressed air plant was started on June 1, 1891 ; but as long as the work was through boulder clay little pressure was required. The experience throughout the work was that the rate of progress was not affected by the fact that the men had to work under air pressure ; but the pressure seldom exceeded 10 pounds. When the men were working without air pressure, the progress was 12 lineal yards for the first month, May, and for the June following, when the air pressure was first started, 14 lineal yards ; in July it was 17 yards. In August, when operations were half in clay and half in sand, the progress was 19 yards, and the average in the sand under air pressure about 20 yards a month. The air pressure varied greatly, from 18 pounds when the sand was first reached, to 2½ pounds when the north shaft was pierced. The highest pressure was reached crossing the middle line of the river, when there was a little wet sand. At high tide there was a head of 60 feet, and at low water of 50 feet over the tunnels.

The east tunnel was started from the south shaft, in boulder clay, as the west tunnel was nearing the north shaft ; but when the east tunnel got into the sand, it was found desirable to add to the air compressing plant, and ultimately it was found unadvisable to continue working the two tunnels simultaneously, even with the increased supply of air, and work in the west tunnel was suspended, and the construction of the eastern one pushed on.

In February 1892, when the airlock for the east tunnel had been completed and the air pressure was ready to be turned on, a " sand back " discovered itself in the boulder clay, and the water from the river came flowing into the tunnel. It was on a Saturday night, so no men were in attendance, but the airlock door was closed, so that the tunnel only was flooded. The difficulty, however, was overcome, for with a 15-pound air pressure the tunnel was blown completely dry in twenty-four hours. That was the only incident in the boring of the east tunnel, which was completed in November 1892, and the men went into the west tunnel and completed it, as already described, in February 1893.

The centre tunnel then only remained to be driven, and it was completed without a hitch by November 1893, the rate of progress being greater than in the other two tunnels. In one month 30 lineal yards were driven in the middle of the river, and in another month 25 yards.

The cost of excavation under air pressure in sand was about 10*s*. per cubic yard, including every operation. The men engaged on the work were well paid, being almost all skilled labourers. The miners got about 8*s*. a day. The total cost per yard of iron-lined tunnel, 16 feet in internal diameter, under the river was from £80 to £85 per yard of length. This price appears somewhat high, but the comparatively short length of tunnel, only 700 yards in the three tunnels altogether, makes the charge per yard for shields and air plant very heavy in proportion to the total working charges.

The Mound Tunnels, Edinburgh

The Mound Tunnels at Edinburgh were constructed in 1893–4 by the North British Railway Company as part of a scheme for improving the traffic facilities at the Waverley Station. Two tunnels, each 16 feet 4 inches in diameter, and 750 feet long, were constructed in cast iron under the "Mound," which is an artificial hill connecting the old and new towns, and lies across the valley in which the railway runs. From the fact that the hill consists of made earth and that it carries some important public buildings—an art gallery, etc.—it was decided to use compressed air to hold up the excavation. Only a low pressure was used, some 15 pounds per square inch, but the work, which was carried out with complete success, was the first tunnel undertaking in which compressed air was used solely with the object of supporting the ground and not of expelling water.

The shields were of the ordinary type.

THE SHIELD IN WATER-BEARING STRATA

The Siphon de Clichy[1]

This work, which consists of a shaft (receiving one of the main outfall sewers) on the Clichy bank of the River Seine, and a tunnel from it under the river which gradually rises to join the open masonry drain which conducts the sewage of Paris to the sewage farm at Achères, was constructed in 1892–4.

It is of interest as being the first undertaking in France in which the Greathead shield was employed, the designs for the shield employed having been supplied by Mr. Greathead himself ; and also as being one of the few examples of compressed air tunnelling in which air pressure was used merely to hold back water in the fissures of otherwise solid and easy material for tunnelling. It is, too, important from the fact that, to the success which attended the employment of a shield in this, and in the similar work at the Pont de la Concorde, is owing the extraordinary amount of tunnel work recently carried out in Paris by means of, in the first place, shields in conjunction with masonry linings, and secondly by roof shields under which only a portion of the permanent tunnel is built under shield, the remainder being constructed in timber lengths in the ordinary way.

The shaft forming the downward limb of the siphon is about 77 feet deep, and is constructed with cast-iron tubbing nearly 10 feet in internal diameter, of the usual pattern.

The shaft was sunk through the later porous beds to what was hoped was fairly watertight material, the marls of the limestone beds, and the tunnel driven through them at a depth of 60 feet below the mean water level of the river, and with a minimum of 29 feet 6 inches between the roof of the tunnel and the river bed.

The sinking of the shaft was carried out on the usual lines. The excavation was made by, in the first place, spade work, the interior of the shaft being kept dry by pumping. A grab was then employed and finally the bottom of the shaft, when it was sunk to the full depth required, was closed by a diver who fitted a domed plate as an invert. At times kentledge to the amount of 200 tons was employed, and the effect of this was increased by the use of dynamite cartridges which loosened the more compact beds passed through.

The work of sinking the shaft occupied eight months, so that the rate of sinking was, on the average, less than 10 feet each month.

The lower part of the shaft was constructed with special castings to allow of opening out from it a tunnel, and it was the hope of the engineers, from the results of the borings, that at that level the material was sufficiently watertight to allow of an easy start being made with the shield work.

But the experience obtained in sinking the shaft showed that the marl and limestone which existed at that level were so much fissured that water came through in large quantities.

When the invert of the shaft had been sealed, therefore, an airlock was fitted into the shaft, and the special castings or " plug " removed in order to commence the shield chamber.

The airlock, instead of being fitted to the top of the shaft, was fixed on a chimney or tube about 3 feet 6 inches in diameter fixed in the centre of the shaft, and splayed out to meet the shaft lining immediately above the tunnel opening, an arrangement the advantage of which is not apparent.

[1] Legouez, *Emploi du Bouclier*, pp. 253–267.

When the air pressure was put on, the "plug" closing the tunnel opening was removed, and the shaft being too small to allow of the erection of the shield within it, it was necessary to build a small brick chamber outside the shaft in which to erect the shield. This brick chamber was 8 feet 10 inches in internal diameter, and 12 feet long. It was closed at the end by a dome-shaped brick head wall which was cut away when the shield, to introduce which the airlock had to be removed and replaced after the shield's erection, was ready to start. Had the shield material been lowered into the shaft before fixing the airlock, for which there would have been room had not a smaller air shaft been introduced into it, this removal and re-erection of the shield would not have been necessary.

The shield was of the ordinary Greathead pattern as used on the City and South London Railway.

Work on the tunnel was commenced with the vertical airlock in use, and was so carried on until some 115 feet of tunnel in all had been constructed, when a horizontal airlock was fixed in the tunnel, and the vertical one removed from the shaft.

The horizontal airlock was 20 feet long, the masonry of the bulkhead being 24 feet 6 inches from front to back. The sides of the lock were like those of the City and South London Railway without any lining of iron. The doors were of cast iron fitted into cast-iron frames built into the brickwork.

The iron lining of the tunnel is 7 feet 6½ inches in internal, and 8 feet 2½ inches in external diameter. Each ring is 1 foot 7½ inches wide, and consists of five segments and one key. When finished the tunnel was lined with concrete to the inside diameter of the lining, and the whole surface rendered over smooth.

The vertical joints are packed with wood, and the horizontal ones, which as at Glasgow had fillets at the back, with cement pointing.

The progress of the tunnel appears to have been uneventful, and as regards speed, fairly uniform. Save in open sand, or where a bed of conglomerate was encountered, the daily advance was seldom less than 6 feet 6 inches per day, and never more than 10 feet.

The maximum air pressure employed was about 40 pounds per square inch, and it is to be regretted that more exact details are not obtainable as to the character and extent of the "fissures" in the marl and limestone beds traversed.

The Siphon de la Concorde, forming a part of the same drainage system of Paris, was carried out a year or two later by the same contractor, and on similar lines.

To the Greathead shield employed on this work, an addition was made of a loose curved plate or "hood," which fitted round the outside of the skin, and could be advanced in front of the cutting edge bay so as to form an additional protection for the miners. This plate extended from the top of the shield down to the haunches on either side, covering one-third of the circumference of the shield, and when fully extended it reached about 1 foot 8 inches in advance of the shield.

This was the first occasion on which a shield was used with other than a vertical face.

Chapter VI

THE SHIELD IN WATER-BEARING STRATA (continued)

THE HUDSON RIVER TUNNEL—WORKS IN COMPRESSED AIR WITHOUT SHIELD—A BRICK TUNNEL CONSTRUCTED WITH AN ADVANCE CASING OF IRON—FAILURE OF THE TEMPORARY LINING OF THE ENTRANCE—RECONSTRUCTION OF THE ENTRANCE BY MEANS OF A CAISSON—THE WORK OF TUNNELLING BY MEANS OF A PILOT HEADING—SUSPENSION OF THE WORKS—RESUMPTION OF THE WORKS WITH A SHIELD AND IRON LINED TUNNEL—THE SHIELD DESCRIBED—THE MECHANICAL ERECTOR—METHOD OF WORKING—PROVISIONS FOR MEN SUFFERING FROM COMPRESSED AIR SICKNESS—THE ST. CLAIR RIVER TUNNEL—DETAILS OF THE SHIELD—METHOD OF WORKING—THE MECHANICAL ERECTOR—THE BLACKWALL TUNNEL—THE CAISSONS FORMING THE SHAFTS—METHOD OF SINKING THEM—LEVEL OF SUBAQUEOUS TUNNEL FIXED WITH INVERT 80 FEET BELOW WATER LEVEL—DETAILS OF SHIELD—THE FACE SHUTTERS—THE RAMS—THE HYDRAULIC ERECTORS—METHOD OF LOWERING THE SHIELD FROM GROUND LEVEL TO BOTTOM OF SHAFT—COMPRESSED AIR MACHINERY—THE VERTICAL LOCKS IN THE SHAFTS—SAFETY SCREEN IN TUNNEL—METHODS OF DRIVING SHIELD—INCIDENTS OF THE WORK—CLAY BLANKET IN RIVER BED—METHOD OF WORKING THE FACE SHUTTERS OF THE SHIELD—POLING OF THE SHIELD INVERT—CONDITIONS OF WORK IN COMPRESSED AIR—THE EAST RIVER GAS TUNNEL, NEW YORK—WORK WITHOUT COMPRESSED AIR—COMPRESSED AIR EMPLOYED—COMPRESSED AIR AND SHIELD USED TOGETHER—DETAILS OF THE SHIELD

The Hudson River Tunnels (1879)

AS mentioned above, the same year, 1879, saw the application of the compressed air system to tunnel work in Antwerp and New York, though, as at the latter place, the air pressure was only put in on December 28 of that year, the small tunnel or adit at Antwerp must rank as the first tunnel in which compressed air was actually used.

The Hudson River tunnel was projected with the object of connecting the City of New York by railway with the termini of the great railways from Washington and the South in Jersey City. They were designed (for the idea of a single large tunnel was soon abandoned—the work is still unfinished), first, as two single line tunnels of elliptical shape, 18 feet high and 16 feet wide inside the brickwork, and are constructed, so far as they are built to the present date, entirely in a very soft mud or silt of an argillaceous character, forming the river bottom, and overlying for the most part sand and gravel. This material is water-logged throughout.[1]

The total length of the tunnels would be, when completed, nearly 6,000 feet from shaft to shaft, not including the shore tunnels and approaches, and the greatest depth of the tunnel invert below mean tide level is about 100 feet.

The undertaking is a particularly interesting one to engineers, not merely as the first example on a large scale of tunnelling by means of compressed air, and

[1] Drinker's *Tunnelling*, p. 961. Work in these tunnels has recently been resumed and carried to a successful conclusion (Oct. 1905).

unhappily as the scene of one of the most unfortunate mishaps recorded in connexion with the system, but at the same time as being the first tunnel where Andersons' "pilot" system of tunnelling was tried, and where, later, one of the first large shields was used in conjunction with compressed air.

Work was commenced on the New Jersey side of the Hudson by sinking a brick shaft to a depth of 60 feet, in which, at a depth of 23 feet below mean tide level, an opening was made and an airlock *A* (Fig. 99) built into it, from which the tunnel could be started. The silt there exposed was of so fine and fluid a character that immediately it was exposed to the air it commenced to run, but this tendency was stopped when the air pressure was put on. It was decided to commence the break-up for the tunnel by opening out and timbering the roof, but after considerable labour the idea was abandoned, as water finding its way down through the silt, probably through the blow-holes made by the compressed air, practically made the material to be excavated liquid mud.

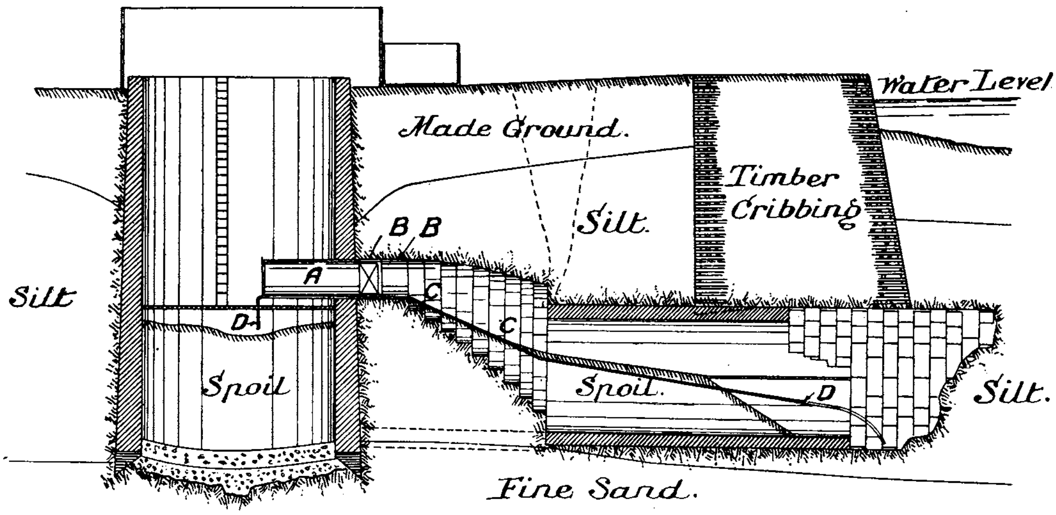


FIG. 99. HUDSON TUNNEL, NEW YORK.
The New Jersey Shaft, and the Tunnel as first begun.

It was then resolved to try to drive a temporary entrance or heading from which to commence the construction of two single line tunnels, the idea of one large one being abandoned. This was effected by erecting outside the air-lock two rings *B*, *B*, formed of wrought-iron plates and angles, 6 feet 4 inches in diameter and 4 feet long and bolted together; and beyond them a series of similar rings *C*, *C*, *C*, each 2 feet 6 inches wide, and each succeeding one increasing about 1 foot 6 inches in diameter, until, with the eleventh ring, the full diameter of the permanent tunnel was reached.

This arrangement of rings composed of segments of insufficient strength (for the plates were only $\frac{1}{2}$ inch thick), and only joined to each other at the crown, so that any extra pressure on a ring was borne by that ring alone, and not distributed in any way on the adjacent ones as in an ordinary iron-lined tunnel, made a very unsatisfactory lining, and its instability doubtless disturbed the cohesion of the bad material with which it was surrounded, and aggravated the danger it was meant to resist.

Such as it was, however, it served for some time as a means of access to the two permanent tunnels which were then commenced.

The lining of these tunnels was constructed in the following manner. The excavation, the air pressure being maintained sufficiently high (about 18 pounds to the square inch) to keep the silt stiff and dry enough to permit of its being cut in steps or benches, the one above the other, was carried forward so that the face of the working sloped upwards and forwards at about 1 to 1. As the excavation advanced, a lining of wrought-iron rings, 2 feet 6 inches wide, each composed of fourteen plates, was put in, each ring being commenced from the top, so that of the five or six rings always in construction at the same time, each ring would be a little nearer complete than the one in front of it (see Fig. 99). These plates were stiffened with angle irons which indeed formed the joints between them. The six top plates in each ring were 3 feet long, the remaining eight being about 4 feet long each. As these rings were completed they were lined with bricks in cement. (For the section of the brick tunnel, see Fig. 102.)

It will be seen that, in this method of tunnelling, in ground such as was passed through at the Hudson tunnel, everything depends on the maintenance of the requisite amount of air pressure, as the face of the excavation was not timbered in any way nor were the incomplete iron rings stretched at the bottom by timber. This condition of equilibrium between the air inside the tunnel, and a varying head of water outside, is much less easy to maintain in actual practice than to lay down as a desideratum in a scheme of compressed air tunnelling, and it is somewhat curious that among the numerous mishaps which befel the undertaking between 1879 and 1889, the one of most likely occurrence, namely a serious "blow" at the top of the face, due to the excess of pressure in the tunnel over the hydrostatic head at the level of the crown and followed by complete flooding of the tunnel does not seem to have happened.

The amount of air pumped into the tunnel was only at the rate of 125 cubic feet of air per man per hour, about one-thirtieth of the amount now considered necessary for health.

Another feature of interest in the work in the more northerly of the two tunnels, which was the one first commenced, was the method of getting rid of the excavated silt, or rather of so much of it as was not left in the invert of the completed tunnel, there to await the completion of the tunnel approaches.

The silt was not carried out from the tunnel through the airlock, but being mixed with about 25 per cent. of its own bulk of water, was in this semi-fluid condition blown out through a 6 inch pipe *D*, Fig. 99, which extended from the invert at the working face where its mouth was inserted in the mud to the shaft in the open air. The high pressure of the air in the tunnel, when the valve in this pipe was opened, drove the mud out.

The method adopted of building out successive incomplete rings of iron plates in advance of the permanent brickwork of the tunnel might have answered if the extent of the hood or canopy so made over the working face had been kept within reasonable limits, and if the segments forming the rings had been more massively constructed. As it was, in the northern tunnel the temporary rings were at the last advanced as much as 55 feet in front of the brick lining, and owing to that fact, and their too light construction, they became distorted, the crown settled down, and the shape of the tunnel was entirely lost.

When work was suspended in this, the more northern, tunnel some six months after compressed air was commenced (June 23, 1880), some 280 feet of tunnel had been constructed; but previous to this date, a commencement had been made with the southern tunnel. To do this it was necessary to widen out the temporary passage, or entrance, of the north tunnel, an operation of considerable difficulty, particularly in view of the peculiar method of construction of the iron roof.

A bridle plate was bolted at one end to the iron rings of the north tunnel, and at the other end to the corner of the temporary entrance (the 6 feet 4 inch rings); and on the same side of the temporary entrance (the southern) a side excavation was commenced 10 feet in length, so that the bridle arch could be put in, the plates forming it being propped by timbers resting on foot blocks. This excavation was made deep enough to clear the proposed arch and the central pier forming the division between the two tunnels got in, thus forming a support for the iron bridle arch. Pits for the two sidewalls of the tunnel arches were then sunk, and the brickwork got in. That done, the invert was completed, and a short length of iron lining of the southern tunnel built, the core of silt being left in.

The brick arch was then carried round these rings, thus completing the entrance of the tunnels. A few feet of tunnel beyond the brick eye was built, and the face was then timbered, and the serious task of replacing the temporary chamber, now in a more precarious state than ever, by a permanent brick one, which should enclose the entrances to both the single line tunnels commenced.

The work in the south tunnel was carried out under a pressure of not less than 21 pounds per square inch, which, seeing that the top of the chamber was only some 25 feet below mean water level, appears rather high, and likely to have put some strain on the roof plates.

The work was then taken in hand of reconstructing the entrance chamber, which, as already described, consisted of the entrance to the north tunnel, as shown in Fig. 99, to which was afterwards added the side excavation necessary for the south tunnel, both being roofed with iron plates, and closed at the tunnel end by the headwall containing two eyes. The end of the temporary entrance on the shaft side had no permanent headwall.

The work of making a permanent brick lining to the chamber was commenced at the tunnel end of the temporary one, by removing one by one the existing rings, and substituting for them similarly constructed rings of the required shape; that is to say, the new arch covered the area occupied by two previously, or in other words, the temporary entrance to the single line tunnels was replaced by a short length of double line tunnel starting at the working shaft and ending at the brick wall already built, through which were made the entrances to the single line tunnels then in course of construction. It was originally intended to open out the excavation so as to put in, for the larger tunnel section, iron rings similar in design to those already described as being used in the north tunnel, and to follow up these immediately with the permanent brick lining, ring by ring, until the chamber had reached far enough for a closing wall or bulkhead to be built adjoining the working shaft. But in actual work the brickwork lining was allowed to get behindhand, so that by the time the roof plates had been put in as far as the wall of the shaft, a distance of some 30 feet, only the brickwork for a length of about 10 feet was in at the other end of the chamber, and that only for the height of 4 feet above the invert. The work had reached the point when all the entrance tunnel had been lined with iron rings almost up to the shaft, and the miners were engaged in putting in the segments of the rings nearest to the shaft when a "blow" occurred, the tunnel filled with water so rapidly that exit through the lock was cut off, and twenty men were drowned.

The cause was undoubtedly the failure of the roof to resist the air pressure; or, in other words, the air pressure overcame the resistance of the silt, already disturbed by the previous mining operations, at some point in the roof of the chamber, probably at one end of the roof,[1] a large escape of air resulted, the pressure in the chamber dropped, and at once the roof, deprived of the sustaining pressure, collapsed.

There can be no doubt that the disaster was caused by excavating too long a length in front of the permanent lining, as was done with the same ill-success in the north tunnel.

It would appear that entire reliance was placed on the sustaining power of the air pressure in the working chamber, but no consideration seems to have been given to the risk run in working in this manner in strata, of a character unsatisfactory to commence with, which had been completely disintegrated by previous operations.

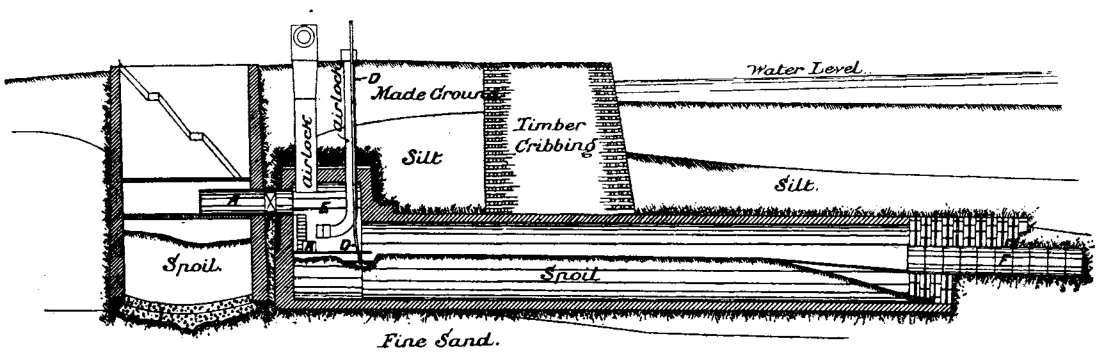


FIG. 100. HUDSON TUNNEL, NEW YORK.
The New Jersey Shaft, and method of construction adopted after the accident in July 1880.

At the time of the accident, the pressure in the chamber was 17 pounds, which was in excess of the amount necessary to balance the hydrostatic head, and consequently easily capable, given a place in the roof weakened by whatever cause, of blowing out through the superincumbent material, and so reducing the amount of air in the comparatively small pressure chamber that practically the pressure would drop at once to that of the ordinary atmosphere, and the chamber fill with water.

Had the permanent lining of the tunnel followed up closely the excavation and the provisional iron plate lining, there would have been a less complete collapse. As it was, the failure of one or two rings of iron probably brought down all the roof of the chamber.

After an unsuccessful attempt to re-enter the collapsed chamber by pumping out the water which had at the moment of the accident filled the working shaft above the level of the airlock, and so pass through the lock, the construction of a caisson, which could be constructed on the ground level above and sunk, under air pressure, to the required position, was resolved on.

[1] The position of the blow, as indicated by dotted lines on Fig. 99, is taken from a sketch in the *Scientific American* of August 7, 1880.

The caisson was made of timbers, and was made (see Fig. 101)[1] rectangular in form, the inside, however, being shaped to the radius of the proposed semi-circular arched roof of the chamber. These timber arch ribs were securely braced to the outside casing of the caisson, the top of which was formed of a double floor of heavy timbers.

The sides of the caisson corresponding in position to the end walls of the entrance chamber were made of extra thickness—the inside arched roof had its ends in fact closed by thick bulkheads.

Beneath the curved arch ribs was placed 4 inch lagging covered with lead and asphalte to make it air-tight.

The whole frame when complete was suspended by 12 inch screw rods 3 inches in diameter and terminating in wrought-iron shoes which were fixed under the lower edges of the caisson, six on each side. By means of these rods the caisson could be lowered uniformly, as the excavation progressed. On the top of the caisson was placed, during the process of sinking, a box about 8 feet in depth, which could be filled with spoil and cast metal to sink the caisson down (not shown in the figure).

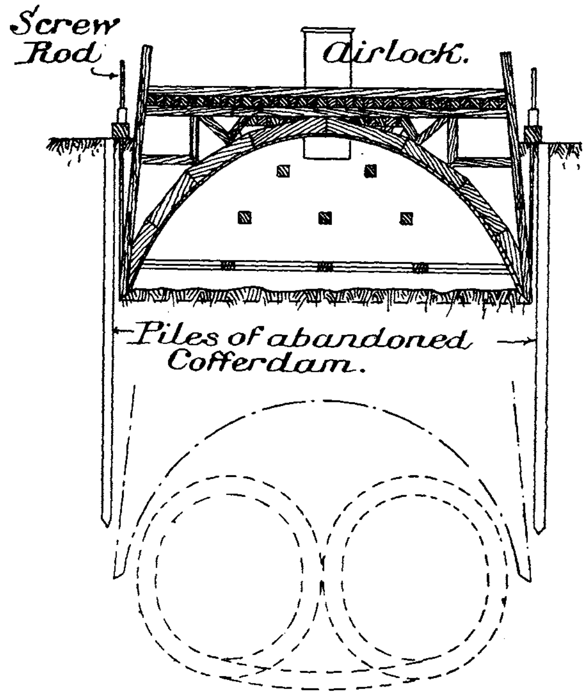


FIG. 101. HUDSON TUNNEL, NEW YORK.
Timber caisson used for constructing Entrance Chamber.

The whole was made large enough to contain within it all the semi-circular upper half of the proposed chamber, which was in length nearly 30 feet, and in breadth over 40 feet, outside dimensions.

It was entered by two air-locks, the one for men, the other for the supply of lime, bricks, excavated material, etc.

The caisson was sunk, with a gradually increasing air pressure, until it reached the position required (shown in Fig. 100), when the wreck of the old temporary roof was cleaned away, and the bodies of the drowned miners recovered.

Communication was then established between the caisson and the shaft by repairing the damaged horizontal airlock, and driving from it, under air pressure, a small heading, 4 feet in diameter, to the caisson, the outside of which was 3 or 4 feet distant from the shaft, and the whole length of the passage so made lined with iron plates. The pressure in the horizontal lock was then raised to equal that in the caisson, 15 pounds, and the inside skin of the caisson consisting, as described above, of 4 inch lagging, with lead and asphalte caulking, was cut through, and communication with the interior of the caisson established.

[1] The Figure 101 is copied from an illustration in the *Scientific American* of Sept. 18, 1880.

A short length of the double tunnel invert had been constructed previous to the accident of July 21, and when the caisson was brought to rest in the proper position for turning the arched roof of the tunnel inside it, its lower edge was some 14 feet above the existing brickwork of the invert, which had only been carried up some 4 feet. (The ultimate position of the caisson is shown in dotted lines in Fig. 101.) It was necessary, therefore, to sink small pits below the caisson to reach this existing masonry, and this was done in holes 4 feet square, which when sunk were timbered, and on the outside side protected with iron plates, behind which the brick walls of the chamber were immediately brought up to the underside of the caisson, the weight of which these walls ultimately took.

By sinking successive holes of this kind, the length of double tunnel previously commenced (it was 8 feet long only) was finished, and then by short lengths the invert was gradually extended, and the corresponding length of walls and arch constructed, until at length all the area under the caisson was enclosed in brickwork, which supported the caisson. This formed the brick entrance chamber *E* of Fig. 100.

The result of the process just described was that the entrance tunnel, or chamber, was reconstructed in a much more stable and satisfactory condition than it had ever been before, and with improved means of access ; the tunnels themselves, however, were still full of water and silt, and were known to be so damaged that the compressed air would escape without expelling the water. To effect an entrance a very ingenious plan was devised, namely the utilization of the fluidity of the silt to overcome the difficulty caused by its own character. It was resolved to fill up the tunnels, full as they were of water, with silt, and so make a solid mass in which mining could be resumed.

To do this, a small hole was drilled through the side of the caisson with an auger and then plugged up, and this was repeated until the opening made was large enough to admit a pipe 2 inches in diameter, which was driven through the caisson into the tunnel. The end of the pipe within the caisson was bent downwards, a tap being also fitted to it.

The downward end of the pipe was immersed in a tank of silt and water mixed to a fluid mud consistency, and the tap opened, whereupon the air pressure in the caisson drove the diluted silt into the tunnel. When in this pipe the flow of the mud ceased, a larger one was substituted and again a larger, until ultimately a 6 inch pipe was employed. When by these means the tunnels were filled with silt, the caisson was cut through, and a small tunnel 6 feet in diameter constructed at the level of the crown of the brick tunnel already completed.

From this tunnel as from an ordinary timbered advance heading in ordinary tunnel work, the excavation proceeded sideways, and downwards, until the whole of the tunnel previously excavated was cleared out, and the work of driving forward recommenced on the lines previously adopted.

At the best, the methods of tunnelling adopted up to this point gave a maximum daily advance of 4 feet.

The work of driving the tunnels, which had been interrupted by the disaster of July, 1880, had not been long resumed when the whole system of tunnelling was altered, and another patented system known as Andersens' Pilot Tunnel system was adopted. This was practically the adoption of an iron-lined tube for the timber heading of ordinary tunnel work.

A small central iron tunnel or heading *F* (see Figs. 100 and 102) was driven some 3 or 4 yards in advance of the iron rings forming the temporary lining of the finished tunnel. This iron heading consisted of rings made of wrought-iron segments stiffened, as were those of the larger tunnel, with angle irons. In every joint, both between those of the rings, and of the segments of each ring, were fixed iron plates *H, H, H,* each 12 inches wide, and arranged so as to form cover plates for the joints, the horizontal ones for the vertical and the vertical for the horizontal joints. These plates projected outside of the cylindrical heading, and greatly increased its stiffness.

As, by the removal of the silt round each successive ring of the pilot heading, the iron lining of the permanent tunnel was put in, this lining was supported by timbers *J J*, Fig. 102, 6 inches by 4 inches, stretched against the longitudinal

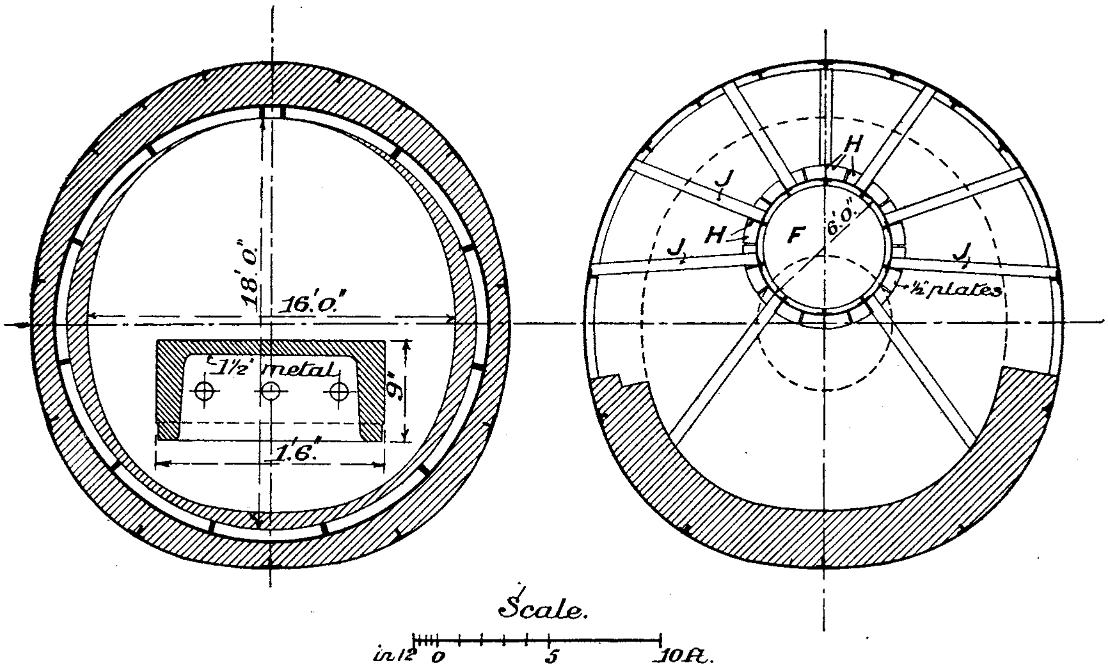


FIG. 102. HUDSON TUNNEL, NEW YORK.
Sections showing comparative areas of excavation for brick lined, and iron-lined tunnels respectively; and Andersen's Pilot System.

joint plates of the heading, so that, so to speak, the pilot tunnel was actually serving as a kind of central shaft, from which radiated spokes which supported the circle of plates round it.

As rapidly as the brick lining of the permanent tunnel advanced, so ring by ring the stretchers were struck and the rearmost ring of the pilot tunnel was taken down to be re-erected in the front.

By this method it was found that the tunnel advanced at the rate of 5 feet per day, and that from the first removal of silt in the front of the heading to the complete enclosure of the same spot in the finished brick tunnel ten days were occupied.

After some experience of the system it was found more satisfactory to place the pilot tunnel in the centre of the larger one, as indicated in the dotted lines in Fig. 102, instead of in the upper part of the tunnel.

The silt excavated was taken in skips drawn by a steam winding engine at *K*, Fig. 100, to a sump near the tunnel entrance, whence it was blown out through the pipe *D*, *D*, in the manner already described. The invert of the completed tunnel was filled with silt to form a trackway, as shown in the same figure.

After the tunnels had made some advance the locks at the shaft were abandoned and new locks built in the tunnel. At the bulkheads first made two locks were provided, one of which was always kept with the inner door open, to serve as a safety lock.

The works described were all carried out from the New Jersey side of the River Hudson, those on the New York side not having been commenced until 1881.

There the engineers commenced operations by sinking, instead of a shaft, a timber caisson similar to the one already described as used in the south side of the river, and by constructing, immediately the caisson was sunk to the required depth, two tunnels in brickwork instead of one single arched chamber for two tunnels to start from.

Much difficulty was experienced in the tunnelling work from this side, due to the fact that the material passed through was not a close silt, as in the New Jersey side, but mainly gravel and sand. It was found necessary, in order to make any advance, to pole carefully the working face of the tunnel, and finally to protect it with iron plates similar to those used for the temporary tunnel lining, and to work very small areas at one time.

In 1882, when the company which had initiated the work suspended operations, only 74 feet of the northern tunnel had been driven from the New York side, while a length of 1,540 feet was completed from the New Jersey end, and of the southern tunnel which was practically untouched at the New York end, 600 feet was built from the New Jersey shaft.

The works, so far as they had then gone, proved, if they proved anything, that compressed air alone was not to be counted on to overcome the difficulties of tunnelling in water-bearing strata, at any rate in tunnels the vertical height of which was sufficient to produce an appreciable difference in water pressure between the crown and invert.

Work on the tunnels was suspended from 1882 until 1889, when a resumption was made under English management, Messrs. Pearson and Sons being the contractors.

For some time the method of working with Andersen's pilot tunnel was continued, but with increasing difficulty as the tunnels advanced and the depth below water level increased. Work on the New York side, which had never made any great progress with the Haskin system of compressed air, was suspended soon after the new contractors commenced work, and after some 500 feet advance had been made in the northern tunnel from the New Jersey end, it was resolved on the advice of Sir B. Baker and Mr. Greathead to substitute for the masonry tunnel a cast-iron one, and to employ a shield for driving it, the use of compressed air being of course continued.

The shield (see Fig. 103) was constructed by Sir W. Arrol, and its working was in the hands of Mr. E. W. Moir. It was 10 feet 6 inches long and 19 feet 11 inches in outside diameter, the external diameter of the cast-iron lining to the tunnel being 19 feet 6 inches.

In general arrangement it resembled the St. Clair shield, with two important differences, namely, in the rigid attachment of the vertical and horizontal girders to the main diaphragm of the shield, and in the provision of doors in the diaphragm at the different levels of the working platforms.

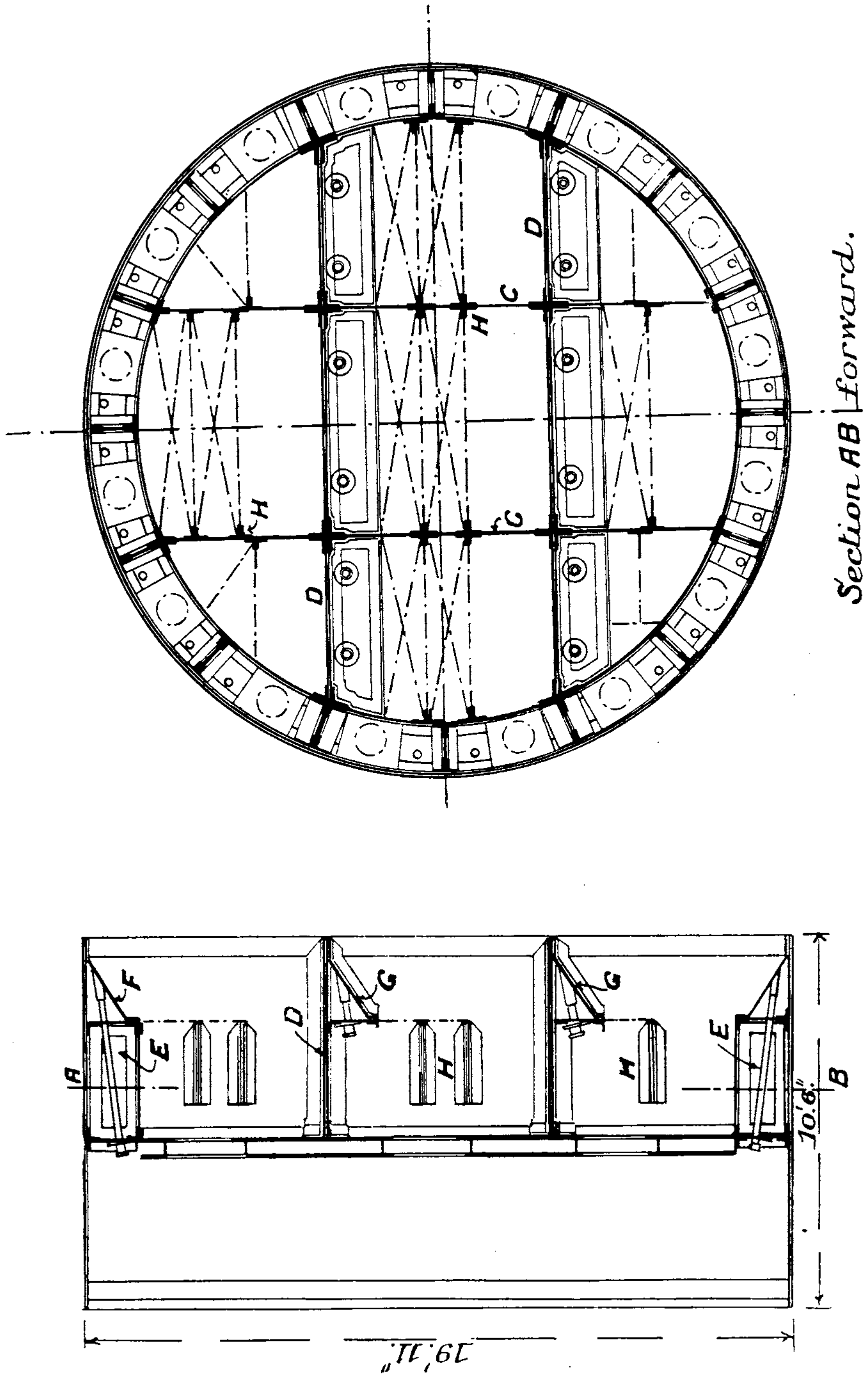


FIG. 103. HUDSON TUNNEL, NEW YORK. The Shield.

The cylindrical skin was formed of two thicknesses of $\frac{5}{8}$ inch steel plate, internal stiffness being given to the shield by a plate diaphragm $\frac{5}{8}$ inch thick, pierced by nine small doors ; and by two vertical and two horizontal girders *C*, *C*, *D*, *D*, immediately in front of the diaphragm, all rivetted together at their respective intersections to each other, and at their ends and edges to the cylinder and to the diaphragm.

The diaphragm was fixed 4 feet 10 inches from the tail of the shield, that distance being left clear for the erection of the tunnel lining. The circular box girder *E*, which consisted of a series of cells in which the shield rams were housed, extended 3 feet 4 inches in front of the diaphragm and in the remaining 2 feet 4 inches of the length of the shield was formed the cutting edge, the inside face of which consisted of a conical plate *F*, rivetted in front to the skin plates, and behind to the inner circular plate of the box girder.

The horizontal girders *D*, *D*, which served also as working platforms, were also stiffened in front by a somewhat similar arrangement at *G*, *G*, the vertical plate of the framing forming also a safety curtain for the miners when working on the platform. There were originally provided, below these vertical plates, sliding shutters shown in dotted lines in Fig. 103, which were arranged to work on angle iron guides *H*, *H*, fixed on the vertical frames and on the inner skin of the box girder, but these were never used, the material proving sufficiently fluid to obviate the necessity for any work in front of the main diaphragm.

The shield was pushed forward by sixteen rams, each 3 feet 4 inches long, and 8 inches in internal diameter, and each capable of exerting a pressure of 100 tons.

With the shield just described was employed the hydraulic erector, shown in Figs. 104, 105, the first of the kind ever constructed.

In 1875, Mr. Greathead designed and patented an hydraulic erector for use in the tunnel under the River Thames at Woolwich, which, however, was never actually constructed. In its general features the one used at the Hudson tunnel, which was designed by Mr. E. W. Moir, followed Mr. Greathead's design.

The erecting gear was carried on a platform consisting of three plate girders *A*, *A*, *A*, bearing on and secured to cast-iron frames *B*, *B*, which were carried on wheels bearing on rails fixed to brackets on the sides of the tunnel.

Directly over the two rearmost girders *A*, *A*, were fixed two cast-iron hydraulic cylinders *C*, *C*, 6 feet in length and 6½ inches in diameter.

The rams of these cylinders had at their ends pulleys *D*, *D*, 17 inches in diameter.

Between the two girders carrying the hydraulic cylinders was fixed a drum *E*, 2 feet 3 inches in diameter, this drum being keyed to a shaft, 7 inches in diameter, which turned in journals fixed in the webs of the three girders, and carried at its forward end, and at right angles to itself, an hydraulic cylinder with forward and reversing action framed into the latticed arm *F*, to one end of which could be secured the segments of the tunnel lining by means of the lugs *H H* specially cast on the segments for that purpose.

The stroke of the ram in the arm *F* was 3 feet 4 inches.

On each of the cylinders *C*, *C*, were cast lugs *J*, *J*, to which were secured the ends of a single chain which passed over the pulleys *D*, *D*, and round the drum *E*.

The working pressure of the hydraulic gear was about 1,000 pounds per square inch, and this was manipulated by the levers at *K*.

The method of working is as follows :—When a cast-iron ring is to be erected, each segment is in turn brought on a trolley immediately under the arm *F*, which is made to point to it by working one or other of the cylinders *C*, *C*, so as to make the drum *E* revolve and with it the shaft to which the arm *F* is fixed.

When the arm is directed properly, it is made to extend itself toward the casting to be picked up by working the cylinder contained in it. The casting being secured to the end of the arm, the cylinder is reversed, and as the arm draws back it lifts the casting with it. The cylinders *C*, *C*, are again put into action and the arm *F* is swung round with the casting at the end of it, until it points to the place where the segment has to be placed ; when the cylinder in *F* is made to push the arm forward until it presses the segment firmly in its position, where it holds it while the miners are bolting it up to the adjacent ones.

The cast-iron lining of the tunnel is 18 feet in internal, and 19 feet 6 inches in external diameter, each ring being 1 foot 6 inches long.

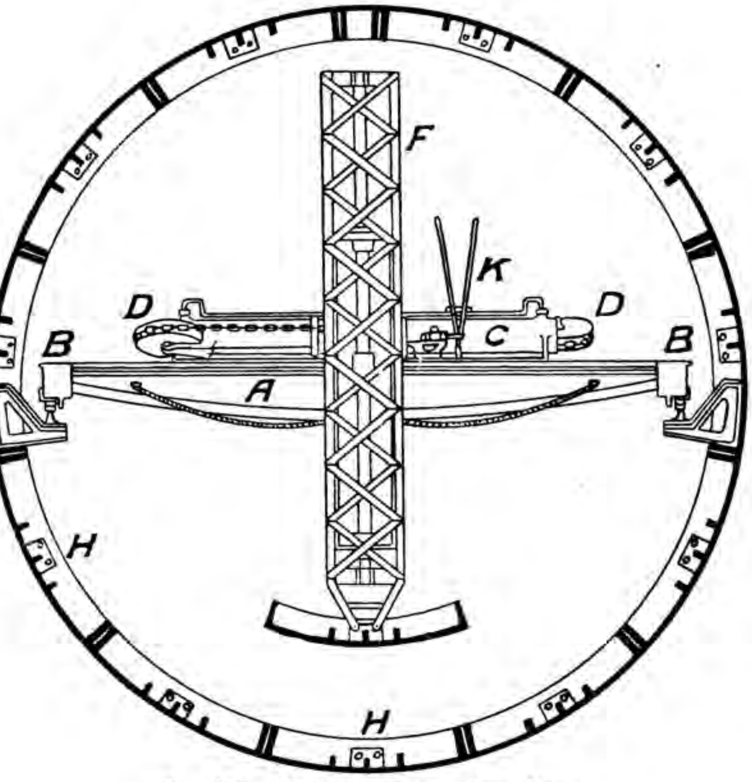


FIG. 104. HUDSON TUNNEL, NEW YORK.
The Hydraulic Erector. Elevation.

When the cast-iron lining was first adopted each ring was composed of nine segments and one key, the segments being of graduated size and thickness from the invert to the crown of the tunnel. This first pattern proved too weak, and subsequently the lining shown in Fig. 102 was adopted.

This consisted of eleven segments and one key, with planed joints provided with caulking grooves. The thickness of the webs was 1½ inches.

The erection of the shield at the end of the tunnel already constructed, under an air pressure of 30 pounds, was a serious operation, and the necessity of using a rivetting furnace in such an atmosphere had a very serious effect on the health of the men, but when once the shield was started, the work went on very regularly and 10 feet advance per day was steadily made.

The mud or silt met with was so fluid that, even against the great air pressure in the tunnel—30 to 35 pounds—it flowed out through the doors in the diaphragm, and when the shield was pushed forward, discharged itself into the tunnel as if pressed out of a mould.

At this tunnel there was used also an expedient frequently tried since, where the crown of a tunnel is near the bed of the river above. When the shield was within 5 feet of the river bed an artificial blanket of clay, 15 feet thick, was laid above the soil as a protection while the tunnel was being driven.

The effect of this was to provide on the bed of the river, and covering the silty permeable material through which the shield was passing, a solid mass of clay, which immediately any settlement of the silt took place sank into the hole thus formed, and automatically caulked it.

In the year 1891, however, after some two years' work by Messrs. Pearson, work on the tunnels was suspended owing to the exhaustion of the promoters' funds, and the undertaking has remained unfinished up to the present.[1]

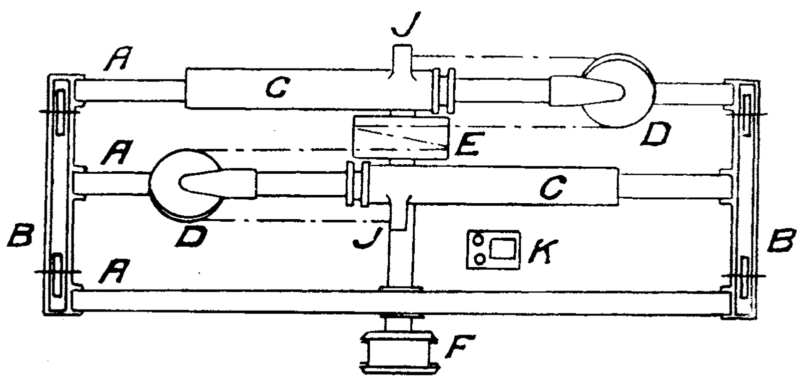


FIG. 105. HUDSON TUNNEL, NEW YORK.
The Hydraulic Erector. Plan.

As previously remarked, the earlier operations in the undertaking, while they demonstrated the great assistance which the use of compressed air gives in affording actual support to a working face, so long as that face is not fissured, proved clearly enough that compressed air was not a substitute, but only a powerful aid to the usual protective appliances or supports used in tunnel work. When used with the pilot heading of Mr. Andersen, and later with the shield, however, work was done which could not have been accomplished by these appliances unaided by compressed air, and it is precisely the succession of experiments made in its use which make the Hudson tunnel so especially interesting to the tunnel engineer.

The use of compressed air for the first time on a large scale in tunnel work (the second period of active prosecution of the tunnel works was contemporaneous with the work on the St. Clair Tunnel) afforded also an opportunity of observation, on a large scale, of its effects on the health of the men employed. Though in the St. Louis Bridge Works, and at the East River Bridge, careful observations seem to have been made of the pathological effects of caisson disease, it was at the Hudson Tunnel that, for the first time, the principal causes of the disease were dis-

[1] The works are now finished (1905).

covered and a practical cure found for many, and an alleviation for all of the cases of sickness among the men due to compressed air work.

Much of the credit for the practical treatment of the difficulty must be given to Mr. E. W. Moir, who was in charge of the tunnel works for Messrs. Pearson, when operations were resumed in 1889. At the time Mr. Moir arrived to take over his duties, the death rate due to caisson sickness in the Hudson tunnel was at the rate of 25 per cent. of the men employed. Mr. Moir, by employing the air hospital, or medical lock, suggested by Dr. Smith in his work on *Compressed Air Sickness*, at once reduced the excessive mortality, and in fifteen months only two deaths occurred out of one hundred and twenty men employed in the tunnel, or say 1·66 per cent. as compared with the previous figures of one in four.

To quote Mr. Moir's own description[1] of the arrangement for treating the men :—

> With a view to remedying this state of things [that is the serious mortality] an air compartment like a boiler was made in which the men could be treated homeopathically, or re-immersed in compressed air. It was erected near the top of the shaft, and when a man was overcome or paralysed, as I have seen them often, completely unconscious and unable to use their limbs, they were carried into the compartment and the air pressure raised to about half or two-thirds of that in which they had been working, with immediate improvement. The pressure was then lowered at the very slow rate of 1 pound per minute, or even less, the time allowed for equalization being from twenty-five to thirty minutes, and even in severe cases the men went away quite cured.

It was on this work that the serious effect of even a small additional percentage of impurity in the compressed air on the health of the men was first noted, and also the further fact that a sudden increase of impurity, that is of carbonic acid, in the air, is most dangerous when it synchronizes with an increase of pressure.

The St. Clair River Tunnel (1888)

This tunnel, which is known also as the Sarnia Tunnel, is constructed under the St. Clair River, which carries the overflow water of Lake Huron to Lake St. Clair, and forms the boundary between the state of Michigan, U.S.A., and the Province of Ontario, Canada, and was built to connect up the Railway systems of the two countries, which previously were only in communication by means of a ferry.

The method of construction adopted, an iron tunnel, built by means of a shield, was determined by the successful progress of the City and South London Railway Works under Mr. Greathead, which were visited and examined by Sir Henry Tyler, at that time President of the Grand Trunk Railway of Canada.

The total length of tunnel constructed under shield is 6,000 feet, of which 2,300 feet is under the River St. Clair (see Fig. 106). All the tunnel was constructed with the aid of a shield, and compressed air was used in the portion immediately under the river.

The cast-iron lining is 21 feet in external and 19 feet 10 inches in internal diameter.[2]

The material through which the tunnel is made is clay of a very soft character, in which pockets of gravel and sand were met with from time to time. The bed of clay was only 38 feet thick, in places, the material above it, being the rim bed, con-

[1] *Journal of the Society of Arts*, May 15, 1896. [2] See p. 64, chap. III.

sisting of sand, while below is a bed of shaly rock, containing an abundance of natural gas.[1]

It was resolved to employ two shields and to drive the tunnel simultaneously from the Canadian and American sides, a method of procedure which involved some risk in making the junction of the two headings under the river.

The shields, weighing 80 tons each were put together on the site and rolled down inclined planes into the excavations made at the tunnel mouths, in which timber cradles were fixed to receive them. On the slope of the excavation longitudinal sleepers of 12 inch by 12 inch timber were laid, the lowering being effected by means of six chains, anchored at one end, passed around the shield, and hitched at the other at the top of the slope. The shields at starting were so arranged that, after rolling down the slope, they arrived on the cradles prepared for them exactly in the right position, as regards the vertical, for commencing work. This operation took little over an hour.

The portions of the tunnel on either side of the St. Clair River were driven without the use of compressed air, 1,994 feet on the Canadian side and 1,716 feet on

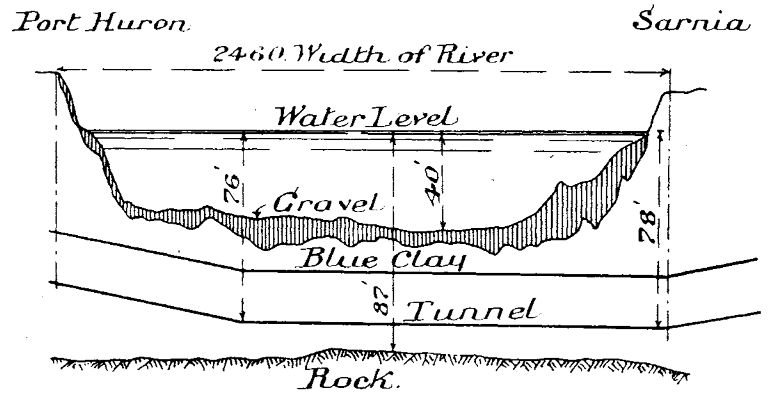


FIG. 106. ST. CLAIR TUNNEL, CANADA.
Longitudinal Section of Tunnel under the St. Clair River.

the American being so constructed. Often the clay was found to be so soft, that it was possible to force the shields forward into it, and as at the Hudson tunnel the material was frequently not excavated in front of the shield, but flowed through the openings in the diaphragm as the shield went forward, and sometimes the amount of clay so entering the tunnel was fifty per cent. in excess of the cubical content of the finished work. It might well have proved cheaper on this account to have used compressed air throughout the tunnel operations, instead of only in the portion actually under the river.

When the shields arrived at the river banks, bulkheads with airlocks were constructed in the tunnel, and an air pressure varying from 10 to 28 pounds per square inch was maintained.

The air was supplied by two compressors to each working face, but as their cylinders were only 20 inches in diameter with 24 inches stroke, and as the pressure pipe to the tunnel was only 6 inches in diameter the amount of free air supplied was much below what it should have been, and it is not surprising to learn that there were many cases of compressed air sickness, and that three cases ended

[1] *Engineering News*, Oct. 4, 1890, p. 293.

fatally. Doubtless the presence of natural gas in the shale below the tunnel did not make the air chamber more healthy. A slight increase in the air pressure, coincident with an increased amount of natural gas, would increase the number of cases of sickness at once.

At the commencement, the miners were in the habit of locking out by means of a valve 4 inches in diameter, but this was found too rapid in action, and a 1½ inch one was substituted.

The locks were 17 feet long and 6 feet in diameter, and in each bulkhead a timber lock 25 feet long and 10 inches in diameter was also provided.

As is usually the case in clay, the escape of air was small except when pockets of ballast were met with, and the air blew out into the river. The amount escaping was kept within limits by plastering the ballast and sand in the face of the working over with clay, and only working a small part of the face at a time. Another source of trouble was the number of boulders met with which could not be removed bodily, nor be broken up by explosions for fear of igniting the natural gas in the tunnel, and therefore had to be split by mechanical means.

The best rate of progress made was 382 feet at the American face in the month of July, 1890, or say 12 feet per day. From the commencement of the shield work to the journey up in the centre of the river, the monthly progress at each face averaged 250 feet, a very fair rate for a tunnel of its size.

The two shields used were identical in pattern, and Mr. Hobson the engineer, to whom their design is due, appears to have followed, so far as he has followed any one model, the Beach shield, though, as stated above, the employment of the shield method of construction was suggested by the satisfactory progre s then being made with the City and South London Railway under Mr. Greathead.

Each shield was 15 feet 3 inches in length, and 21 feet 6 inches in external diameter (see Figs. 107, 108).[1]

The cylinder or skin was made of plates 1 inch thick, and was made in four rings, each ring consisting of twelve plates with butt joints. The front ring was 3 feet 3 inches long, and had its front edge chamfered off to form a cutting edge. The other three were 4 feet long. The last of these, *C*, formed the tail of the shield, and the joints of the plates composing it were covered by plate covers inside and out, ½ inch and ⅝ inch thick respectively. All the other joints, longitudinal and circumferential, of the skin plates were formed by angle irons rivetted to the plates and to each other (see Fig. 107).

These circumferential joints were the weak part of the design, and no doubt were responsible, in conjunction with the fact that the vertical and horizontal frames of the front of the shield were not braced to the diaphragm behind, for the tendency to distortion shown when working.

At the tail of the shield an attempt was made to reduce the escape of air between the shield and the last ring of the cast-iron lining, by means of an india rubber collar fixed inside the skin.

Two angle irons *D*, *D*, 3 inches by 1¼ inches, and having a space between them of 2½ inches, were rivetted to the skin, and carried right round (see Fig. 107) forming a groove into which rubber packing of square section was fitted, and held in place by set screws working through one of the angles. It was hoped that this

[1] The drawings of this shield are reproduced from *Engineering*, of Nov. 14, 1890.

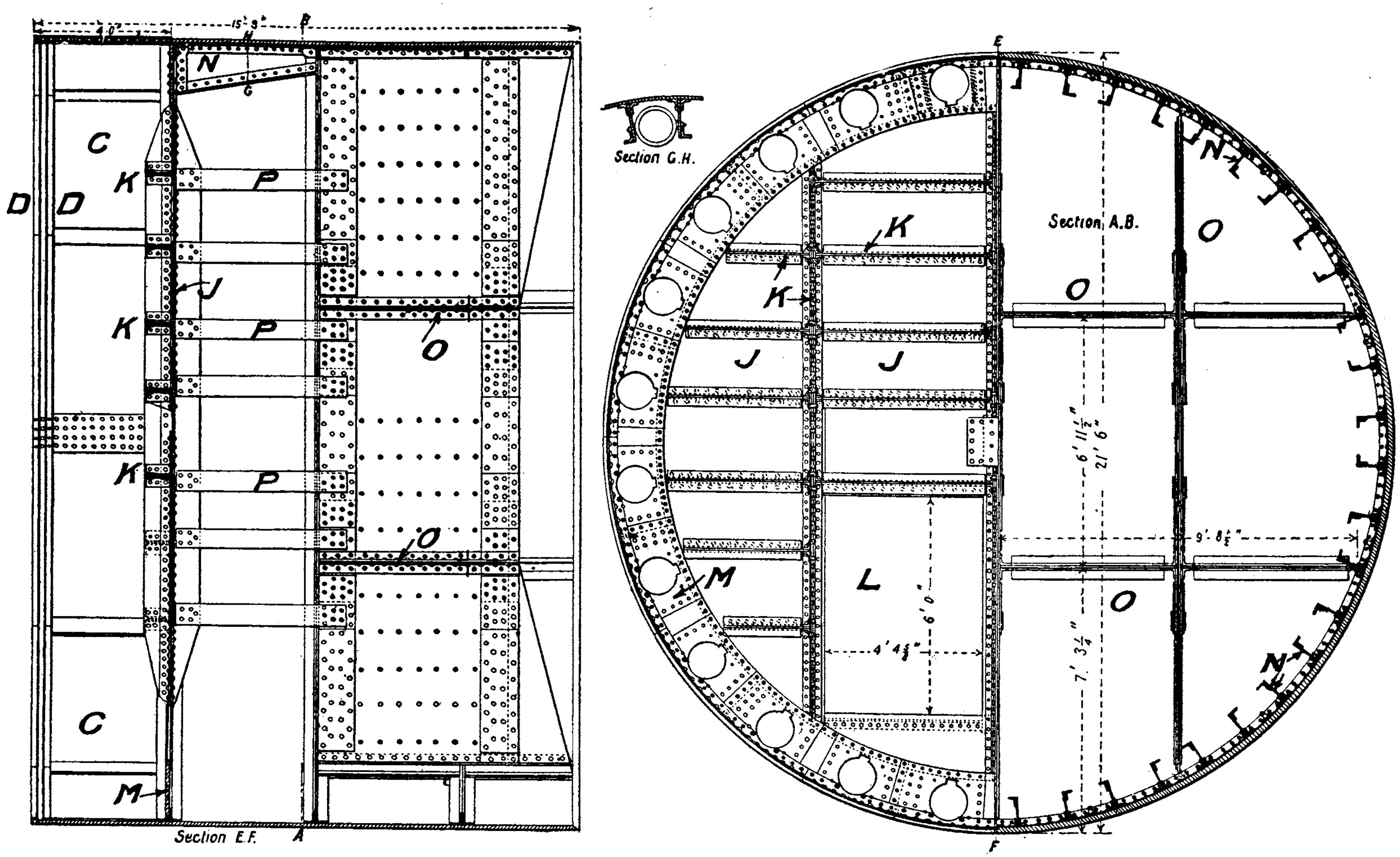


FIG. 107. ST. CLAIR TUNNEL, CANADA.
The Shield.

arrangement would, in addition to reducing the opening round the tunnel, aid also in reducing the amount of friction caused by either the tunnel or the shield being out of line, and so bearing heavily on one side or the other. It was not found possible, however, to keep the rubber from tearing out of its channel, and a metal ring was subsequently substituted for the rubber with satisfactory results.

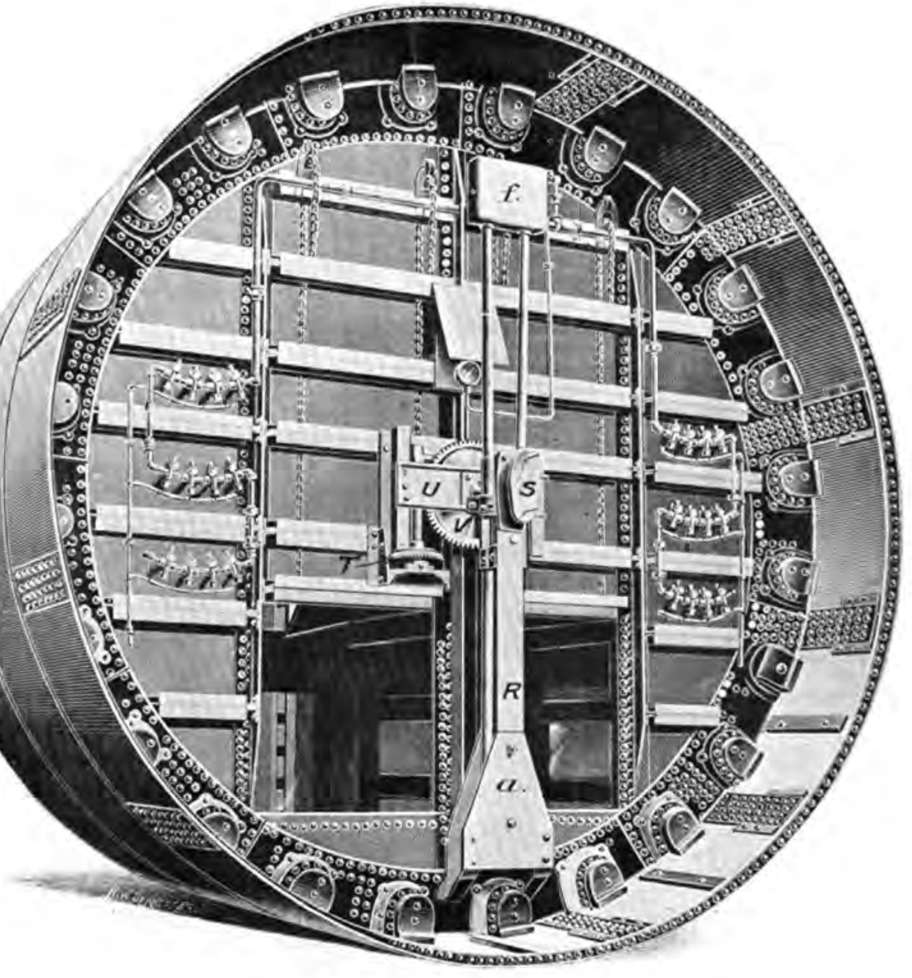


FIG. 108. ST. CLAIR TUNNEL, CANADA.
The Shield. Back View, showing Erector.

The main bulkhead or diaphragm J of the shield consisted of plates $\frac{1}{2}$ inch thick, and was placed 4 feet from the tail of the shield, and at the junction of the two rearmost rings of the cylindrical skin, and to the angle irons forming the joint between which it was secured. It was further stiffened by three vertical and seven horizontal girders K, K, K, made of plates and angles (see Fig. 107).

This bulkhead was closed except for the openings through which the rams for driving the shield passed, and also for two openings or doors L, L, at its lower part which could, however, if required, be closed by sliding doors suspended above them.

These openings were 6 feet high by 4 feet 6 inches wide, and were provided with girders in which the sliding doors worked, and made practically air-tight joints when the doors were down.

The position of these doors at the bottom of the shield does not appear very satisfactory. In the case of a sudden blow in the face it is likely that they would be choked before the miners working in the upper part of the face could possibly escape. At the Blackwall and Hudson tunnels, in both of which shields with closed diaphragms were used, openings were provided at the level of each working platform to provide for this contingency.

Fortunately the necessity of closing the doors never arose at the St. Clair tunnel.

To compensate for the weakening of the diaphragm by the openings for the rams, an extra plate *M*, 16 inches wide and ½ inch thick, was rivetted all round the diaphragm, which was further strengthened by the gussets *N*, *N*, rivetted to the front of the diaphragm and to the cylindrical skin, and carrying the rams, twenty-four in number.

The tail of each cylinder was fitted in a ring bolted to the gussets, and the head was flanged and bore against the main bulkhead. The rings are shown in the section *G*, *H* (Fig. 107), and the flanged heads are seen clearly in the detail drawing in Fig. 109.

About 4 feet in front of the bulkhead, the shield was stiffened by three vertical and two horizontal girders *O*, *O*, *O*, all of which served to stiffen the shield, and the latter of which formed working platforms. It will be seen from the section *E*, *F*, in Fig. 107, that by this arrangement an open space 4 feet wide was provided between the working platforms and the bulkhead, thus enabling the miners to cast the spoil from the face down into the invert in front of the doors in the bulkhead.

A peculiar feature in the shield was the securing of the bulkhead to the vertical girders by straps of wrought iron *P*, *P*, *P*, 4 feet 9 inches long, 7 inches wide, and ½ inch thick. These were intended to support the bulkhead or diaphragm in the event of an inrush of water or material, when of course, if the doors in it were closed, the pressure to be sustained would be very great.

The straps in question were useless as stiffeners of the shield: had the vertical girders been carried back to the main diaphragm or bulkhead, the shield would have been much stronger.

It was found in actual work that these shields required, in addition to the stiffening provided by these vertical and horizontal girders, considerable timber framing in each of the working chambers formed by the girders.

Probably the dividing up of the skin of the shield into four rings, with three cylindrical joints, and the coincidence of two of these joints with the rear of the bracing girders and the main diaphragm or bulkhead, respectively, thus leaving the ring between them entirely without support beyond that given by the gussets carrying the rams, had something to do with the lack of stiffness in the shield; the insufficient support provided for the cutting edge had also its effect, and no doubt the vertical and horizontal girders, or bracings were themselves somewhat wanting in stiffness, considering the material the shield had to pass through.

The rams used for driving the shield were of a pattern which has not been imitated, save in one or two French shields, since. The main rams were single acting, but provided with an auxiliary piston for drawing back the piston of the ram after the full stroke had been driven (see Fig. 109).

The main cylinder had a diameter of 8 inches, the auxiliary one a diameter of 2 inches, and, the pressure provided being about 1 ton per square inch, the effective thrust of each was 45 and 4 tons respectively.

The cylinders were of cast steel, and the pistons of cast iron, the head of the piston of the main cylinder being made with a projection on the outer edge, so as to bear only against the webs of the tunnel castings, and not against the flanges. The supply of water to the cylinder was so arranged that on the piston reaching the end of its stroke, the pressure was automatically lowered so as to avoid breaking the smaller piston. That this provision was necessary will be seen in reference to Fig. 109, by which it will be seen that without some such precaution the piston could have blown out of the cylinder.

The small cylinder was, so to speak, always under pressure ; when the valve of the main cylinder was open, it, the small cylinder, was forced to follow the greater pressure ; immediately the pressure in the main cylinder was cut off, the smaller one asserted its power, and the piston of the larger one was drawn back.

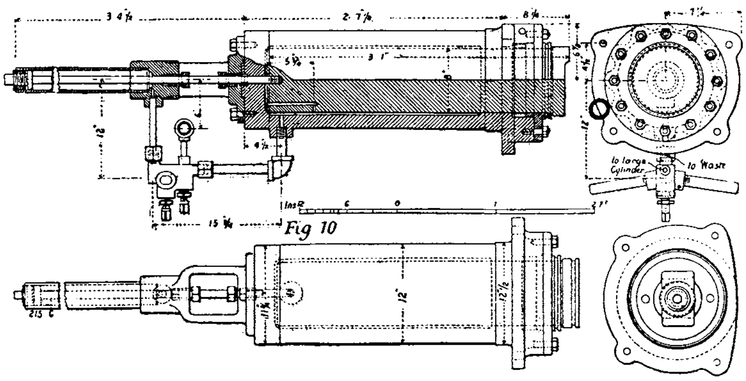


Fig. 109. St. Clair Tunnel, Canada.
Hydraulic Rams of the Shield.

This arrangement apparently gave satisfactory results, but has not been followed since in English and American practice, and elsewhere only in Paris, in a shield on the Orleans Railway extension, in another on the Metropolitan Railway, and in a third, when it was used with the curious twin rams of the roof-shield of the Meudon Tunnel, mainly on account of the inconvenience caused by the additional length occupied by the auxiliary cylinder, which amounted to 3 feet. By using a double action or reversing cylinder, the length of ram required is only that necessary for driving the piston in one direction, plus the 2 or 3 inches necessary for the water inlet at the other end. The only advantage gained by the use of a smaller auxiliary cylinder for drawing back the piston is that the amount of water required for the operation is much reduced.

The method of working the shields does not present any special features.

Work was carried on day and night, in eight-hour shifts, and it is said that there were employed in each working face seventy-five men, twenty-six of whom were engaged in excavation.

In good material—that is to say, when the clay appeared sufficiently stiff—excavation was carried on in front of the shield for a length of two rings of the cast-iron lining at a time and the shield then pushed forward, but usually the character of the clay was such that the shield followed close on the excavation and no unprotected area of face was allowed. Sometimes, indeed, as mentioned above, clay of so soft a nature was met with that it actually flowed through the shield, and, issuing by the doors in the diaphragm, was then first handled by the miners and loaded into skips. This was frequently the case when nearing the end of the headings which had been driven to ascertain the character of the material to be passed through, and which, having collapsed, were filled with ballast, and other porous material. In some of these cases the air pressure required to keep the tunnel dry was as much as 35 pounds to the square inch.

The ground in front of the shield was always tested about 8 to 10 feet ahead by means of shell augurs, and this precaution proved especially useful in enabling the men to detect in good time the presence of the natural gas already referred to as producing an ill effect on the miners' health.

It was found that the best tool for getting the clay, when, as was sometimes the case, it was very tough, was a scraper formed of a piece of hoop iron bent to a semicircle of about 6 inches radius and furnished at either end with wooden handles, much in the nature of a joiner's spokeshave.

The cast-iron tunnel lining is described on page 64, and for its erection a hand-worked erector was employed.

It was an arm or joist *R* mounted (see Figs. 108 and 110) on a pivot *S* fixed on the diaphragm or bulkhead of the shield, or rather on the vertical and horizontal girders which stiffened it.

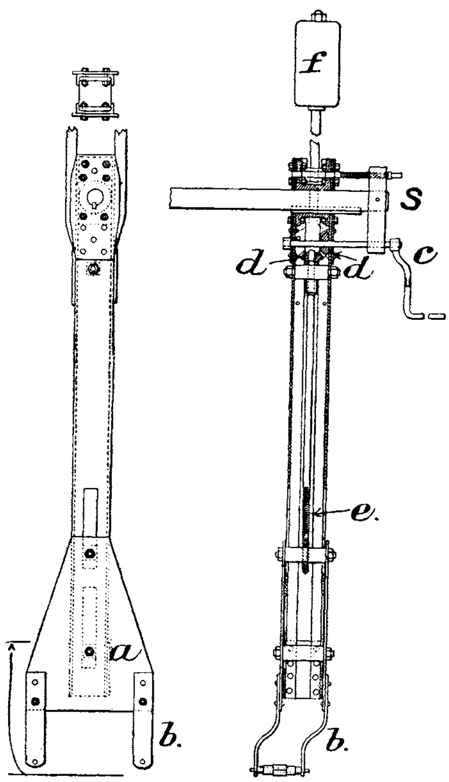


FIG. 110. ST. CLAIR TUNNEL, CANADA. Details of Erector on Shield.

This arm was made to rotate on the pivot by a handle inside the diaphragm of the shield which turned the wheel *T*, on the shaft of which was an endless worm *U* (behind the plate bracing shown in the back elevation, Fig. 108), which in turn revolved the wheel *V*, fixed on the pivot *S* of the erecting arm. By this arrangement the arm could be directed at any point in the circumference of the tunnel. The arm *R*, which is shown in a vertical position in Fig. 108, and details of which are given in Fig. 110, terminated in a head *a* provided with four arms *b*, *b*, *b*, between each pair of which could be secured bolts for lifting the segments.

A segment having been attached to the arm, it was lifted clear of the ground or of the trolley which had brought it, by turning the handle *c*, which actuated two mitre wheels, *d*, *d*, which turned the screw *e*, causing the head *a* to draw back towards the pivot *S*, bringing of course the segment with it.

The arm was then swung round by means of the gearing *T*, *D*, *V* (Fig. 108), and directed to the place where the segment was to be placed, when the head *a* was again advanced to push the segment into its place.

To facilitate the rotation of the arm, a counter balance *f* was fixed on it.

The vertical axis of the arm could be moved nearer to, or away from, the diaphragm of the shield by applying the handle *c* to the screw *g* which worked in the crosshead at the end of the shaft *S*, the other end of which was secured to the diaphragm.

A small detail in the working arrangements of the tunnel, due no doubt to the fact that especial accuracy in the alignment of the work was of first importance to enable the two shields to meet exactly in line, was the provision of a special lock or pipe 1 foot in diameter through the bulkhead in which was the airlock, for setting out the centre line. For this purpose this pipe, fitted with valves at either end, had near its extremities fine wire " cross hairs " similar to those in a theodolite, and, like them, capable of accurate adjustment, and thus serving as the change points whereby the line outside the pressure chamber could be transferred within.

The Blackwall Tunnel (1892)[1]

This tunnel is constructed under the River Thames about one mile below Greenwich, and connects the manufacturing districts of Poplar and Blackwall, on the north or Middlesex side of the river, with East Greenwich on the Kent or south bank (see Fig. 111).

The river at this point is about a quarter of a mile in width, and the tunnel with its approaches is 6,200 feet in length. Of this total length 1,735 feet were in the open approaches, 1,349 feet in cut and cover tunnelling, and 3,116 feet in shield and compressed air work, this latter portion being lined with cast-iron segments.

The external diameter of the cast-iron lining is 27 feet,[2] and the internal finished diameter about 24 feet 8 inches, affording space for a roadway 16 feet in width, with a headway of 17 feet 8 inches, and two footways each 3 feet in width.

It is, therefore, much the largest and most important of the subaqueous tunnels constructed since the Thames Tunnel at Rotherhithe was built by Brunel in 1825–42, though tunnels of 30 feet internal diameter have been built in the London Clay, and it is only in the past year (1904) that the projected road tunnel also under the Thames at Rotherhithe, which both in diameter and in length will exceed it, has been commenced.

The material in which the tunnel was driven is for the most part water-bearing, and for nearly one-half the width of the river consisted of open ballast, the water in which was in direct communication with the river above, and as from considerations connected with the men's health it was deemed advisable to keep the tunnel within 80 feet of the high-water level of the river, the shield had to be driven in places within 5 feet of the bottom of the river, the work thus having, so to speak, to be carried on in the river itself. These conditions were successfully overcome, and the record of the operations is an important part of the history of subaqueous tunnelling.

Fig. 111 shows the longitudinal section of the tunnel, and it will be seen that,

[1] *Proc. Inst. C.E.* vol. cxxx. The Blackwall Tunnel, by David Hay and Maurice Fitzmaurice. This paper is the main source of the information given in these pages.
[2] For details of the cast-iron lining see page 59.

in addition to the open approaches, access is obtained to the tunnel by means of shafts.

The open approaches, and the portions of the tunnel built by cut and cover work, were carried out in the ordinary manner, and the details of their construction do not come within the scope of this work, but the sinking of two of the shafts and the working of the shield was conducted entirely in compressed air.

There are four shafts in the line of the tunnel; Nos. 1 and 2 situated on the north side, and Nos. 3 and 4 on the south side of the river. Their positions were determined by the horizontal or vertical changes of direction of the tunnel, which was driven straight from shaft to shaft, the difficulty of driving the shield on a curve and the trouble and expense of special castings being thereby avoided.

The avoidance of curves in the tunnel was, no doubt at the time, a justifiable precaution, but, given sufficient ram power, the shield could have been driven without any great difficulty round curves with a radius of about 800 feet.

The caissons forming the shafts (see Figs. 112 and 113) are 48 feet in internal, and 58 feet in external diameter, and are formed of two skins, partly of steel, and partly of iron rings. The plates, forming the rings, generally 4 feet in depth, vary in thickness between $\frac{3}{4}$ inch at the bottom and $\frac{5}{16}$ inch at the top of the shafts; they are stiffened by belts of angle-bars, carried round inside at every lap-joint, and are braced together by horizontal and diagonal angle-bars. The lower portion is constructed of steel to 8 feet 6 inches above the cutting-edge, which is formed by bending the inner skin outwards to meet the outer skin, and is stiffened by a band 1 inch thick and 2 feet deep, running round the outside, and by

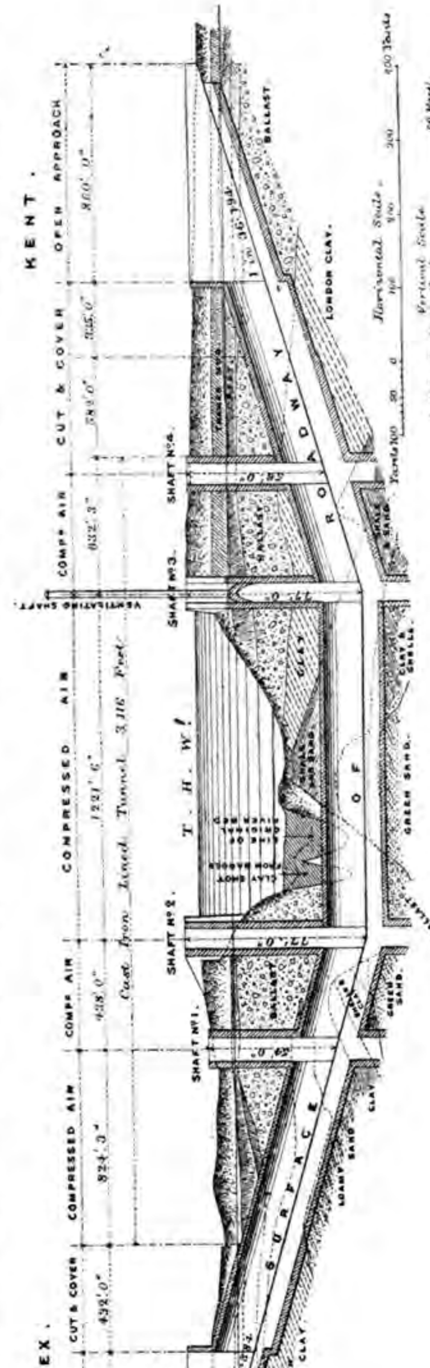


Fig. 111. The Blackwall Tunnel, London, Longitudinal Section.

vertical plate diaphragms between the skins (see Fig. 114.) The inner surface of the shaft is vertical, the inside plates of each successive ring being set at such an angle as to bring the upper edge of each into line with that of the plate below; the outer surface has a batter of about 1 in 100 due to the lap of the plate form-

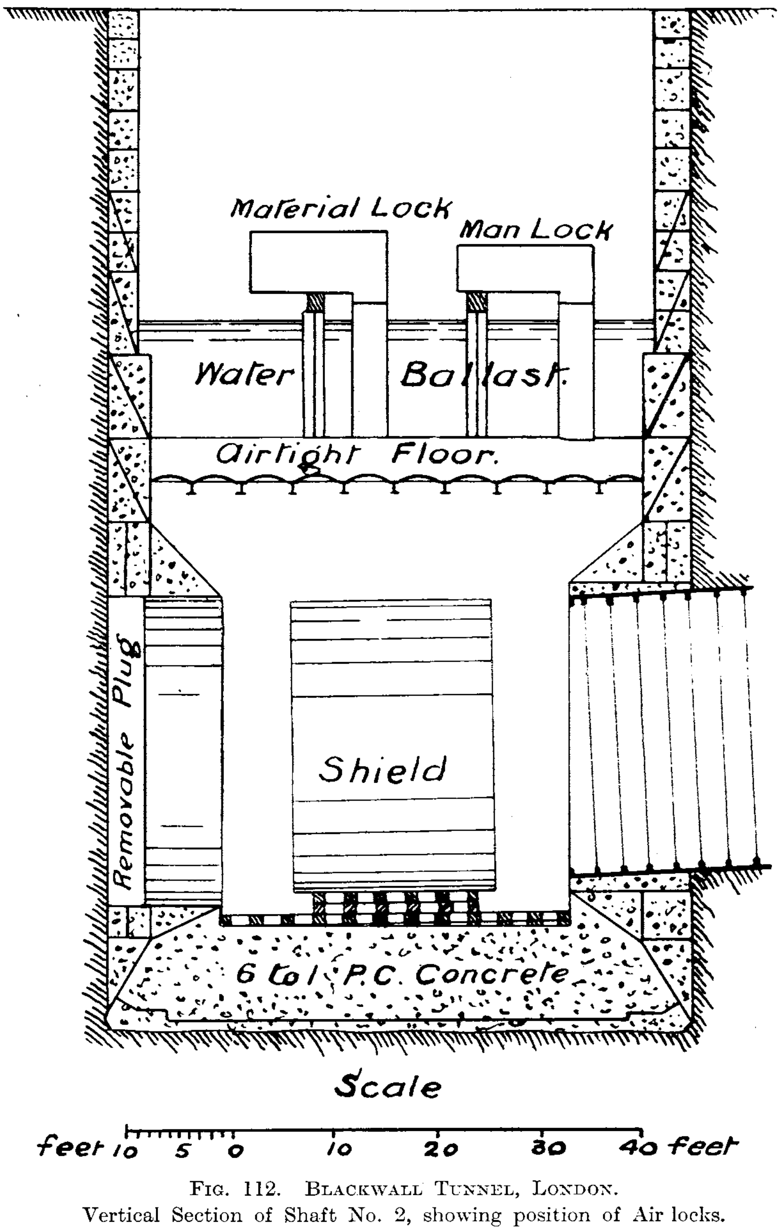


Fig. 112. Blackwall Tunnel, London.
Vertical Section of Shaft No. 2, showing position of Air locks.

ing the outside of each ring being vertical, and rivetted inside of the plate immediately below it.

It may be doubted whether a batter of 1 in 100 to the outside of such caissons is in any circumstances advisable, and perhaps some of the difficulties experienced in sinking the caissons at Blackwall were due to the considerable difference between the top and bottom diameters.

The Author's own experience at the Greenwich Tunnel under similar conditions as regards the nature of the strata passed through, was that caissons with parallel sides were entirely satisfactory, but in that case the employment of a second air-tight floor close to the cutting edge of the caisson, and the consequent placing of the kentledge used below the centre of gravity of the caisson, was also an important factor in keeping the caisson plumb during the process of lowering it.

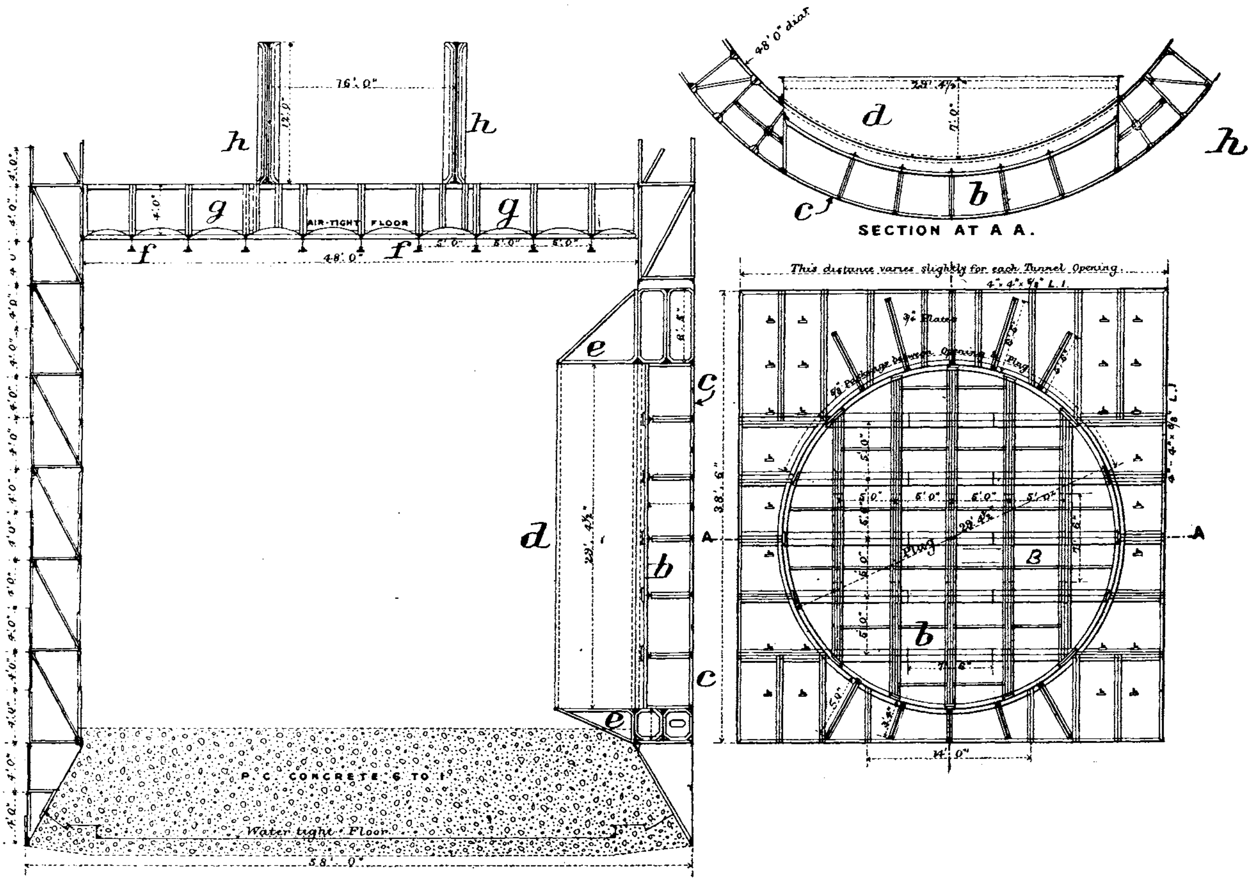


FIG. 113. BLACKWALL TUNNEL, LONDON.
Section of Shaft at Tunnel Opening.

Mr. E. W. Moir has suggested [1] that a better arrangement than that actually adopted would have been to have given an outside batter of 1 in 300, or to have made the lower part of the caisson, say for 20 to 30 feet above the cutting edge with the outside skin, truly cylindrical, the upper part being tapered.

Such a cylindrical length would certainly assist in keeping the caisson steady when going down, and, by being limited to a portion only of the shaft, would avoid the risk, always possible in making a large caisson with parallel sides, that the upper rings in the process of assembling and rivetting, by becoming distorted,

[1] *Proc. Inst. C.E.*, vol. cxxx. p. 80.

make one diameter of the upper part of the caisson larger than that of the cutting edge. The space between the skins, 5 feet near the cutting edge and reduced by the outside batter to about 4 feet at the top, is filled with 6 to 1 Portland-cement concrete.

When sunk to their proper depth the inverts of the shafts were formed of 6 to 1 Portland-cement concrete about 11 feet thick. In this was placed a skin or plating of wrought iron with the object of making the invert water-tight (see Fig. 113), but it was in no sense a structural support to the concrete, and still less a bracing to the shaft.

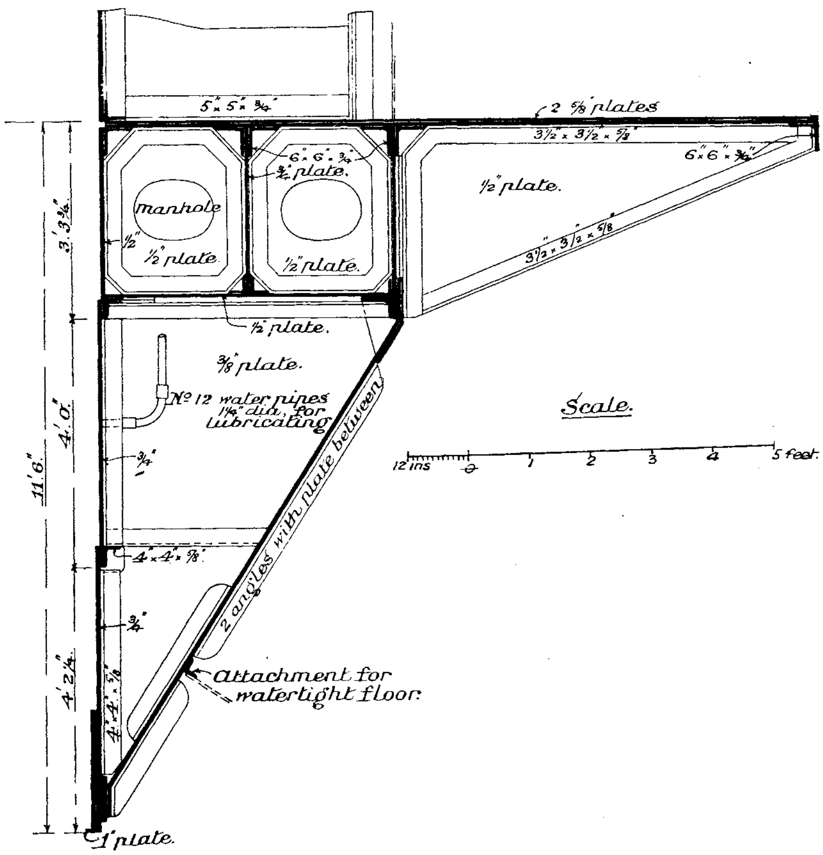


FIG. 114. BLACKWALL TUNNEL, LONDON.
Detail of Cutting Edge of Shaft.

During the process of sinking the caissons, brackets formed of plates and angle irons were attached to the inside plates of the cutting edge to serve as bearings from which the caisson could be held by timber packings from foot-blocks on the bottom of the excavation.

In each shaft two openings were provided through which, when the shaft was sunk to its full depth, the tunnel could be constructed. During the sinking of the caissons these openings were closed by a "plug" or frame-work *b*, Fig. 113, consisting of girders, vertical and horizontal, having bolted to them plates or shutters *c*, *c*, which, when the plug was in position, formed a part of the external plating of the shaft. The girders were bolted to the sides of the opening, and the whole was made water-tight by wood packing and caulking, and in the circumferential joint by current caulking. The caisson itself is strengthened round these openings by extra plate diaphragms and bracings, and the circular plates forming the opening itself are extended into the caisson so as to form a hood *d*, the end of which is vertical, and which serves as a circular stiffening plate round the opening, to which numerous gussets can be fixed, as at *e*, *e*.

Provision was [1] made for attaching air-tight floors to the inner skin of caissons, above the level of the tunnel openings, for use either in sinking the shafts or constructing the water-tight floors should compressed air be found necessary, or when it was required in order to connect the tunnels with the shaft. The floor consisted of $\frac{5}{8}$-inch buckled plates resting on girders *f*, *f*, 18 inches deep; above these 4-foot girders *g*, *g*, were placed at right angles, the whole being surmounted by two girders *h*, *h*, 12 feet deep. The ends of the girders and the buckled plates were attached to the inner skin of caisson, which, in the case of the 12-foot girders, was strengthened by a $\frac{1}{2}$-inch doubling-plate to take up the shear. Stiff iron diaphragms or bulkheads were also built between the skins in the line of the two main girders. When the air pressure exceeded 20 pounds per square inch above atmospheric pressure, the upward thrust on the floor was relieved by 10 feet or 14 feet of water-ballast.

The use of one floor only for sinking the shaft, and subsequently for starting the tunnel work—or, if the shaft be one towards which the shield is driven, for completing it—has the advantage of economy in first cost over the use of two floors, one near the cutting edge for sinking the shaft, and the other above the tunnel opening, as in the case shown in Figs. 152 and 153, for the subsequent work, but for convenience of working, and easy control of the caisson, during sinking, the provision of a second or lower floor is to be recommended. The fact that by its use, the centre of gravity of the kentledge employed is kept below the centre of gravity of the caisson itself, makes for stability, and of course, the lower the floor is placed, the greater is the amount of kentledge which can be loaded on it. The cost of fitting such a floor would have been, in the case of shafts of the size of those at Blackwall, about £2,000, against which, however, must be set the cost of the water-tight plating subsequently used in the concrete in the invert, which with a second lower floor would be unnecessary.

A further cost, however, is that of the extra depth of shaft necessary with the second floor, and some idea of this may be obtained by comparing the Blackwall caisson in Fig. 112 with the Greenwich one in Fig. 152. In the latter case the extra depth required for the lower floor involved an expenditure of £1,500 extra in the shaft, and the floor itself cost an equal amount. But when all these considerations are allowed for, the lower floor is to be recommended in all cases where compressed air is likely to be required.

At Blackwall water was used for kentledge, and there, as elsewhere, the ease with which it can be put in or taken out of the caisson, and its utility when in, in limiting the escape of air through the air-tight floor, made it very convenient in application. Its use, however, has one drawback, and that is, that in case of a sudden settlement of the caisson on one side, the rapid adjustment of the water to the new levels tends to increase the load on the side where the settlement has taken place, and so to aggravate the fault.

[1] Originally a lower second floor at the cutting edge was proposed, but cut out at the wish of the contractors.

Pipes were provided in the caissons by which water under pressure could be forced outside them near the level of the cutting edge with the object of "lubricating" the outside surface and so facilitating the sinking, but the results obtained were only meagre.

The shafts on the south side of the river were sunk by pumping down the water and removing the excavation from the inside in the ordinary way. The weight of caisson and concrete filling was generally sufficient to overcome the skin friction, until about 20 feet from the bottom, when more weight had to be temporarily added. The sinking of No. 4 shaft was accomplished without difficulty, the ground being good and almost cleared of water by the pumps for the cut-and-cover portion and the open approach about 200 yards distant; and, as very little water was found below the London Clay, it was possible to construct the water-tight floor in the open. Considerable trouble was, however, experienced in dealing with shaft No. 3 at the river bank. The ground for about 25 feet of the lower part of the shaft was found to be composed of fine sand, and numerous "blows" were caused by the head of water in the ballast above (charged afresh by every tide), washing in large quantities of gravel and sand. The ground was of such a heavy clinging nature that the caisson was often stationary for several days, although the cutting-edge was free and the structure was heavily loaded; and it was not until a blow occurred, the movement of the ballast decreasing the skin friction, that further downward progress could be made. The caisson was at one time 14½ inches out of level, and various expedients were tried to induce blows on the high side in order to correct it. The best results were obtained by striking heavily on the inside of the shaft with a baulk of timber swung horizontally from a girder above. Considerable subsidence of the surface was caused by the sand and gravel entering the shaft; the wharf wall completely disappeared, leaving the river free to surround the caisson at every tide and to find its way through the numerous cracks in the London Clay to the heading of the advancing tunnel. Some damage was also caused to some buildings 40 yards distant.

As all the weight had been placed on the skins for which room could be found, the girders of the air-tight floor were fixed and loaded; better progress was then made, and when the top water was cut off no difficulty was encountered in dealing with the springs in the sand below the London Clay; the floor was therefore constructed, as in the case of shaft No. 4, without the aid of compressed air. In both floors the suction-pipes of the pump were carried through the iron water-tight floor near the bottom of the concrete, and, after ascertaining that no sand was being drawn out with the water, pumping was continued until the concrete was thoroughly set, when the valves, which had been provided in the suction-pipes near the top of the concrete, were closed. The friction on the outside skin for the last 20 feet in the case of No. 3 amounted to about 5·6 cwt. per square foot, the cutting-edge being entirely free. Little or no reduction of friction resulted from the outside batter in this case, as there is little doubt that the ground closed in almost instantaneously as the caisson descended. As it is sunk upon private property this shaft is covered by a dome, the inner skin of the caisson being set back about 34 feet below the surface to form a springer. A chimney 70 feet high is built on the centre of the dome for ventilation, and to prevent fumes from a neighbouring tar distillery above from entering the tunnel.

On the north side of river No. 2 shaft was sunk, behind a new river wall, Fig. 111, which had been built to reclaim part of the foreshore. From borings taken round the site it was ascertained that the whole of the ground to be penetrated consisted of ballast; and to avoid the difficulty and delay experienced on the south side, it was decided to employ a grab for the excavation, allowing the water to remain inside. The grab was worked by a 10-ton crane supported on girders inside the shaft; and, as the material was removed, the caisson was forced down by weighting it heavily, in addition to the concrete, with tunnel castings distributed round the top and on special brackets attached to the inner skin. The total weight of the caisson and sinking-load amounted to nearly 4,000 tons, the skin friction being therefore about 4½ cwt. per square foot of outside surface. Trouble was found at first in working the grab on account of the twisting of the long wire ropes; flat ropes were therefore substituted, and no further difficulty arose, the rate of sinking averaging 1 foot in twenty-four hours.

As it was not practicable to construct the floor without the aid of compressed air, the water was pumped down, after the caisson had reached its correct level, sufficiently low to admit of the air-tight floor being fixed. Divers were, however, previously employed to fix stools on the inner skin of the cutting edge, and packings were inserted beneath to prevent further sinking of the shaft in consequence of the lowering of the water. Clay bags were also placed round the cutting-edge to prevent any ballast running in. When the air-tight floor was completed, the water remaining inside was partly blown and partly pumped out, and the work of constructing the floor proceeded. An air pressure of 35 pounds to 37 pounds per square inch, the highest employed on any part of the work, was necessary to dry the ground at the cutting-edge. Although this shaft was sunk within 6 feet of the river-wall previously referred to, no crack or settlement of any kind was caused.

The first 28 feet of No. 1 shaft were sunk in the same manner as Nos. 3 and 4, but on reaching this depth, large quantities of water were encountered, and the grab system was again used. This method was continued until the cutting-edge had passed through the ballast and sufficiently far into the clay below to cut off the top water. The water inside was then pumped out and manual labour was again employed. It was found, however, that the caisson was not sinking uniformly, owing, no doubt, to some part of the ground offering more resistance to the cutting-edge than others, and additional weight had, therefore, to be placed on the high side. The continual rocking of the caisson, due to its falling out of level and being corrected by weighting, no doubt broke up the ground to a certain extent, and, in addition, the shaft would probably carry down some ballast with it in sinking. The effect was a serious blow under the cutting-edge, and the shaft was again filled with water. As the air-tight floor was not in position, it was decided to provide a sump outside in order to lower the head of water, that inside the shaft being meanwhile allowed to rise. The sump was sunk to a depth of 34 feet, and the head of water lowered about 20 feet. The water in the shaft having been pumped out, preparations were made for constructing the floor as in shafts Nos. 3 and 4, but on clearing out the bottom, the ground was found to be too soft to support the weight of the caisson, which began to sink, although the packings were in position under the stools. The construction of the floor in the open was abandoned, and, on the completion of the air-tight floor (which had meanwhile been proceeded with), it was carried out under an air pressure of 28 pounds per square inch.

Although in uniform strata, such as that found in No. 2 shaft, the grab may be employed with good results, the control of the structure is imperfect, and it is extremely difficult to maintain it vertical in sinking. The same remark may apply to sinking without compressed air in variable material where water is encountered,

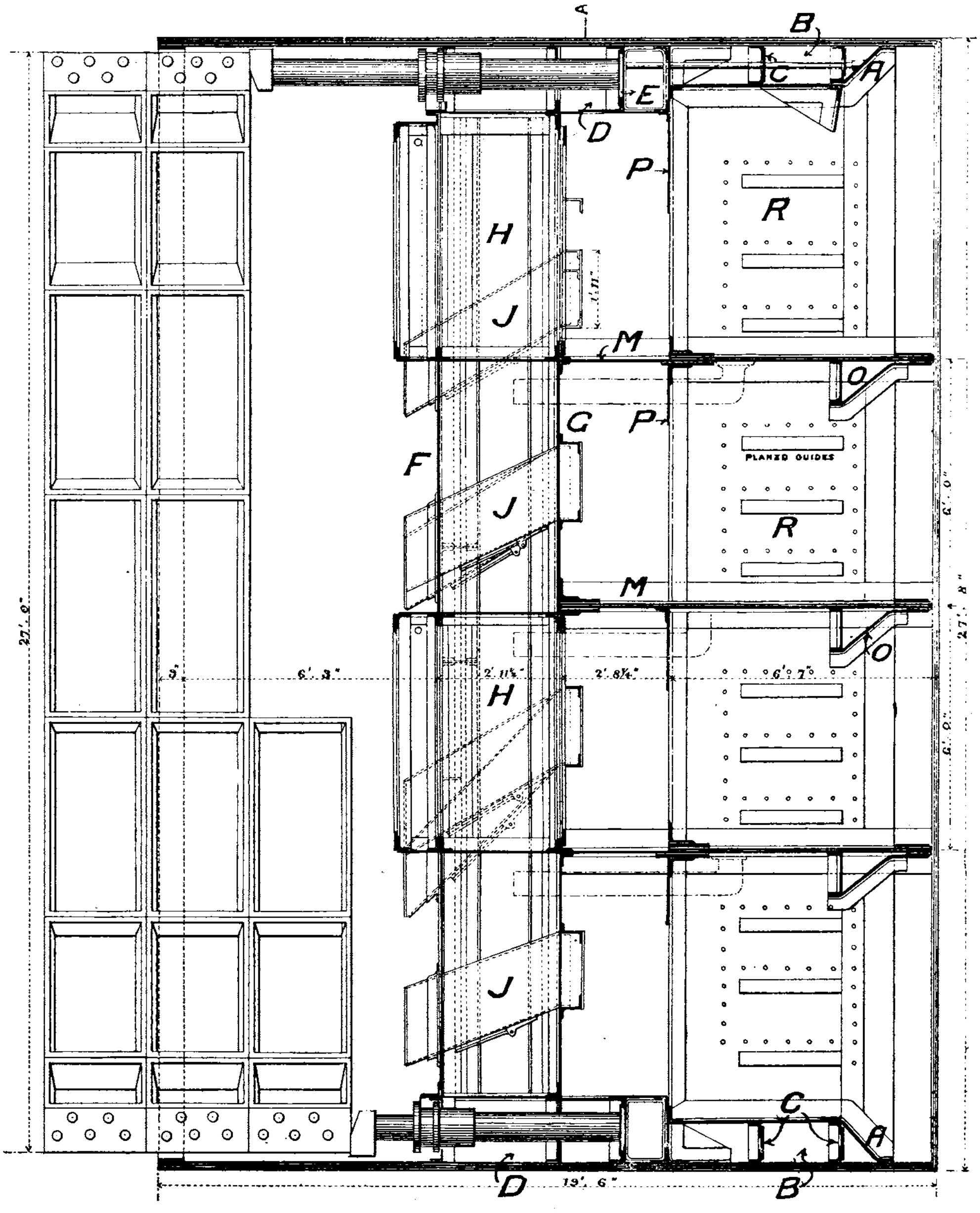


FIG. 115. BLACKWALL TUNNEL, LONDON.
The Shield: Longitudinal Section.

because bad ground immediately becomes softened by the water and the caisson falls out of the vertical before measures can be taken to prevent it. With compressed air, however, the difference between what is known as "good" and "bad" ground may disappear altogether, and it may even be that what is bad ground in the open is good working material in compressed air ; as, for example, wet sand, which in the open air is perhaps the most treacherous of all materials in mining work, but when partly dried by compressed air, is the easiest of all kinds of excavation.

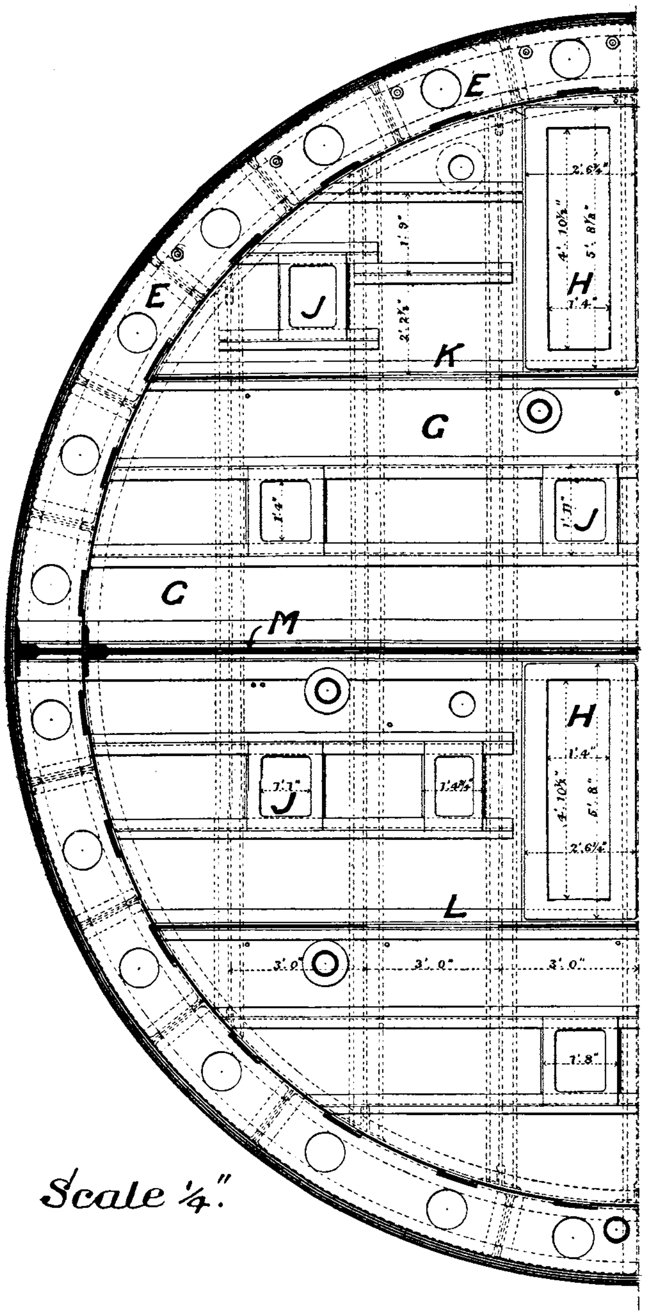


FIG. 116. BLACKWALL TUNNEL, LONDON.
The Shield : Half Cross Section.

The caissons, when the work of construction was complete, were finished internally with a lining of brickwork, the invert being composed as shown in Fig. 112, of about 11 feet of cement concrete above and below the wrought iron water-tight floor.

In two shafts, Nos. 1 and 4, circular staircases are placed ; in shaft No. 2, the necessary pumps for the drainage of the tunnel are fixed, and shaft No. 3, as stated above, was, on the completion of the tunnel, arched over, and only a brick ventilating chimney marks its place on the surface.

The actual work of driving the tunnel under shield, and with compressed air as distinct from cut and cover work, was commenced at No. 4 shaft in the south or Kent side of the river. The determination of the depth at which the tunnel could be safely and economically driven was matter for very serious consideration, and the position of the tunnel was ultimately fixed partly by engineering and partly by traffic considerations.

It was not possible on the north side of the river to extend the approach beyond the East India Dock Road, nor was there room, owing to docks and other properties, to improve the gradient between this road and the river by "development," or lengthening of the approach. It followed therefore that the gradient on that side accepted as necessary for the accommodation of the traffic determined the depth of the tunnel below the river.

It was found that with a ruling gradient of about 1 in 35, the tunnel, for which 27 feet had been fixed as the minimum external diameter capable of accommodating wheeled traffic, would have to be constructed with its invert about 80 feet below highwater mark, and with the crown about 5 feet, at the worst place, below the bed of the river.

This depth of 80 feet below high water was satisfactory from another point of view, namely, the capacity of miners to work under the air pressure corresponding to that depth. It was judged by the engineers, though subsequent experience proved that there was considerable difference between the theoretic and actual air pressure required, that the pressure of 35 pounds, corresponding to the 80 feet of depth decided on, was the greatest air pressure per square inch which, on general grounds of the men's health, cost of work, etc., could be considered economically safe.

The nature of the ground to be passed through was known as well as is usual in such cases by means of borings and dredgings in the river, and in preparing plans for the shield the Contractor's Engineer, Mr. E. W. Moir, to whom the design is chiefly due, had before him the fact that he had to design a shield which would have to cope in turn with clay, with water-logged sand and ballast, as well as with the various hard strata known as the Woolwich beds.

This facility of working in whatever kind of material was met with, was the first condition of a successful machine.

It was also, bearing in mind the variable nature of material anticipated, necessary to make the frame of the shield of sufficient strength and with stout bracing to resist unequal pressure on its outside cylindrical skin, as well as in front, without interfering unduly with the miners' access to the working face. How strong the shield had to be is best shown by the fact that the total thrust of the shield rams amounted to over 5,000 tons, and that this pressure was actually employed in driving the shield through the water-bearing ballast.

This was done by making the cylindrical casing of the shield a circular box girder for the greater part of its length, and by placing within the double cylinder so formed vertical and horizontal girders, which latter also served as working platforms strongly framed together, as well as two vertical diaphragms each completely closing, except for the working doors, the whole area of the shield. These diaphragms served also to protect the tunnel behind from any irruption of water from the face, and also when the shield was designed, were intended to accommodate air locks, it being at one time intended to work the shield with a different air pressure in the front to that in the tunnel itself, and in the upper compartments of the shield as compared with that on the invert. This, however, was never actually done, the practical difficulties in the way of maintaining differential pressures in compartments in close proximity to each other, and both communicating with the same face of material, being found insuperable.

But though these two diaphragms were useful only in strengthening the shield, the removable diaphragm formed of numerous independent plates or shutters, provided at the front end of the shield, by which, when required, practically the whole face of the shield could be closed, proved of the greatest possible utility, and the success of the work may be said to be due as much to facility of working on bad ground which the provision of the shutters allowed, as to any other feature in the machine.

In the Hudson River Tunnel a similar arrangement of shutters was proposed, and provision made for them in the shield; they were, however, never actually used, the silty material met with there not calling for their employment.

The curtain plates provided at the face under the main horizontal girders were also similar to those of the Hudson River shield.

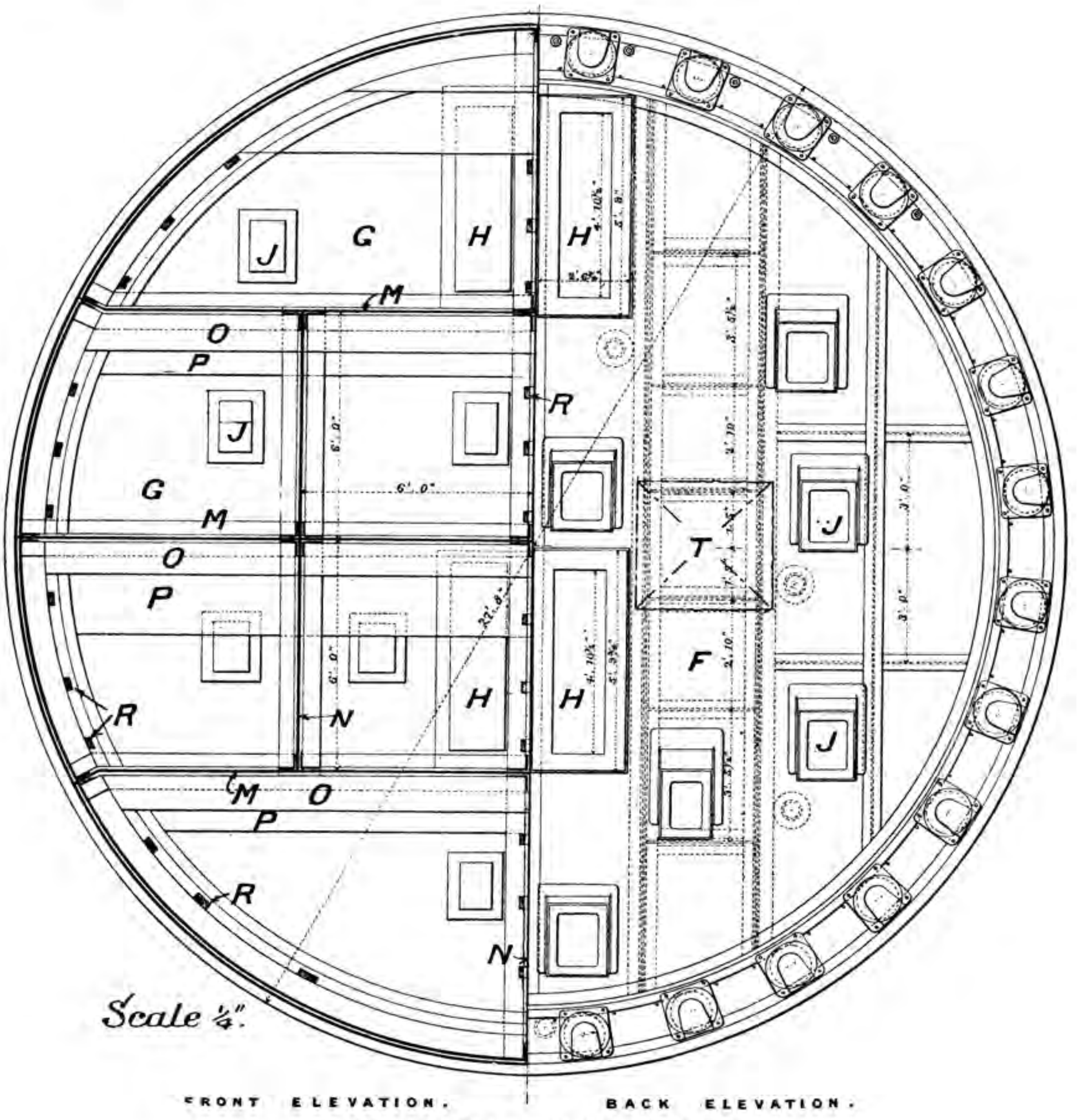


FIG. 117. BLACKWALL TUNNEL, LONDON.
The Shield: half front and back elevations.

The details of the shield are shown in Figs. 115 to 120, 122, 123, and 124.

Its total length was 19 feet 6 inches and its outside diameter 27 feet 8 inches. The skin consisted of four thicknesses of $\frac{5}{8}$ inch steel plates. The plates were made the same length as the shield, and in each layer they broke joint with the plates above and below them. There were twenty-eight plates in each layer, the width of each plate being therefore about 3 feet.

The rivets in the skin plates were $\frac{7}{8}$ inch in diameter and $3\frac{1}{2}$ inches pitch, all having countersunk heads on the outside.

The front ends of these plates were bevelled off to form a cutting edge,[1] and at the rear end of the shield a steel strip, 3 inches wide, was rivetted on the inside so as to form a ring which partially closed the space between the skin and the cast-iron tunnel lining, and so reduced the escape of air, as well as, in some measure,

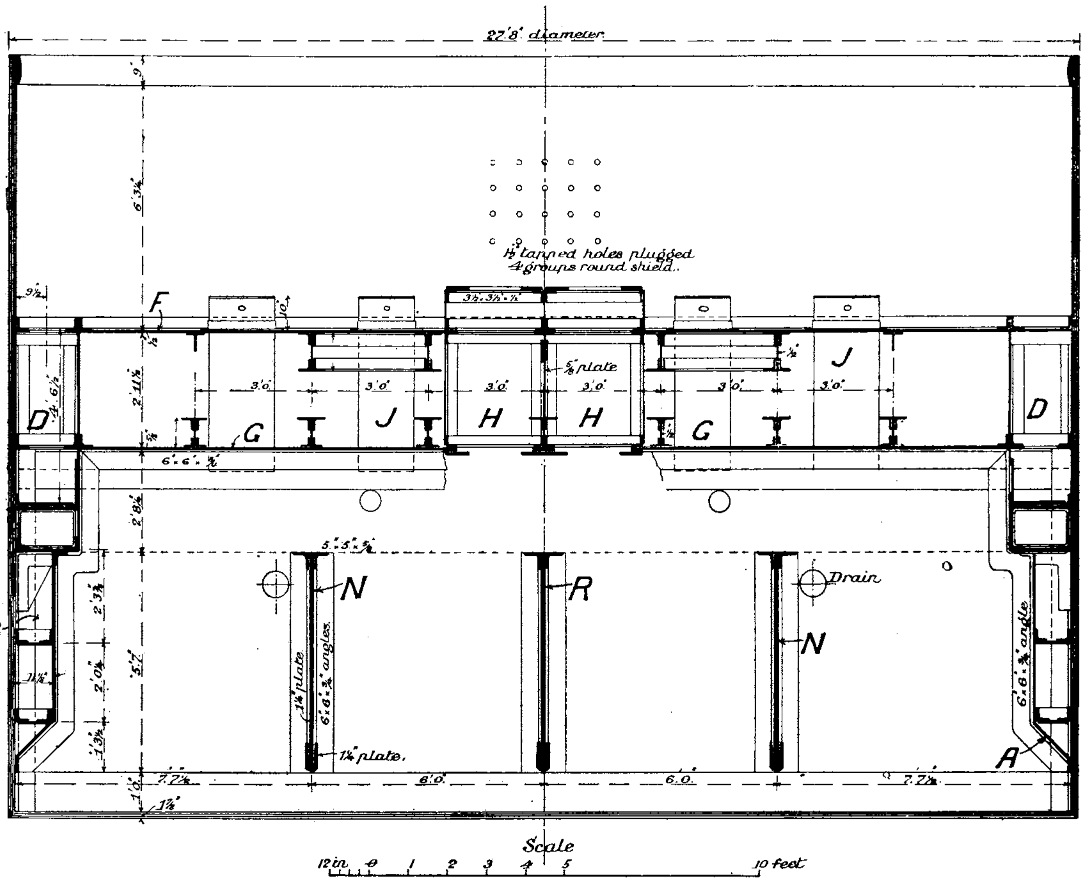


FIG. 118. BLACKWALL TUNNEL, LONDON.
The Shield: sectional Plan.

the friction between the two surfaces when the shield was being driven forward, particularly during a change of direction.

The actual cutting edge was formed of the skin of the shield only, but about 12 inches from the front it was supported all round by inclined plates *A A*, which sloped outward from the inner flange of the circular box girder *B*, *B*. This box girder, the rear end of which was 6 feet 7 inches from the cutting edge, consisted of a ring of $\frac{7}{8}$ inch plates connected to the skin of the shield by plates *C*, *C*, also of $\frac{7}{8}$ inch

[1] This cutting edge was subsequently strengthened by the addition of a $\frac{5}{8}$ inch strip on the outside, see page 209.

plate, which extended completely round the shield. The inside diameter of this box girder was 25 feet 3 inches in diameter, and its length 4 feet 3 inches.

Behind this was another similar but deeper circular box girder *D, D*, which contained the rams for forcing the shield forward, to accommodate which the two rearmost of the gusset plates in the box had holes cut in them, the rams bearing on the front gusset *E*. The internal diameter of the box girder *D* was 24 feet, and its length 6 feet, the plates being ⅝ inch thick.

The remainder of the skin forming the tail of the shield, 6 feet 8 inches in length, was unsupported. It will be seen, however, that of the total length, 19 feet 6 inches, of the shield, as much as 10 feet 3 inches, or if the sloping plates *A, A*, be included, 12 feet 7 inches is contained in a double cylinder formed of a circular box girder, divided longitudinally and transversely into cells by the gussets *C, C*, and *E, E*. There are, it is to be noted, no cross joints in the skin of the shield, nor, except at the junction of the boxes *B* and *D*, in the inside frame.

The framing inside this double cylinder was of equal solidity. About 6 feet 8 inches from the rear ends of the shield was a solid diaphragm *F*, composed of plates ¾ inch thick, and 3 feet in front of this again a second similar diaphragm *G*. These completely divided the working face of the shield from the tunnel, the only apertures in them being the air locks *H, H*, and the shoots *J, J*, which could all be closed and worked as airlocks in case it was necessary to work with a higher air pressure in the face of the shield than in the tunnel.

It will be noticed that while there are twelve shoots *J, J*, or one to each working compartment in the shield, there are only four large airlocks, two in the first platform, and two on the uppermost. Access to the invert and to the second floor was provided, however, by manholes at *K* and *L* (Fig. 116) respectively, and after the idea of working with differential pressures in the shield and in the tunnel was abandoned, some of the plates at the bottom of the diaphragms were removed and direct access thereby given to the invert at the face from the tunnel.[1]

In front of these diaphragms the shield was stiffened by three horizontal girders *M, M, M*, and three vertical ones *N, N, N*, securely rivetted to the circular box girders and to each other, this forming a rigid frame 9 feet 3 inches long.

The horizontal girders were further stiffened by the frames *O, O, O*, which formed a kind of curtain under each.

To these horizontal girders, as well as to the crown of the shield, were attached curtain plates *P, P, P*, which were intended to serve as a protection to the men working at the face in a higher pressure than that in the tunnel.

The sliding shutters for closing the face of the shield were, when in position, in a line with the rear end of the frames *O, O, O*, their ends sliding on the planed guides *R, R, R* (Fig. 116), fixed on the vertical girders *W, W, W*. Fig. 119 shows their arrangement in the face of the shield, and Fig. 120 the details of the construction of one of those in the central compartment. From Fig. 119 it will be seen that the area of the face through which material could pass when the shield was being pushed forward amounted to 380 square feet, the total area of the shield front being 600 square feet.

There were in all thirty of these shutters, of varying length, and generally 1 foot 6 inches in depth. Each consisted of a ⅝-inch iron plate, stiffened at the edges by heavy angles, 6 inches by 4 inches by ⅝ inch, and sliding on guides fixed

[1] Drain pipes, shown in dotted lines in Fig. 115, were also provided for carrying away water from each floor.

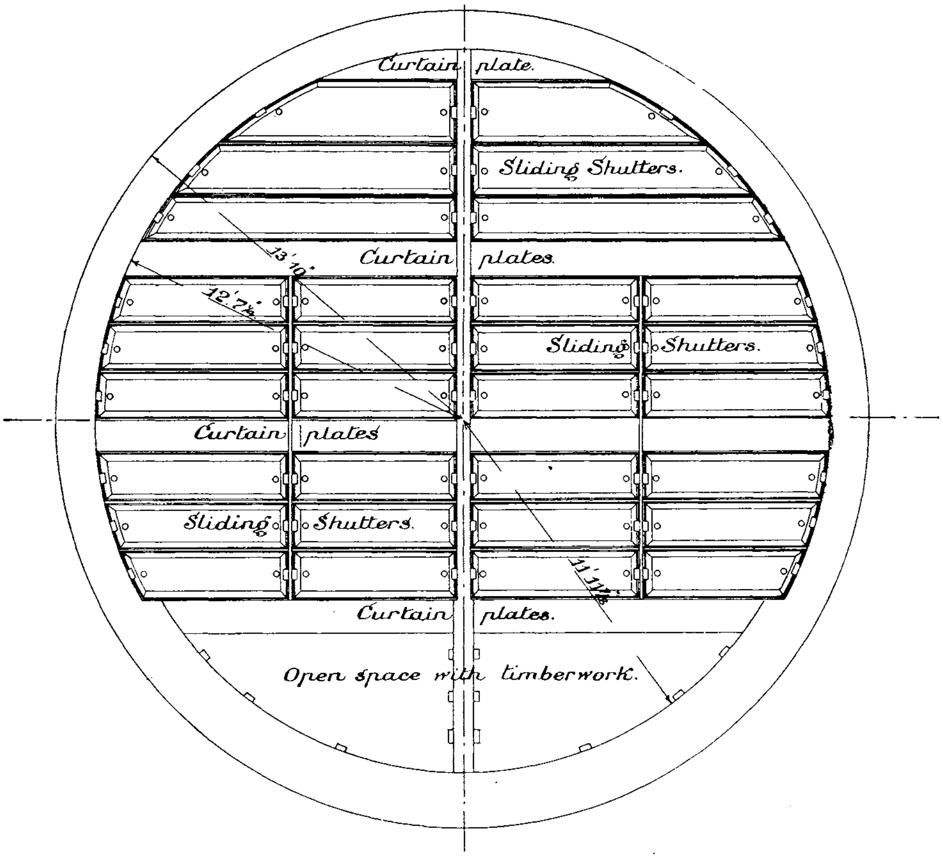


FIG. 119. BLACKWALL TUNNEL, LONDON.
The Shield: Sliding Shutters of the Face.

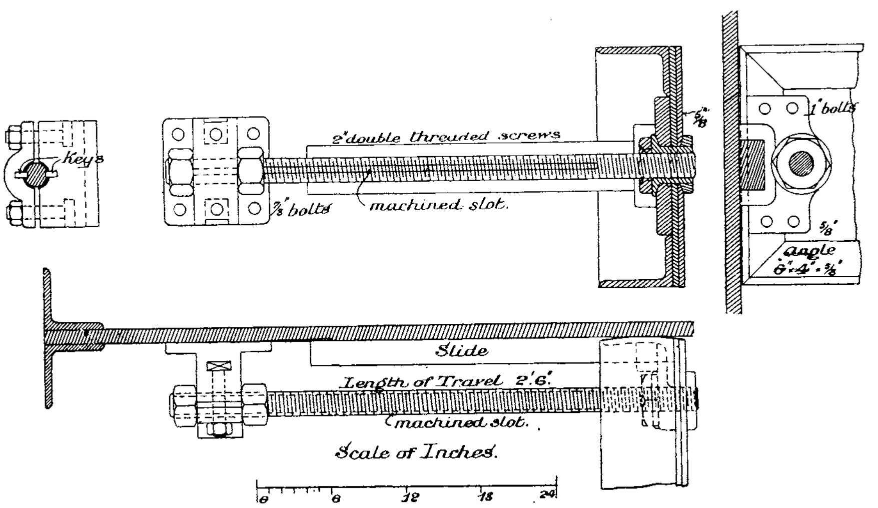


FIG. 120. BLACKWALL TUNNEL, LONDON.
The Shield: details of Sliding Shutters of the Face.

to the sides of the compartment. The shutters were controlled by long screws, fixed to their ends and extending through bearings on the side of the compartment. There were two slots machined the whole length of each screw, and two keys in each bearing ran in these slots, thus providing a means of graduating the rate of movement of the shutters if necessary. Two nuts running on the screw, one on each side of the bracket, made it possible either to shove forward or draw back the shutter.

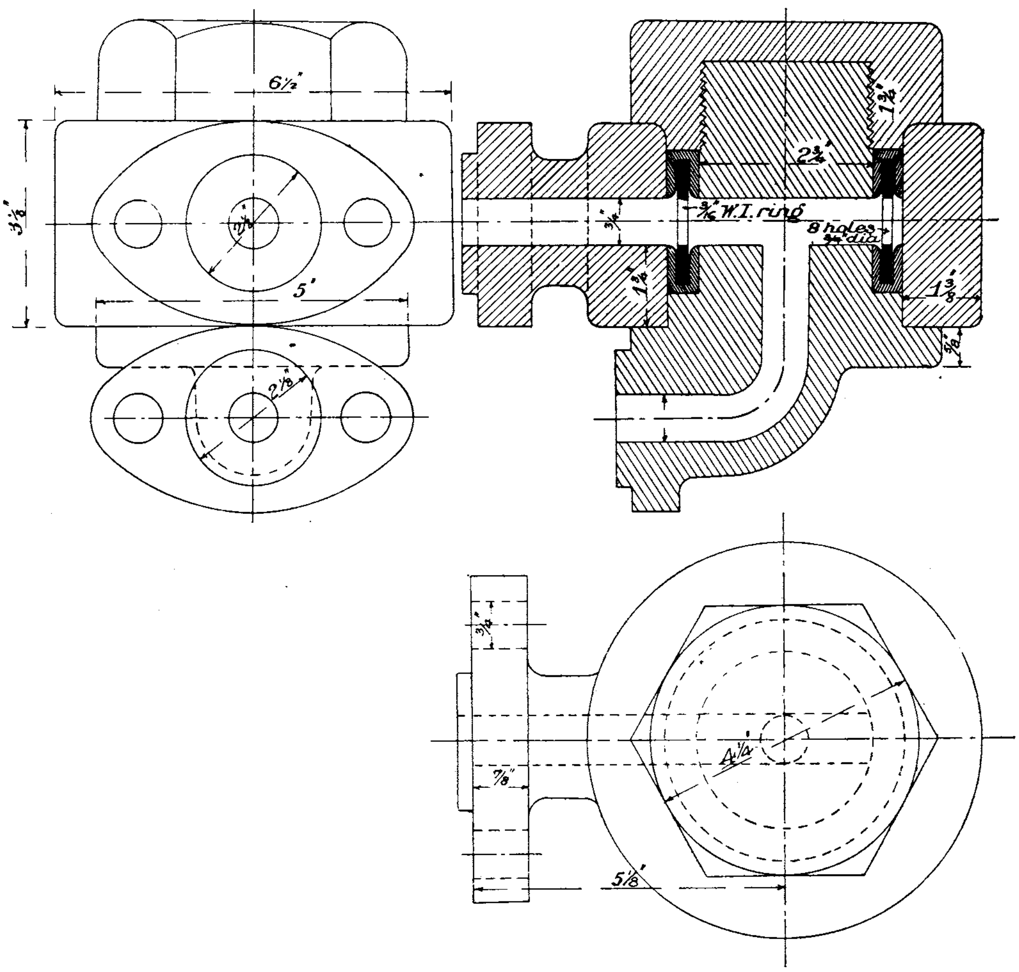


Fig. 121. Blackwall Tunnel, London.
"Walking Joint" for Hydraulic Mains.

The number of hydraulic rams originally provided for advancing the shield was twenty-eight; they were 8 inches in diameter and had a stroke of 4 feet; but while driving through the wet sand and ballast under the river this number of rams was found insufficient, and was therefore increased by six other rams, 10 inches in diameter, but with a shorter stroke. The maximum water-pressure used was about $2\frac{3}{4}$ tons to the square inch, or a total, when all the rams were employed, of 5,165 tons, making no allowance for the friction of the rams. The pressure was obtained direct from pumps on the surface and the water was conveyed to the shield by means of $1\frac{1}{4}$ inch steel pipe, to which, immediately behind the shield, a "walking joint" was fitted. The type of joint employed here, and in similar positions on the hydraulic erectors, etc., is shown in Fig. 121.

The pressure was distributed to the shield rams through nests of valves on the shield in the usual manner, save that the rams were arranged to work in pairs, that is there were only half the number of controlling valves which would have been required if each ram had separate pushing and drawing valves.

The rams were attached to the shield by bolts through the collar of the cylinder and the rearmost gusset *E* of the circular box girder *D*, the collar bearing solid on this gusset. The forward, or butt end of the cylinder bore on the foremost of the three gussets *E*, *E*, *E*, a packing block being fitted to the latter to give the end a good bearing (see Fig. 115).

The design of the rams, and particularly the arrangement for the drawback, whereby a defective leather in the glands could be removed without the necessity of unstripping the ram, is due to Mr. Moir, and is shown in Fig. 122.[1]

The cylinder and piston are turned out of wrought steel blocks.

The cylinder, which is 4 feet 9 inches over all, is 11 inches in external, and 8 inches in internal diameter, and the piston with a 4-foot stroke terminates in a head bevelled in the usual manner to ensure that its thrust should bear on the skin, and not on the flanges of the tunnel castings.

This piston was bored with a 3-inch diameter hole to within $3\frac{1}{2}$ inches of the end, the hole being closed at the front end by a brass plug in the ram head, thus making a second cylinder within the piston. In it was a steel tube, 2 inches in external diameter, which was screwed into the end of the cylinder, making a water-tight fit with the piston where it passed through its base.

On this 2-inch tube were fitted at either end U-shaped leathers, and at its front end a small cross hole connected the inside of the tube with the cylinder in the piston. At the other end of the tube it connected with the main hydraulic high pressure supply by means of the pipe and cross hole in the end of the cylinder.

It will be seen that pressure was supplied to the main cylinder at one end only by the pipe and cross hole *D*.

The pressure was maintained continuously in the small centre piston, so that, immediately water was allowed to escape from the main cylinder after using, the constant pressure in the smaller one forced the main piston back again automatically.

It will be seen, if repairs to the glands were necessary, that by removing the brass plug in the ram head, access could be obtained to the phosphor bronze nuts on the end of the 2-inch tube. These removed, the leathers could be removed from and replaced in the piston without removing the entire cylinder from the shield.

The smaller auxiliary rams added after the shield had started were of the same type, Fig. 123. As they could not be fixed permanently to the shield, owing to lack of space, they were employed in the invert and bore against the rearmost gusset *E* of the box girder *D*, an extension block, Fig. 124, being used for the latter part of the push for each ring of the tunnel.

Two hydraulic erectors for placing in position the cast-iron segments of the

[1] See Minutes of *Proc. Inst. C.E.*, vol. cxvii. p. 27.

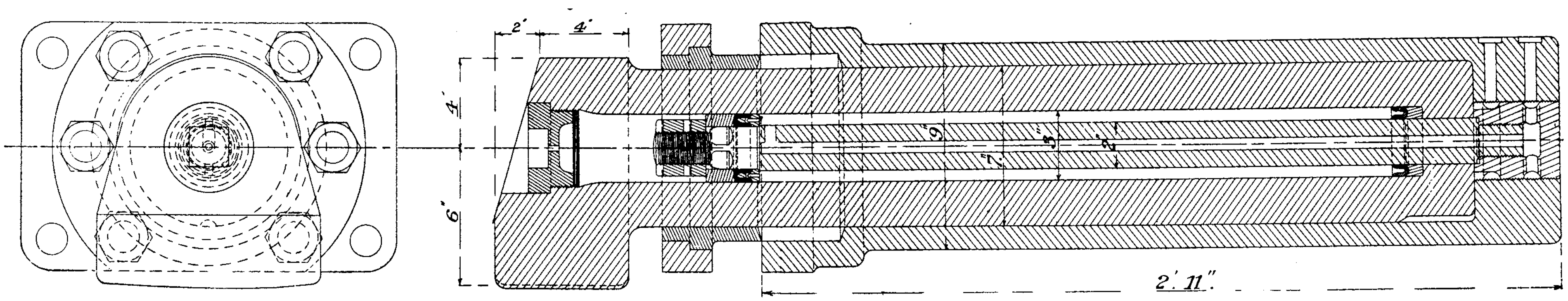


Fig. 122. Blackwall Tunnel, London.
The Shield: Details of Hydraulic Ram.

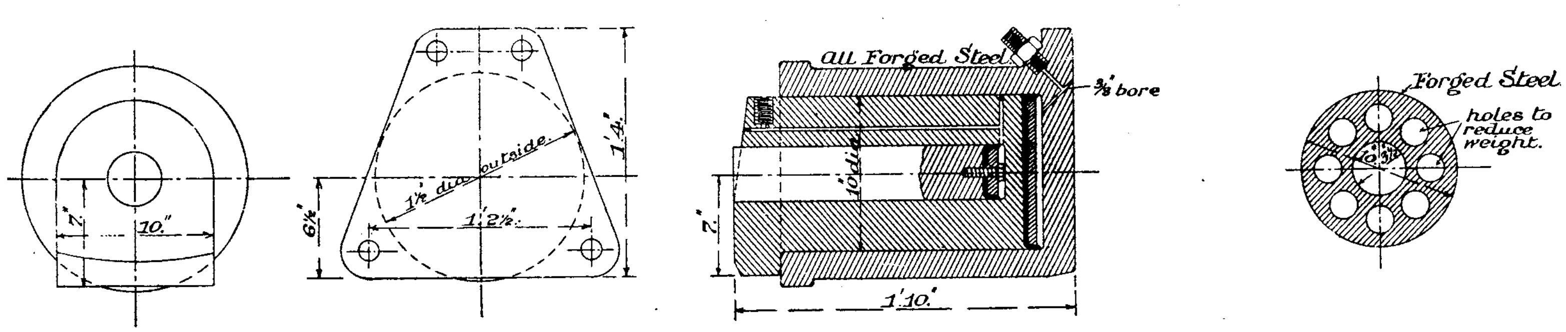


Fig. 123. Blackwall Tunnel, London.
The Shield: Additional Hydraulic Rams.

To face page 196.]

tunnel lining were provided. They were fixed on the main diaphragm *F* (Figs. 115, 116) of the shield, one on either side of the vertical centre line, and 4 feet distant from it, on its horizontal axis.

The position in outline of the central casting on which the central arm of one of them revolves is shown in Fig. 116, at *T*, by a thick dotted line.

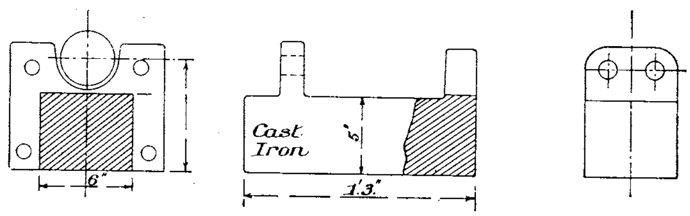


FIG. 124. BLACKWALL TUNNEL, LONDON.
The Shield : Extension Block for Additional Rams.

Each erector consisted (see Figs. 125 and 126) of two vertical single acting hydraulic cylinders *A*, *A*, $8\frac{1}{2}$ inches in diameter, having a common piston *B*, on which was fixed a toothed rack *C*, operating a pinion *D*, which when revolved carried with it a cast steel box *E*, through which an H beam *F*, having at one end a hand *H*, to which could be secured the casting to be lifted, was made to slide by means of a double-acting hydraulic cylinder *G*, also secured to the box *E*. By admitting water from the pressure main, which for these erectors was at about 1,000 pounds per square inch to the cylinders *A*, the box *E* carrying with it the arm *F* was made to revolve, and by pressure supplied through a swivel joint (see Figs. 127 and 128) to the cylinder *G*, the head of the arm *F* could be advanced or withdrawn from the tunnel lining, the full extent of this movement being 6 feet 6 inches. The motion of the arm *F* was therefore in a vertical plane at right angles to the axis of the tunnel, but this arm *F* could be inclined some inches from this vertical plane by an adjusting screw and hand wheel, by means of which the position of the hinged box *E* could be moved relatively to the shaft on which it and the pinion *D* moved.

The arrangement of the hydraulic supply pipes, by means of which pressure was conveyed to the cylinder *G* of the revolving arm *F*, was ingenious.

The shaft on which the arm and the pinion D turned was hollow (see the en-

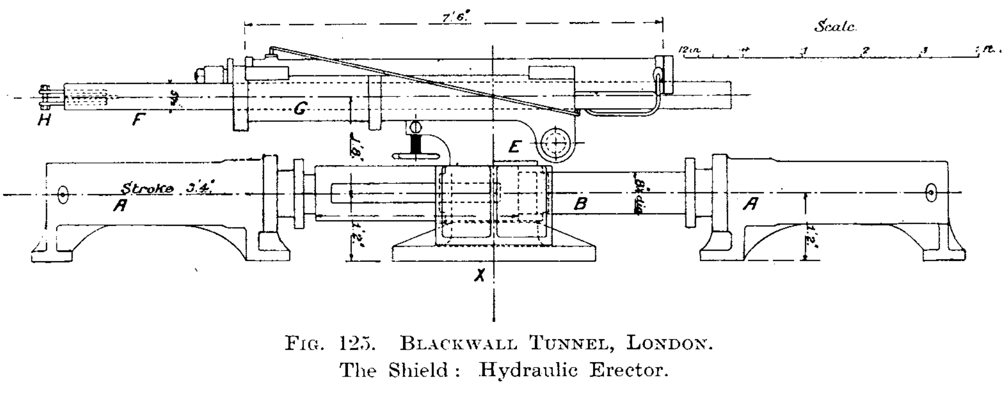


FIG. 125. BLACKWALL TUNNEL, LONDON.
The Shield : Hydraulic Erector.

larged section of this part in Fig. 127), and through it the supply pipes were carried, the detail of the joints at *X* and *Y* being shown in Fig. 128.

The copper pipes connecting the joint at *X* with the hydraulic supply main were brought to the point *X* on the front side of the back diaphragm of the shield, to the back of which the erector was fixed, and brought through it at X. The joint at X is a double swivel one, similar in character to the single one shown in Fig. 121, and is clearly shown in Fig. 128. The brass collar *a*, to which the supply pipes are secured, is of course, immovable, and in it the spindle *b* turns, there being between *a* and *b* the circular glands *c*, *c* enclosing wrought-iron rings perforated with numerous holes, the other end of *b* terminating at Y in a rectangular flange *d*, fitting into a hole cast for the purpose in the hinged box E.

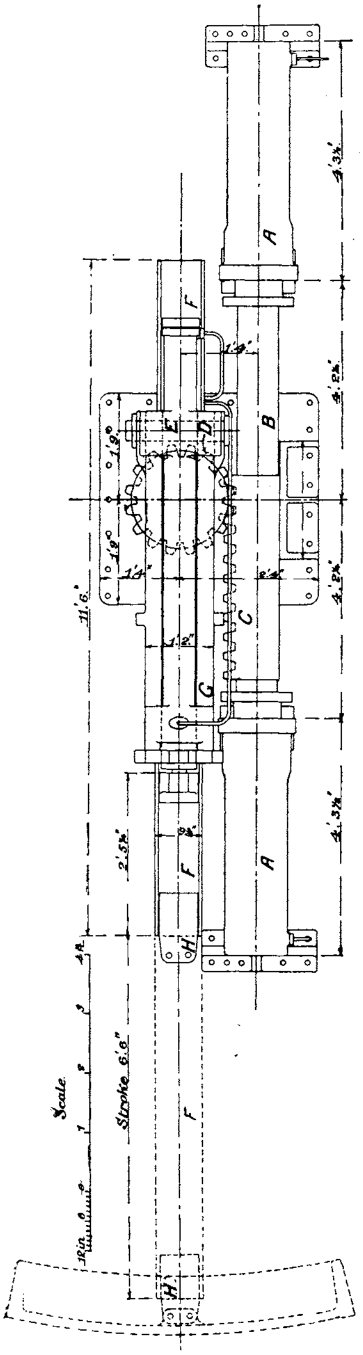


FIG. 126. BLACKWALL TUNNEL, LONDON. The Shield: Hydraulic Erector.

In *b* were cast two wrought-iron pipes, ¼ inch in diameter, which made a connexion at one end of *b* with the circular joint *a*, and at the other were secured in a brass boss *e* fastened with studs to *b*, and from which copper pipes led to the valves of the cylinder G of the arm F of the erector.

When therefore the arm F revolved the spindle *b* turned with the hinged box E, *a* remaining fixed, and the pressure water always being free to pass through one or another of the perforations of the valve ring at *c c*.

These erectors, each served by one man, could erect one complete ring weighing nearly 15 tons in about an hour, and occasionally, in very favourable conditions in two-thirds of that time—a very satisfactory rate of speed.

Mr. Moir's own criticism of his machines is as follows :—

> The erectors attached to the back of the shield had worked well, but on another occasion he would adopt two hemp-packed cylinders for pushing out and pulling in the telescopic girder, instead of one with double leathers, which were more trouble to keep in order than common glands. Double leathers inside a hydraulic jack always gave trouble ; they were out of sight, and if they failed the whole machine had to be pulled to pieces to reach them. Ordinary hemp-packing with common glands was much more serviceable in ordinary work. In designing the erectors he had allowed a margin of 50 per cent. in the power of the telescope cylinder, and 60 per cent. in the turning cylinders. He might with advantage have increased that allowance, as sometimes the power was reduced owing to leaky slide-valves, the surfaces of which would always wear.[1]

The details of these erectors were in a large measure repeated in the erector of the Great Northern and City Railway Shield, afterwards employed in the Holborn Subway shield.[2]

[1] *Proc. Inst. C.E.*, vol. cxxx. p. 80. [2] See p. 128.

The lowering of the shield, which to advance the work as quickly as possible had been erected on the surface near the top of No. 4 shaft, where it was to be first

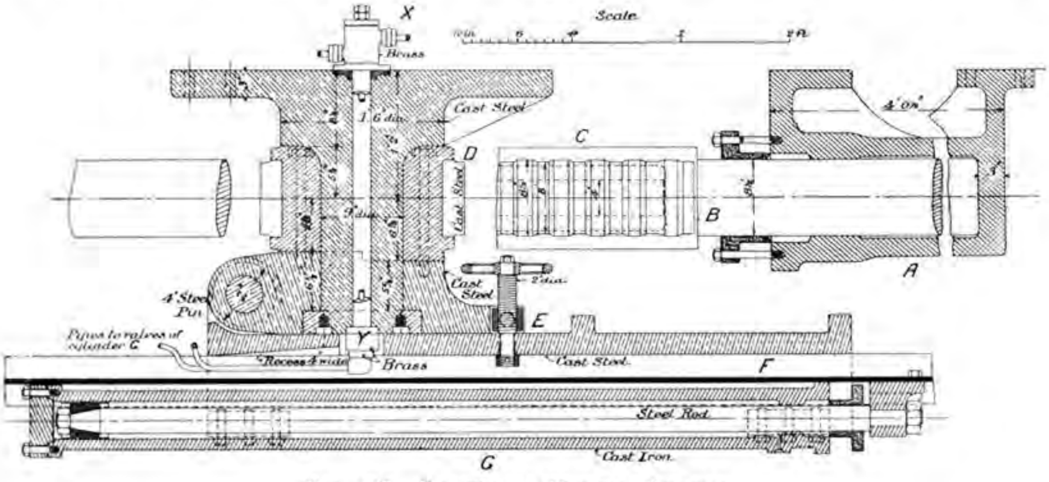


FIG. 127. BLACKWALL TUNNEL, LONDON.
The Shield: details of Hydraulic Erector.

employed, was effected in a very ingenious manner. The great weight of the machine, some 200 tons without the hydraulic rams and other fittings, made the

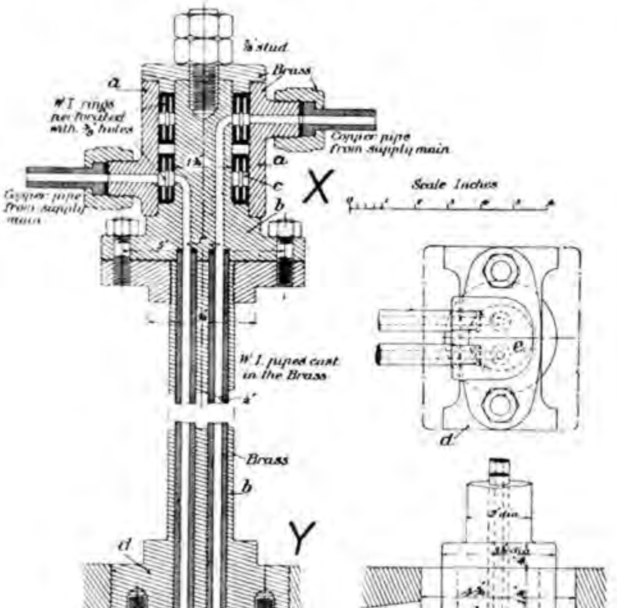


FIG. 128. BLACKWALL TUNNEL, LONDON.
The Shield: Enlarged Details of the Hydraulic Pipes of Erector at X and Y (Fig. 127).

provision of tackle to lower it to the bottom of the shaft 50 feet below a very serious matter, and it was finally decided (on the suggestion of Sir W. Arrol) to float it down, by filling the shaft with water, launching the shield on its surface, and, by pumping the shaft dry, lowering the shield gradually to the bottom (see Fig. 129).

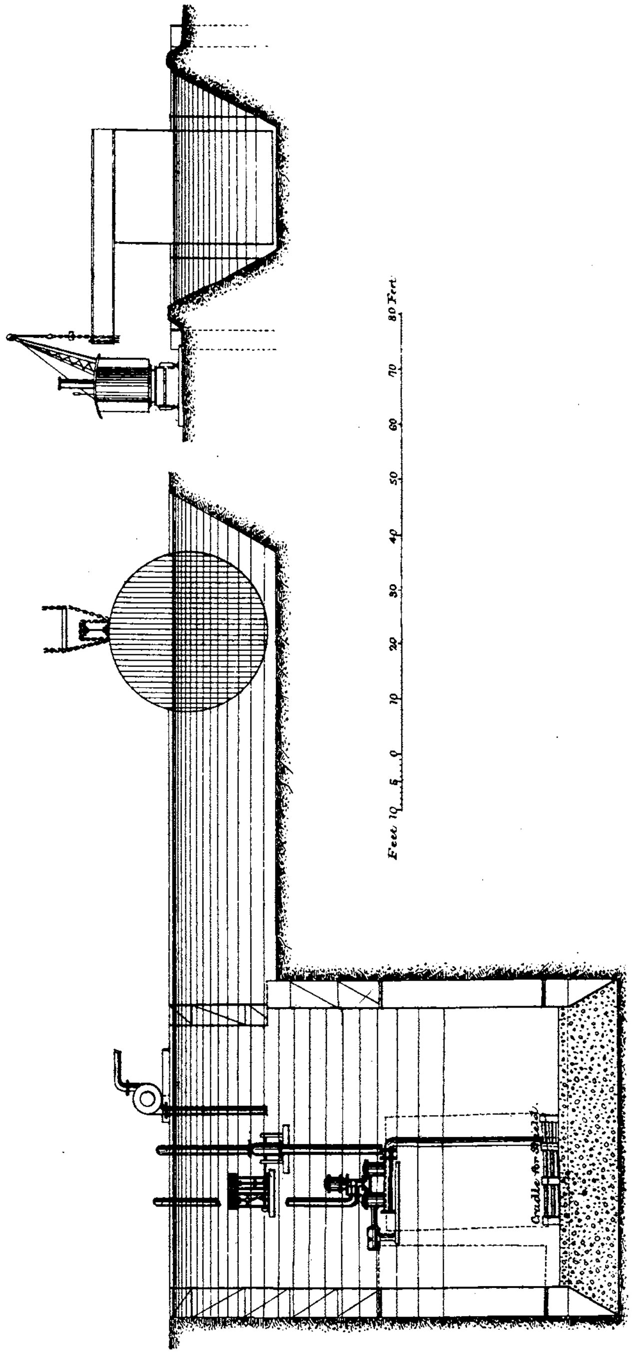


Fig. 129. Blackwall Tunnel, London.
Method of Lowering the Shield to the Bottom of the Shaft.

The shield was erected in a kind of dry dock adjoining the shaft, the upper part of which was constructed so as to permit of the temporary removal of sufficient iron plates to allow of the passage of the shield.

When the shaft was sunk, and the shield put together, the shaft, and the "dry dock" adjoining were filled with water, the shield having been made into a water-tight cylinder by closing its ends with 4-inch planking soundly caulked.

When properly ballasted, the shield thus made buoyant drew about 17 feet of water and could be drawn through the side of the caisson into it. The caisson was then pumped dry and the shield lowered on to a cradle previously prepared for it.

Behind the shield, when tunnelling operations were in progress, a travelling platform or gantry, 40 feet long, and nearly the full width of the tunnel, was used, rails for its support being fixed on brackets in the tunnel castings.

It was attached by chains to the shield and so moved forward with it. It had three floors from which the whole periphery of the tunnel save the invert could

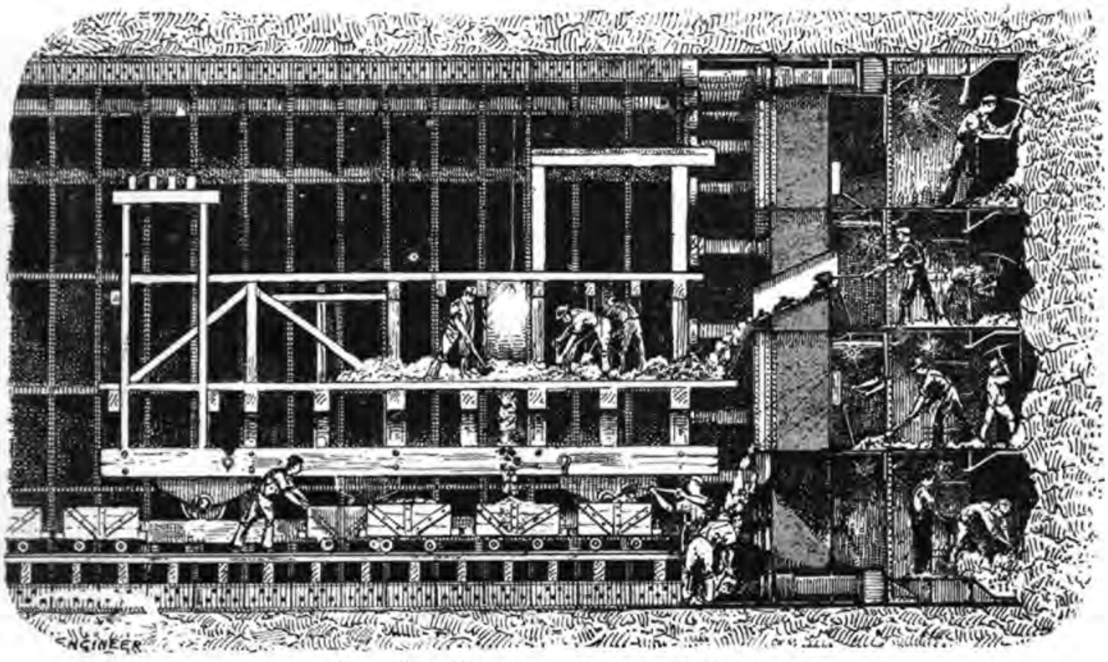


FIG. 130. BLACKWALL TUNNEL, LONDON.
Travelling Gantry behind Shield.

be reached for the purposes of grouting and caulking, and on which the spoil from the upper platforms of the shield could be received. This platform is shown in Fig. 130.[1]

The arrangements for working with compressed air, and the machinery for supplying it were very complete, and in particular the provisions made for ensuring that the miners employed worked under the most satisfactory conditions as regards their health were thoroughly efficacious, with the result that the work was carried through without loss of life, and indeed almost without permanent disablement to any workman due to the natural conditions of working in compressed air.

The machinery for the supply of air consisted of six air compressors, of a total capacity of about 1,500 HP. Of these the two largest were of about 300 HP. each.

[1] Figs. 130, 135, 138, and 140 are reproduced from the *Engineer* by courteous permission of the Editor.

A small compressor was also in use for the air required for grouting purposes. The air for grouting purposes, the pressure of which was about 40 pounds per square inch greater than that for the tunnel, was carried in a 5-inch pipe. The high-pressure water for the rams was carried in a steel pipe $1\frac{1}{4}$ inch in diameter, and as the end of the pipe was connected with the moving shield, a "walking joint" was used at some distance back from the face.

Electric incandescent lamps were used for lighting throughout the construction of the work to avoid vitiation of the atmosphere by lamps or candles as much as possible, and electric motors driven from the lighting dynamos were used to operate drills and other small machinery in the tunnels.

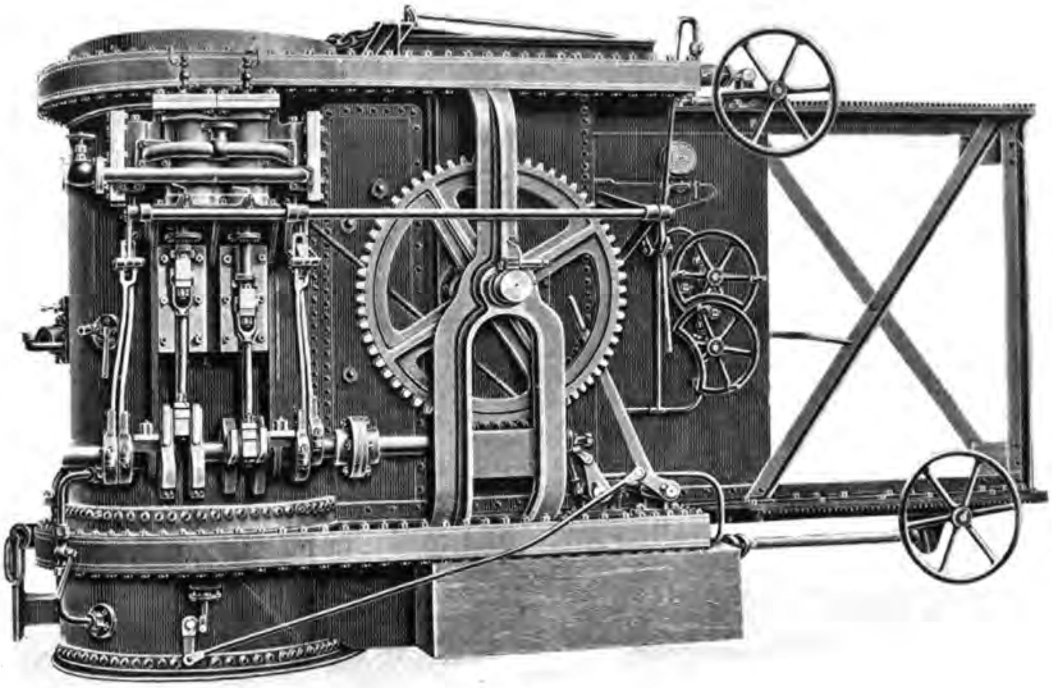


FIG. 131. BLACKWALL TUNNEL, LONDON.
Vertical Airlock for Material.

The various arrangements for giving access to the pressure chamber follow in general previous equipments for similar work, but present some special features in details.

The locks for giving access to the caissons were fixed above the temporary airtight floor (see Fig. 112), and were two in number, one being used for men and the other for material.

The former does not call for any special remark; the latter is shown in Figs. 131, 132, 133;[1] both were employed on one of the large caissons at the Forth Bridge, and the material lock was again erected in the caissons of the Greenwich Tunnel in 1900.

[1] These drawings are reproduced from *Engineering*, by courteous permission of the Editor.

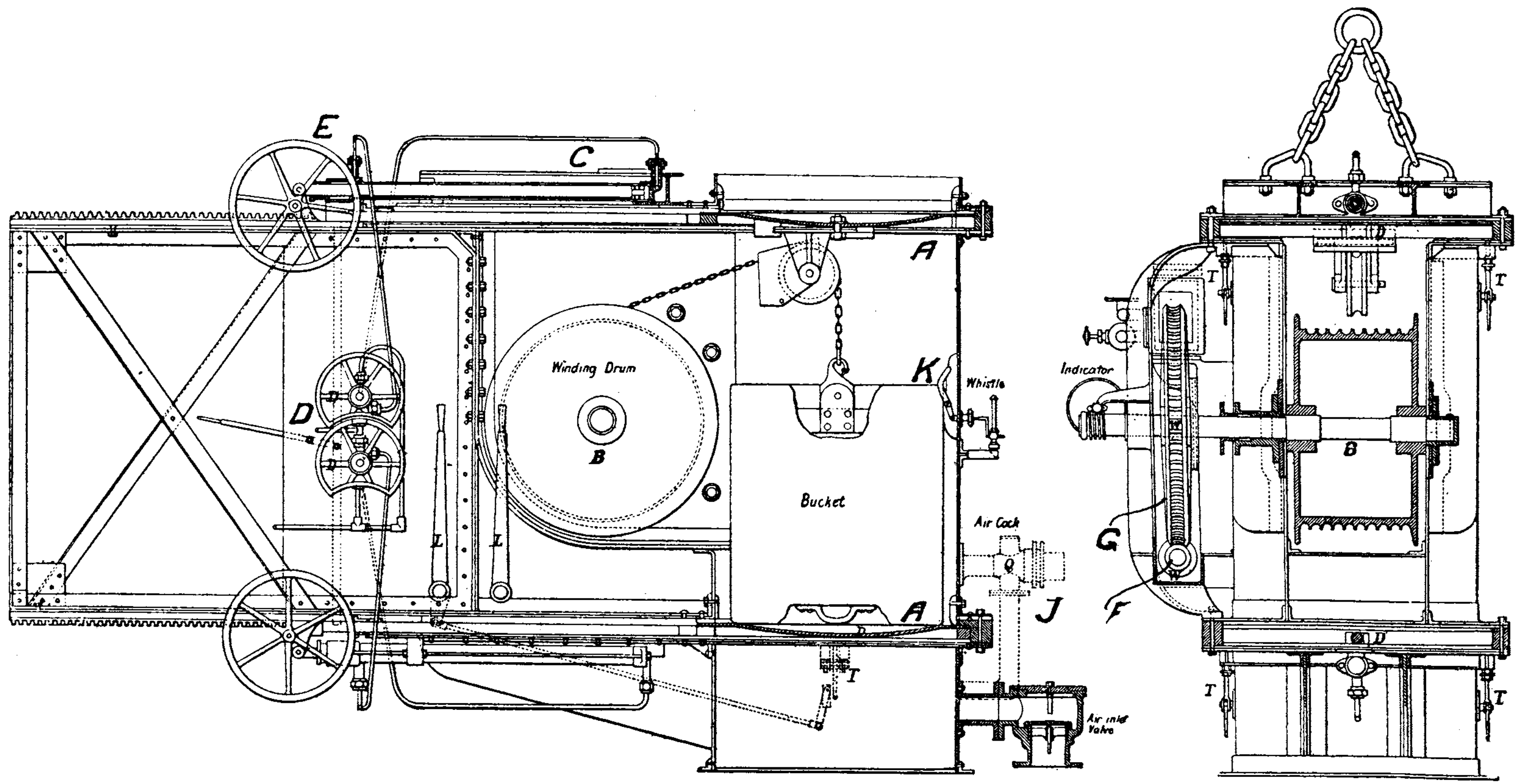


FIG. 132. BLACKWALL TUNNEL, LONDON.
Vertical Airlock for Material: Sectional Elevation and Cross Section.

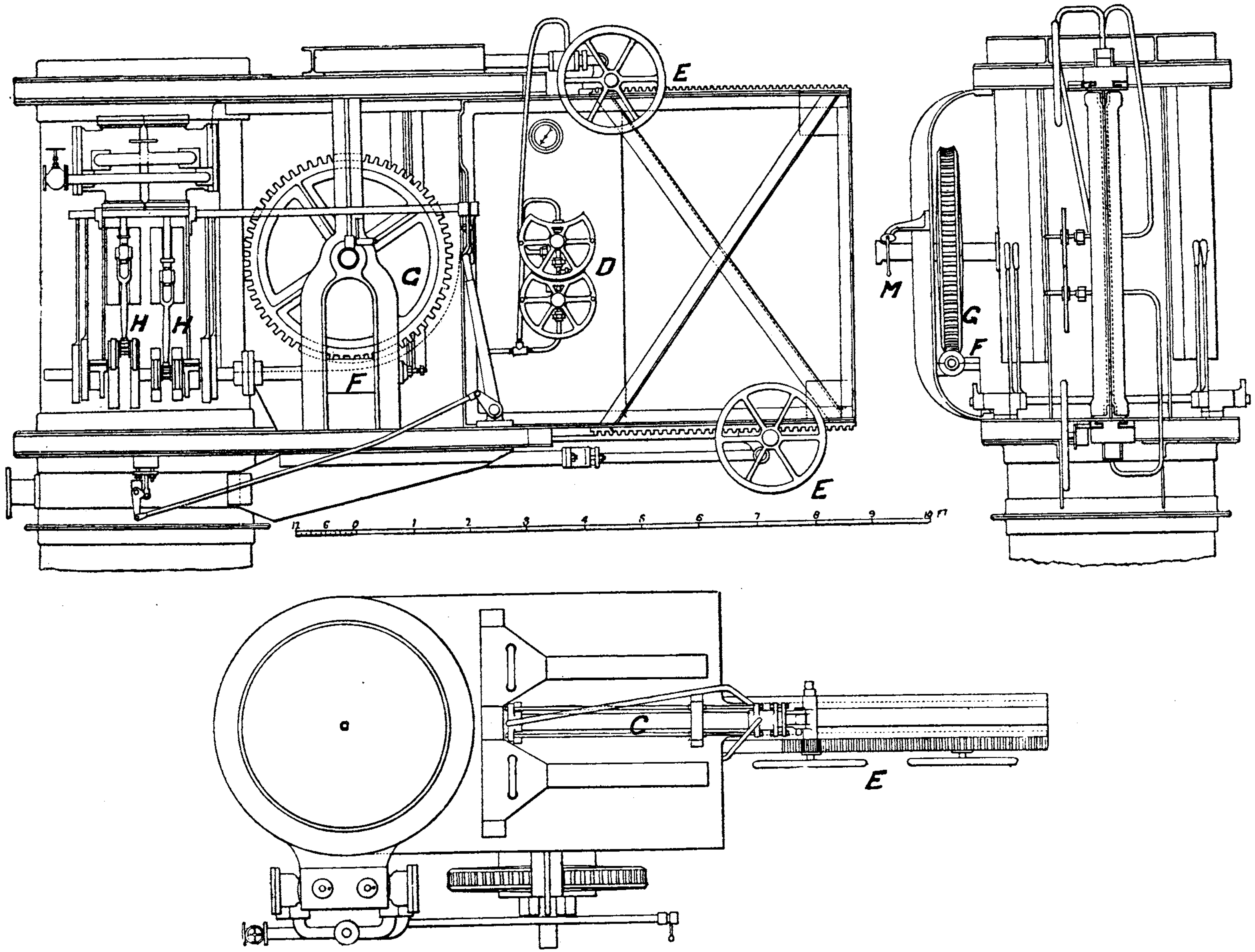


FIG. 133. BLACKWALL TUNNEL, LONDON.
Vertical Airlock for Material: Side and End Elevations and Plan.

This lock, like the men's lock, was fixed in the top of a shaft 3 feet 6 inches in diameter, and consisted of a box at top of the 3 feet 6 inch shaft, closed at top and bottom by sliding doors *A*, *A*. These doors, when opened, slid into airtight recesses, and the chamber itself was large enough to contain on one side of the shaft proper the drum *B* of the engine for raising and lowering the buckets. The sliding doors were worked by hydraulic rams *C*, *C*, or alternatively by rack and pinion and handwheel *E*, *E*. By an interlocking arrangement of simple construction, *D*, *D*, Fig. 132, it was made impossible that both doors should be opened at once, a very necessary precaution. The valves admitting water to the rams actuating the doors were worked by the handwheels *D*, *D*, Figs. 131, 132, 133, from each of which a segment is cut out, and into this the rim of the other wheel fitted. In the position shown in Fig. 132, the upper valve is closed and its handwheel cannot be turned unless the handwheel of the lower is turned round to bring its cutout segment opposite the other one. In that position, however, the lower valve would be closed and the lower door prevented from opening. A similar adjustment being made for the yalve of the upper door, it will be seen that, short of removing the special handwheels *D*, *D* altogether, it was impossible to open both sliding doors at one time.

The winding drum *B* was driven by a worm *F*, and a worm-wheel *G* outside the lock, and actuated by a pair of ordinary reversible engines *H*, *H*, the main shaft which carried the drum being provided with airtight glands at both ends where it passed through the sides of the airlock. A chain passed over the drum and over a snatchblock suspended to the underside of the upper door and sliding in and out with it, thus bringing the point of suspension to the centre of the shaft for lowering the skip or bucket when the upper door was shut, and when, consequently, the lower door could be opened.

The mode of working these locks was as follows : A crane was fixed so that the end of its jib could swing exactly over the centre of the shaft, and when it was required to lower an empty bucket into the air chamber, the bucket was hung over the upper door of the lock by this crane ; the upper door of the lock was then opened, and the bucket lowered into the lock, and rested on the lower door, and the shackle of the inside winding chain attached to it. This done, the upper door was closed, and by means of the engines the bucket lifted clear of the lower door. A cock or valve *J*, $2\frac{1}{2}$ inches in diameter, which communicated with the compressed air in the working chamber, was opened and the air in the lock put at the same pressure as in the shaft beneath.

The sliding doors were fitted with india-rubber joints, and the effect of admitting the air from below into the lock was to absolutely seal the upper door, and when that was secured, a turn of the interlocking wheels *D*, *D* enabled the lower door to be drawn back, and the bucket was lowered to the bottom of the shaft to be filled. To remove the loaded bucket the process just described was reversed ; the bucket was drawn up into the lock, the lower door closed, the compressed air let out of the lock, the upper door drawn back, the winding chain taken off the bucket, and the crane chain attached,when the crane swung away the bucket, discharged its contents and returned the empty bucket to repeat the process.

In Fig. 132, it will be seen that the bucket when rising into the lock touched a lever *K*, which opened a steam whistle and so indicated to the men outside who were working the lock machinery that it had arrived inside the lock. As an additional precaution a small dial and pointer *M* was attached to the worm-wheel *G*, so that the exact position of the bucket was indicated at any moment of its ascent or descent.

The levers L, L worked bolts, which fitted in the frames of the sliding doors and so made more certain that both doors could not be opened together. Locks of this character cannot, however, be worked very rapidly, and consequently the rate of excavation in the air chamber was slow. The number of skips sent through this lock at the Forth Bridge was about twelve per hour, and later at Greenwich tunnel, where, however, the doors were worked by the hand gear only, not more than eight per hour were dealt with.

The bulkheads (see Fig. 134)[1] in the tunnel, of which four were at different times constructed, were 12 feet 6 inches thick, the first being constructed of concrete, and the others of brickwork, the latter materials presenting less difficulty when the bulkhead came to be removed. All were rendered with cement on the pressure side.

The working locks, two in number in each bulkhead, were 16 feet long, and 7 feet in diameter, the skin being of $\frac{3}{8}$ inch plate. The use of this thin metal was made possible by the fact that the locks were made to project beyond the bulkhead on the atmosphere side only, and therefore the skin of the lock was never subjected to compressive strain. The valves for working them were respectively $2\frac{1}{2}$ and $1\frac{1}{2}$ inches in diameter for locking through materials and workmen respectively.

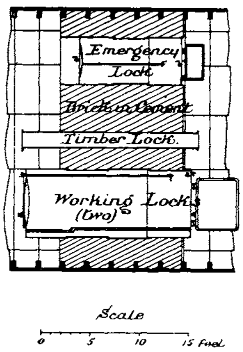


FIG. 134. BLACKWALL TUNNEL, LONDON. Bulkhead in Tunnel.

A special feature in these locks was the doors, which were hollow, each door, which had an area of 20 square feet, being made of two buckled steel plates, $\frac{5}{16}$ inch thick, rivetted together, thus combining lightness with strength.

A pipe lock 18 feet long for timber and rails was provided.

In the upper part of the bulkhead, a small lock for use by the men, in case of flooding of the tunnel, and accessible by means of ladders, was provided.

An airtight hanging screen or diaphragm (see Fig. 135) was always fixed a short distance behind the shield to ensure the safety of the men. It reached down to the centre of the tunnel, and was fitted with an airlock at the top, the doors of which were hung to open towards the bulkhead; this could be reached by a gangway which was added to as the shield advanced. In the event of an inrush of water, the men could thus escape to the other side of the screen, where they would always find an air-space, and thence, by a gangway, to the emergency lock in the bulkhead.

The service pipes fixed in the bulkheads for the tunnel work were two 8-inch air pipes for the supply of compressed air to the working chamber, one 5-inch air-pipe for the supply of compressed air at 60–70 pounds pressure for grouting purposes, three 5-inch blow-out pipes, three hydraulic mains, and a pipe for water at ordinary pressure of public mains, besides electric mains, telephone, etc.

The blow-out pipes, which were all fitted with flexible hoses at the ends for draining away the water in the invert of the shield, were prolonged as the shield advanced, but the advantage of carrying forward the supply mains is not obvious. By bringing them forward, the air in the rear portion of the pressure chamber was not renewed, save to the extent of the compressed air wasted in locking through, and

[1] The various pipes, etc., are not shown in this figure.

the increased length of pipe meant increased cost, and increased loss of pressure by friction.

The supply pipes appear also somewhat small in the light of the experience gained in the work.

During a large portion of the time, while passing through loose ballast, as much as 10,000 cubic feet of air per minute was sent into the tunnel. It was carried into the tunnel by steel-rivetted pipes 8 inches in diameter, taken down No. 4 shaft, on the Kent side, and thence along the tunnel as completed to the end at the Middlesex side, or say a distance of nearly 3,000 feet at one time. When the air was escaping freely at the face, the amount pumped through these pipes was very large, and the velocity consequently very high. On this account the

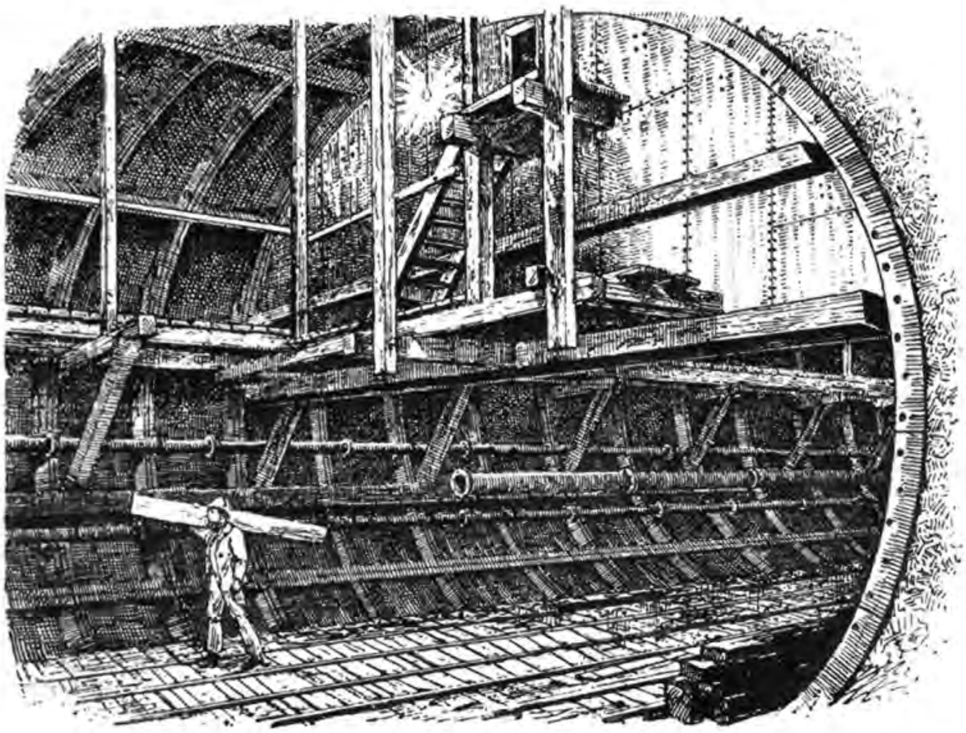


FIG. 135. BLACKWALL TUNNEL, LONDON.
Safety Diaphragm in Tunnel.

difference between the air-pressure in the engine-house and the tunnel sometimes showed a loss of 40 per cent. It is evident that for a long tunnel it would be economical to have pipes of ample size, so that the velocity of air could be kept at say about 30 feet per second, as the extra cost of pipes would soon repay itself, and though the point is of less importance, the temperature of the air would be lower.

A good plan in laying out the pipe arrangements at the commencement of a tunnel where more than one pipe was required, would be to make the length of pipes in the bulkhead of double the sectional area of the supply mains considered by the contractor as sufficient. These could be fitted with reducing pieces to suit the mains in use, and would permit of the whole service being increased later if desired.

All the haulage work in the tunnels was by endless ropes driven from winches worked with compressed air.

After the shield had been sunk to the bottom of shaft No. 4, as already described, and placed in position for entering the tunnel opening (towards shaft No. 3) in which cast-iron guides had been bolted to ensure true line and level being followed, a portion of the cast-iron lining, extending to the other side of the shaft, was temporarily built up behind the shield to form an abutment for the hydraulic rams in driving the shield forward. To remove the plug from the tunnel opening a commencement was made at the bottom, and as the girders carrying the bottom outside plates were removed the latter were temporarily strutted to the shield. Clay, chiefly in bags, was then built against the plates to support the face when they should be taken out. The second row of plates being similarly dealt with, a sufficient height was obtained to draw out the bottom row by means of a tackle or union screw; the same process was continued with the other plates until the whole of the plug was removed and replaced by a wall of clay, through which the shield was driven into the face beyond.[1] This method of removing the plug refers more particularly to that adopted in gravel, etc.; when the face consisted of clay such extreme care was not necessary. The ground in front of the plug was sometimes

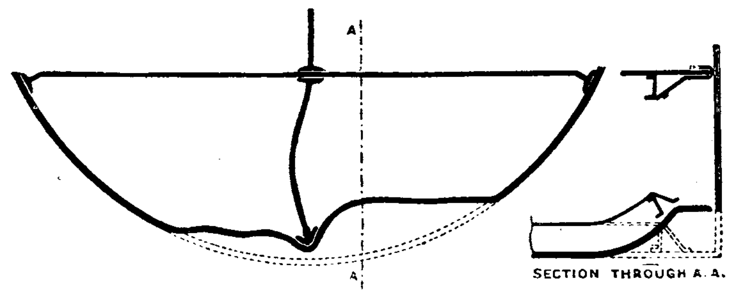


FIG. 136. BLACKWALL TUNNEL, LONDON.
The Shield: Damage to Invert at Cutting Edge.

grouted with cement before the plug was removed. The strata on starting from No. 4 shaft consisted of 1 foot of sand at the bottom overlaid by 25 feet of London Clay with about 1 foot of ballast showing at the top. The latter had been drained to a large extent by the pumps for the adjacent "cut-and-cover" work, and, as it was known that on account of the gradient of the tunnel the ballast would soon disappear, it was decided not to use compressed air at the outset, but to drive a top heading to deal with the gravel and water. As soon as the clay was sufficiently thick to cut the water off, the top heading was discontinued.

At first progress was somewhat slow, only 125 feet being driven in the first two months, but after the gravel disappeared and the top heading was discontinued, better progress was made, an average length of 25 feet being completed per week. An accident, however, soon after happened to the shield which caused some delay. At the base of the London Clay, and in the sand immediately below it, large pieces of rock were embedded and considerable damage was caused to the cutting edge by driving against them (see Fig. 136). This was first discovered after fifty-four rings had been erected, and, although great care was exercised in

[1] Compare the similar operation at Greenwich Tunnel, page 240.

clearing the excavation in front of the upturned part of the cutting edge, the damage continued to increase, and, after another twenty-six rings had been erected, the shield was found to be unworkable. As it was not practicable to repair it in its then position, it was decided to construct a concrete cradle for it to slide upon. A timbered heading, 19 feet wide, was therefore driven and kept about 50 feet in advance of the shield, so that the concrete should have time to become hard before the shield came upon it. During the driving of this heading trouble was again experienced from water in the ballast above finding its way through cracks in the clay, and the top heading was accordingly recommenced, so as to intercept the water and carry it through the shield. This method of working was continued until No. 3 shaft was reached, when the repairs to the shield were effected.

Until about 490 feet had been driven towards No. 3 shaft no great quantity of water was met with, but at that point a large volume suddenly broke into the bottom heading. Considerable difficulty was then being experienced in sinking No. 3 shaft, and the water which broke into the heading undoubtedly came from the ballast, and found its way either down the side of the shaft or through the cracks in the clay which had been caused by the numerous blows. As the shield was then only 67 feet from the shaft (the bottom of which was to be 15 feet below the invert of tunnel) it was deemed prudent to suspend any further tunnelling operations until the shaft was sunk to its full depth. Meanwhile the first bulkhead was built, and No. 3 shaft having been completed to its proper depth, tunnelling operations were resumed as soon as the bulkhead was completed, the remaining length of tunnel from this point to the shaft being driven under compressed air.

A fire which occurred in the top heading on this portion of the work caused considerable anxiety. It was feared that the escaping compressed air might carry the flames through the ground saturated with very inflammable material to a distillery above, in which case a serious conflagration would have resulted. Happily a good supply of water was at hand, and the fire was extinguished before any such accident happened.

The air-tight floor was fixed and pressure applied in shaft No. 3 when it was required to drive the shield through the tunnel opening.

On the arrival of the shield at the shaft it became necessary to undertake the repairs required on account of the buckling of the cutting edge. It was decided to cut away the distorted portions of the skins and vertical stiffener, Fig. 136, and substitute heavy steel castings, as shown in Fig. 139. At the same time the projecting plates of the undamaged part of the cutting edge were cut off, and, although sharpness was thereby lost, the edge was much stronger to sustain a blow against any obstacle in front. The steel castings were made to a larger radius than the outside skin, so that they should stand "proud" of it and thus decrease the skin friction when the shield was being pushed forward. A steel band, $\frac{5}{8}$ inch thick, was also carried round the outside of the undamaged part of the cutting edge, with the same object, and to further strengthen it.

The portion of the tunnel under the River Thames is that between shafts Nos. 2 and 3, a distance of 1,222 feet (see Fig. 111).

Clay was found over the tunnel for a distance of about 700 feet, where it was lost, and a deep pocket of ballast going down far below the invert of the tunnel met with. The work was carried out expeditiously, and without difficulty in maintaining a sufficient pressure of air as long as the clay cover continued. In starting from No. 3 shaft the upper part of the shield was in clay and the lower part in sand. The latter would, without air pressure, practically be a quicksand, but with compressed air it formed most favourable material. It was more or less stratified and interleaved with thin beds of shale, so that the face would stand with practically no timbering, only an occasional face-board being required, and being very fine and close there was little escape of air. The rate of progress here surpassed that in any similar tunnel previously constructed. In two months, more than 500 feet of tunnel were completed, and occasionally five rings, or a length of 12 feet 6 inches, were constructed in twenty-four hours. During a day, therefore, 300 cubic yards of material was excavated, and about 75 tons of cast iron erected. When it is considered that these materials, in addition to lime, other necessaries and empty wagons, had to pass through the airlocks, the feat appears a very notable one, involving the nicest care on the part of the contractors in arranging the work.

The bricks, sand, etc., for No. 2 bulkhead, which was built under the river at a distance of about 220 feet from the shaft, had also to be brought in during this time. As the tunnel approached the centre of the river the lower part passed through mixed deposits, such as thin beds of clay, clay and shells, chalk and green-sand. Fig. 137 shows a characteristic section of the strata below the ballast. The excavation of the chalk required more time than that of the sand, but still the progress was well maintained, and in eleven weeks after starting from the shaft half the distance across the river was completed. When 700 feet had been driven, ballast appeared in the top, and it was decided to stop to fix the shutters at the face of the shield, so that as much or as little of the face could be closed as required to prevent undue loss of air and any sudden rush of ballast.

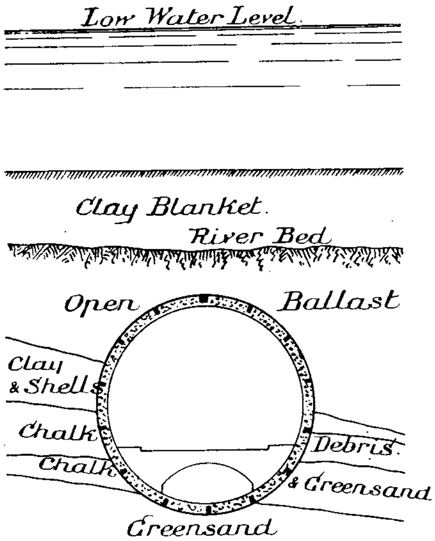


FIG. 137. BLACKWALL TUNNEL, LONDON. Section of Tunnel under River Thames.

Soon after entering the ballast, which was of a very open character, the shield passed within about 5 feet of the original river bed, which, however, had previously been raised by tipping into the river, by consent of the Conservators of the River Thames, a temporary layer of clay (see Fig. 137) for a distance along the line of the tunnel of 450 feet. It offered resistance to the air escaping from the tunnel through the open ballast, and its weight prevented the bed of the river from being blown up by the pressure.

Without the provision of this blanket of clay it would have been impossible to construct the length of tunnel across the pocket of ballast.[1] It will be remembered, that after the accident at the Thames Tunnel in May, 1827, the hole caused by the giving way of one of the frames of Brunel's shield was filled with clay, through which the shield was afterwards driven.

The shutters in the front of the shield (see page 193 and Figs. 119, 120 and

[1] Mr. Moir states: "If the Thames Conservancy had found it impossible to allow the river-bed to be raised, it had been intended to dredge a channel and fill it again with puddle."

138) were invaluable in the work in ballast. When driving the shield in this material the procedure was as follows :—

Previous to shoving the shield forward, the face of a compartment was completely closed by its three shutters which had been screwed forward as close to the cutting edge as possible, the shutters being directly over each other, and the small space between them being filled with clay. When the shield was to be shoved forward the nuts on the screws were loosened on the forward side of the bearings, allowing the shutters to move back as the shield was shoved forward. Any sudden movement was guarded against by running the nut only 1 inch or so in front of the bracket at a time. If the ground was very loose, and, consequently, the air escaped quickly, a man in each compartment kept the spaces between the shutters filled with clay, the rate of travel being sufficiently slow. The movement of the shutters

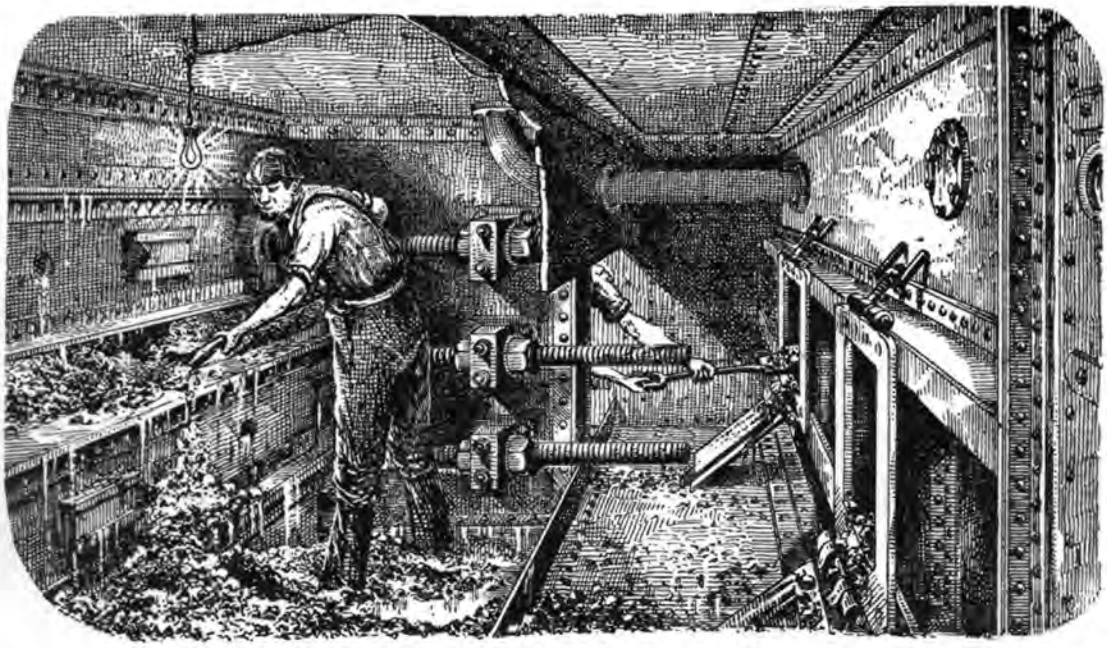


FIG. 138. BLACKWALL TUNNEL, LONDON.
The Shield: Sliding Shutters.

was nearly double that of the shield, as their area was considerably less than that enclosed by the cutting edge. After the shield had been shoved as far as required, the shutters would be considerably behind their former position, the space in front of them being filled with ballast. The method and rate of removal of this material depended on the consistency of the ballast, and whether the air pressure in the tunnel was sufficiently high. Under favourable circumstances the ballast might be shovelled out from the top of the shutters, or a shutter might be drawn somewhat further back and the material shoved out between that shutter and the next lower one; but in any case the top shutter was first excavated and screwed forward and then those at the middle and bottom. When the gravel was very coarse, and other circumstances unfavourable, all the ballast in front of the shutters was scraped out by small iron rakes or by hand through holes 7 inches by 4 inches in the shutters,[1]

[1] One of these holes is shown in figure 138.

which were furnished with sliding doors, the greatest care being taken to open as small an area of the face as possible, and each shutter being screwed up as the stuff was excavated. It is not surprising that when working in this way, which was often necessary for safety, the progress was sometimes only 1 foot per day. The amount which the shield was shoved forward at one time varied greatly ; sometimes only a few inches could be obtained, but in clay the length necessary for a complete ring was occasionally completed.

While driving through the ballast the cover above the tunnel was so small and of such a character that sufficient pressure could not be maintained to dry the ground at the invert ; and as the river was then in direct communication with the face a large and constant stream of water found its way into the bottom floor of the shield. It was dealt with by blow-out pipes, four 5-inch pipes being generally necessary for the purpose. These pipes had flexible hose terminations at the

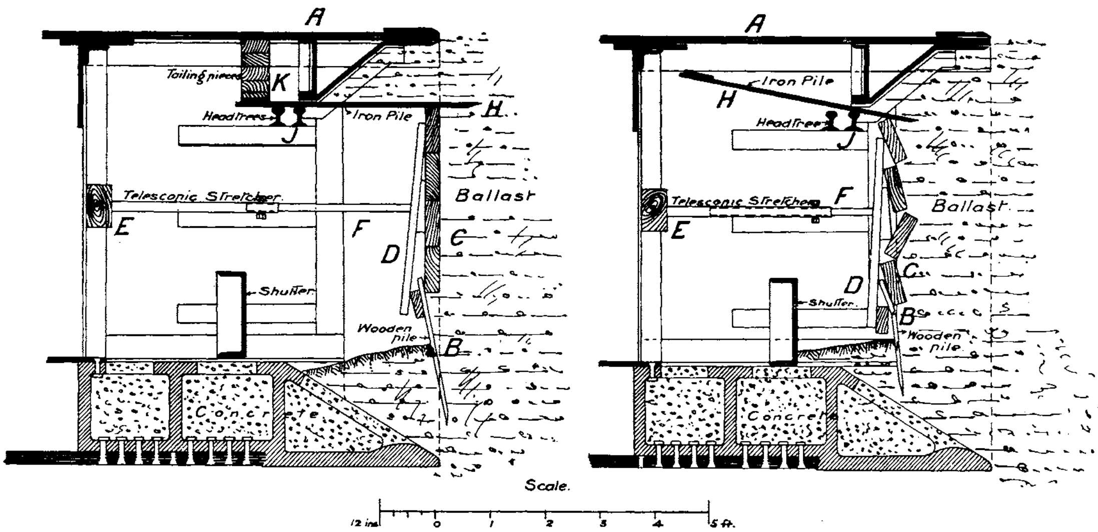


FIG. 139. BLACKWALL TUNNEL, LONDON.
The Shield : Timberwork in Invert.

shield, and the water was blown out into the finished part of the tunnel behind the bulkhead and thence pumped to the surface.

The sliding shutters were not used in the two bottom pockets, and in their place a combination of long horizontal iron piles and short vertical timber piling with horizontal poling boards above was adopted. In Fig. 139 (the left hand section) the shield is ready for pushing forward, excavation of the face having been carried forward to the line of the cutting edge, and timbered by short piles *B* and 10 inch by 4 inch polings *C*, *C*, the whole secured into position by soldiers *D*, strutted back to a byatt *E* fixed in the frame of the shield by the telescopic stretcher or " gun " *F*, and the roof being secured by iron needles or piles *H* fixed under the framing of the platform *A*, and by means of head trees *J* (of old rails) resting on the guides made for shutters and tailpieces *K*.

As the shield was pushed forward the stretcher *F* was allowed to slide back, or shut up, and at the end of the " push " of the shield, the timbering was in the position shown in the section on the right hand of Fig. 139. By this arrangement it was possible to clear out the ballast up to the cutting edge, which could not be done with the shutters. Great difficulty was experienced in the bottom floor, and the men working here were generally standing in about 18 inches of water throughout the day. Perforated tunnel-plates were occasionally built in to relieve the water at the face by allowing it to enter the tunnel further back. Jets of high-pressure water were used at times at the face to keep the material moving while the shield was advancing, to diminish the pressure required to shove the shield forward. Small shots were also used to shake the ground and to remove any hard material; and a man was constantly employed testing the face with a bar in front of the shield to discover any large boulders which might damage the cutting edge.

Serious "blow outs" occurred while working in the ballast, and on two occasions the air pressure fell so suddenly, and the water from the river poured in so fast in the two upper floors, that the tunnel was flooded to a depth of 7 feet or 8 feet in a few seconds. The first of these blows occurred on April 30, 1895, and the second and largest about a week later, when about three-quarters of the distance across the river had been covered. The escape gangway had not at that time been provided, and, owing to the dense fog, caused by the sudden fall of air pressure, completely obscuring the electric lights, the men had difficulty in escaping back to the lock, then distant about 700 feet. The clay which had been placed on the bed of the river was then of the greatest possible value; it followed down upon the ballast, which was washed in by the water as through a funnel, and choking the passage, the air pressure soon increased.

During the progress of the shield through the ballast, careful daily observations were made both of the material in front of the shield, by pricking ahead from the shield itself, and also of the clay in the river bed, by soundings from above.

How difficult the work of tunnelling under the river in the ballast was may be inferred from the fact that at one time the rate of progress did not amount to more than 5 feet a week, but this was an extreme case, and as the depth of cover increased on approaching the north shore of the Thames the weekly advance was about 20 feet per week.

The total time occupied in tunnelling from shaft No. 3 to shaft No. 2 (see Fig. 111), was fifty-four weeks.

When the shield approached No. 2 shaft, and before removing the plug to allow of its entry, iron piles were driven from the inside of the shaft over the top of the shield, and no difficulty was experienced in driving the shield into the shaft, and connecting up the tunnel lining with the iron skin of the caisson.

The driving of the tunnel from shaft No. 2 to the cut-and-cover position of the work presented, for the first part of its length, as far as shaft No. 1, the same difficulties as had been met and satisfactorily overcome before, and were dealt with in the same manner.

Beyond shaft No. 1, the difficulty encountered was, for the most part, the thinness of the cover over the tunnel, which made the maintenance of sufficient air pressure to keep the invert dry very difficult.

The grouting behind the cast-iron tunnel lining was carried out usually a few rings behind the shield, as no satisfactory arrangement could be made to prevent the leakage of the grout into the tunnel between the tail of the shield and the iron tunnel lining. In the large shield employed, the use of grouting timbers (see page 96) was impossible, and an attempt to close the opening at the tail of the shield by means of a pneumatic packing was, after careful trial, abandoned.

Neat lias lime was used for all grouting work.

The caulking of the tunnel lining was satisfactorily carried out (see page 62); the mixture employed being ¼ pound of sal ammoniac to 100 pounds of iron filings, lead wire being caulked into the joints to keep them dry while the rust concrete set.

The contract for carrying out the whole of the tunnel works was let to Messrs. Pearson and Son in 1891, and the whole of the engineering works were complete early in 1897, the cost being about £850,000.

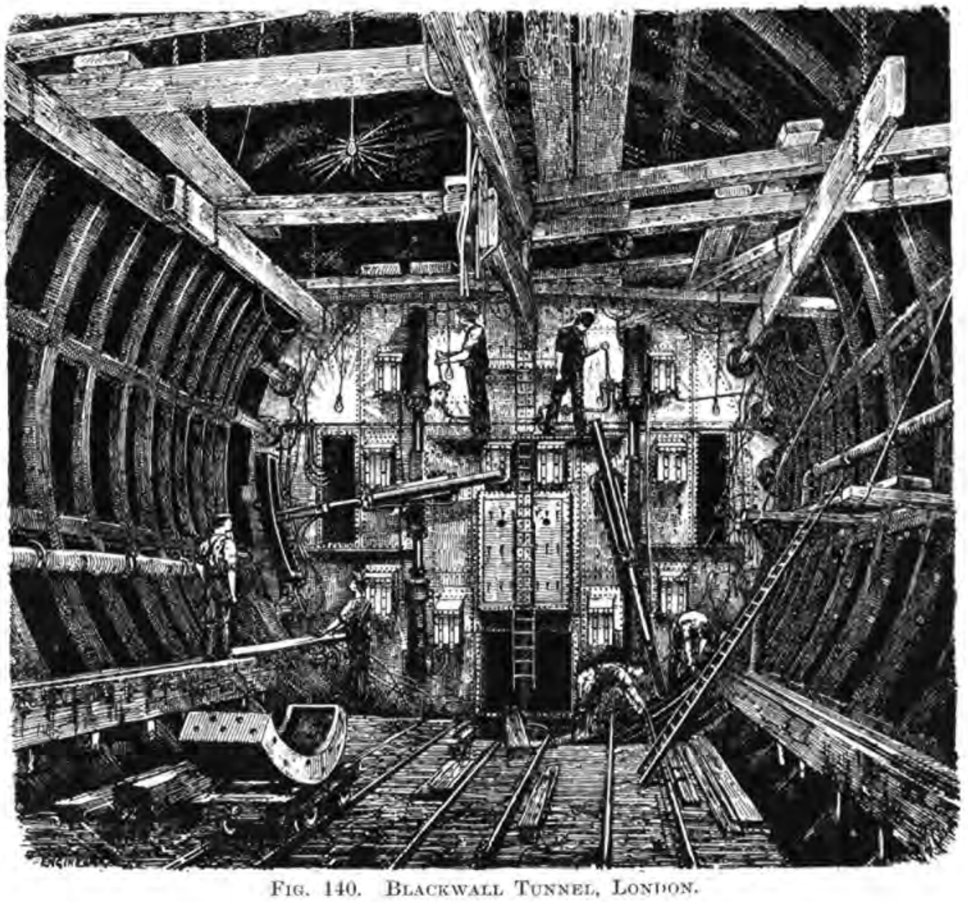


FIG. 140. BLACKWALL TUNNEL, LONDON.
The Shield: Back View.

The cost per yard of the iron-lined tunnel was £378 where the heavy section of cast-iron lining was used, and £315 where the shallower castings were put in, the cost of the roadway and internal concrete and tile lining not being included.

The London County Council showed great interest in the health of the men employed in compressed air; and a stringent clause was inserted in the contract specifying, among other particulars, proper ventilation at the working face, the provision of lifts and resting-places for the men, including a compressed air chamber fitted with locks, and that no workman should be engaged for compressed air-work without his fitness for such duties being proved by previous experience or by medical examination.[1] After the commencement of the work the Council obtained parlia-

[1] For observations made at this tunnel on compressed air conditions, see p. 41.

mentary powers to compensate men who might be injured by working in compressed air, although the men were not employed directly by the Council. A resident medical officer was also appointed to examine all men previous to working in the compressed air, or who might be injuriously affected by it, and to thoroughly investigate the nature of compressed-air illness. The cases of illness due to compressed air were few, and only three cases of permanent illness have been attributed to this cause, and there were no deaths. This is probably due to the fact that a sufficient supply of air was delivered, and that the men did not work in too long shifts. The general period of work was eight hours, but there was a break of three-quarters of an hour in this time as near the middle as possible. Hot coffee was supplied by the contractors to the men in the middle of their shift, and also before coming out ; and proper drying rooms with lockers were provided for their clothes.

The East River Gas Tunnel, New York (1892)

In 1892, the East River Gas Company, the works of which are situated on the Long Island side of the East River, commenced an extension of their supply system to the city of New York on the other side of the river. The principal engineering feature in this extension was the construction of a tunnel [1] under the East River for the conveyance of the gas mains to the other side, and from the results obtained by trial borings on the line selected for the tunnel it appeared that rock would be met with for the entire length across the river ; and on this supposition a contract for the work was let.

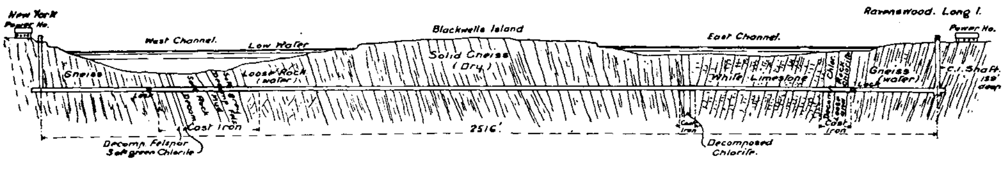


FIG. 141. EAST RIVER TUNNEL, NEW YORK.
Longitudinal Section.

A longitudinal section of the tunnel is shown in Fig. 141, and its internal dimensions were originally fixed at 10 feet 6 inches width and 8 feet 6 inches height to accommodate one main 4 feet in diameter, and two each 3 feet in diameter. Its length between shafts is 2,500 feet.

The tunnel was designed to be on a gradient of 1 in 200, falling towards Long Island, the minimum cover over the roof of the tunnel being 41 feet on the New York side of the river and 85 feet on the Long Island side. In the centre, for a length of about 800 feet, the tunnel is under Blackwell's Island.

Work was commenced by sinking shafts at each end of the proposed tunnel, rock being in both cases met with about 8 feet from the surface, and tunnelling was commenced in hard gneiss rock, that in the Long Island side being, however, fissured, and, in consequence, making the work of excavation expensive and slow by reason of the pumping required.

At a distance of 338 feet from the New York shaft, a fissure in the hard gneiss was struck, and salt-water came in some quantity into the tunnel. On pushing on

[1] The description of these works is mainly taken from Mr. W. L. Aims' Paper, "Notes on the Construction of the East River Gas Tunnel," read before the Boston Society of Civil Engineers, April 17, 1895.

further, the hard gneiss became softer and more micaceous, and at about 360 feet from the shaft the material cut through changed in character, a vein of soft material being met with, with the same dip and strike as had the rock previously passed through, of which it was no doubt a decomposed vein. In composition it was a decomposed feldspar, crumbling easily with no perceptible grit, and perfectly dry when undisturbed; but it was easily acted on by water, which it absorbed, and which caused it to break away over the surfaces exposed to the air. On either side of this soft material at its junction with the hard gneiss, water was found in considerable quantity, and it was this fact which made the use of compressed air a necessity.

An endeavour was made by driving a heading, 6 feet high by 4 feet wide, in advance to ascertain the extent of the soft vein, but had to be abandoned owing to the increase in the quantity of water which found its way in at the face. The action of the water in the soft material was curious in its effects.

The water running along the face of the (hard) rock had washed out a cavity above the tunnel in the soft ground. The walls of this cavity were gradually breaking away, and the clay-like substance falling down would close the outlet of the water into the tunnel. The water would then accumulate in this pocket, softening up fresh material on the sides (of the pocket), until it had gained a sufficient head to burst through the dam which confined it, when it would come rushing into the tunnel, carrying with it large quantities of the softened material. These rushes were accompanied by a loud bubbling sound, that quite mystified the men, which was, of course, the sound of the air displacing the water in the cavity. As soon as the pocket had emptied itself, for a time the trouble was over, until with the falling of more material the outlet was again closed, and the operation was repeated.

Ultimately a bulkhead was hurriedly constructed across the face of the tunnel, hay being used in front of it to prevent, as far as possible, the washing out of the soft material.

It was under consideration to abandon the length of tunnel already constructed and to sink the shaft to a greater depth, but, from the fact that the dip of the decomposed was so nearly vertical, there was little reason to suppose that at any reasonable depth better conditions would obtain. The continuance of the tunnel already commenced was therefore resolved on, but with the aid of compressed air. The depth of the tunnel invert at the centre of the New York channel of the river was nearly 120 feet below mean high water and at the centre of the Ravenswood channel about 127 feet; the theoretic air pressure required to hold back the superincumbent water was therefore 55 pounds. In actual working a pressure of 48 pounds was sometimes employed, or 80 per cent. of the calculated amount for the depth, a proportion that shows, with such an amount of cover, that very large and open fissures must have existed to admit water. An airlock and bulkhead were fixed in the tunnel about 40 feet behind the soft rock face described above, the bulkhead, 8 feet thick, being built into chases cut in the rock; and the usual equipment of compressors, electric light, etc., was installed.

The operations up to this date, including the sinking of the shaft, had taken from July 1892 to February 1893. On the 25th of that month, work was resumed under an air pressure of 38 pounds, which was soon raised to 42 to cope with the water which came in through the ground disturbed by the driving of the earlier advance heading.

The excavation was advanced under a cylindrical steel roof, built up of plates 3 feet long and 1 foot wide, of ⅛ inch sheet steel, to the four sides of which were rivetted angle bars 2½ inches by 2½ inches by ¼ inch. These plates were bolted together in a heading about 6 feet high. In the erection of this roof, poling boards were used for each plate, and a bulkhead carried down with each ring as erected. When the heading had been advanced about 20 feet from the rock, a 12 inch by 12 inch yellow pine mudsill or long foot block (see Fig. 142) was introduced along the bottom of the heading, and on this the roof was carried by means of radia timber bracing. The excavation was now carried down on both sides of this mudsill, to a distance of about 10 feet from the rock, the steel roof being extended well down on the sides. A circular section was thus excavated, in which brickwork was laid, four courses thick, and with an internal diameter of 10 feet. Between March 4 and 16 a great deal of trouble was experienced. Air pressure was several times to 48 pounds, and the work progressed very slowly on account of the many inrushes of water, and softened material. It was not until April 8 that the last section of brickwork in the soft material was completed, and rock again entered, after passing through 29 feet of this decomposed material. Of the material met in driving through this vein, at first 9 feet of the grey decomposed feldspar was penetrated, a vein of 4 inches of hard quartz was then met, and this was followed by 6 feet of pure white decomposed feldspar, smooth and soft as plaster. The remaining 14 feet was made up of layers of feldspar and chlorite. This chlorite, deep green in colour, flaky, and grease-like to the touch when wet, proved to be very troublesome material, as it was easily converted into a fluid state by the water, which was again encountered next to the rock.

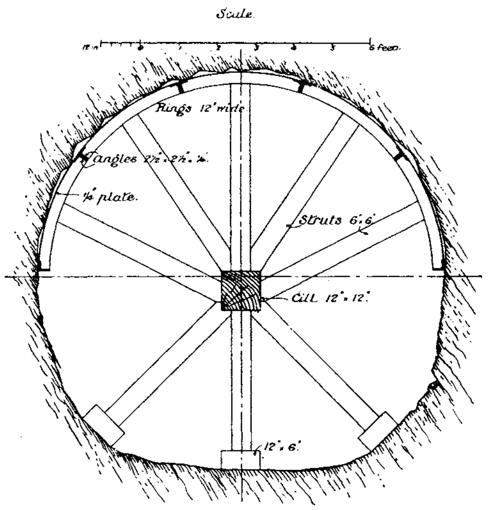


FIG. 142. EAST RIVER TUNNEL, NEW YORK. Iron Polings of Roof.

The rock encountered beyond the soft seam closely resembled the decomposed material which had been penetrated before, and consisted of alternate layers of feldspar and chlorite with an occasional vein of quartz. It was quite soft, though requiring drilling and blasting, and eventually it had to be lined. After the heading had been driven about 69 feet into this rock the company decided, in spite of the uncertainty as to the material ahead, to remove the air pressure. On this being done, however, the brickwork through the soft seam proved so unsatisfactory in excluding the water, that air-pressure was again put on, and it was decided to line the brickwork with a circular cast-iron lining. Although this brickwork was only 10 feet in inside diameter, a lining was designed 10 feet 2 inches in the clear, as it was now desired to make the tunnel bore as large as possible. To put in this lining, some of the brickwork had to be cut out, which was then removed in sections, enough for one ring of plates at a time. The lining consisted of rings of plates or segments, each segment being about 3 feet long and 1 foot 4 inches wide, with internal flanges 4 inches deep, from the back of the plate. The metal in both the back of the plate and the flanges was 1¼ inches thick. All the joint-faces of the segments were planed and 1-inch bolts used for fastening them together. A complete tunnel ring was composed of nine segments and a small inverted key, about 8 inches wide. The weight was a little more than 1 ton per lineal foot of tunnel. The work of putting the cast-iron lining into the brickwork was necessarily a very slow operation. The lining was extended well into the rock on both sides of the soft vein, and a wall built at both ends between the rock and the iron lining, to confine the Portland cement grout which was now introduced back of the plates. To effect this grouting 1¼-inch holes had been drilled and tapped through the back of several plates in each ring. Through these holes the grout was pumped, and after the space between the brickwork and the lining had been thoroughly grouted, the work was found, on taking off the air pressure from the heading, to be perfectly water-tight. It was not until toward the end of July that the work of lining the brickwork was completed and driving ahead in the rock was resumed. Then, when an advance of only 10 feet had been made, a second soft seam was encountered about 80 feet beyond the first one, and a test pipe was driven to a distance of 70 feet without encountering anything solid, the material consisting of decomposed feldspars and chlorites, alternating with black mud and sand.

Water was again found next to the rock, but was to some extent held in check by the compressed air. As from the results of the test pipe there were no special difficulties to apprehend from the indicated material, it was decided to drive ahead, under the open heading method, as this involved no delays in waiting for special machinery. The light steel cylindrical roof was again used in advancing the excavation, but for the permanent lining the cast-iron rings were to be introduced instead of brickwork, as heretofore. A start was made on August 7 to drive the heading into the soft material, but two days later, after the work had been advanced 6 feet into the soft vein, orders were received to suspend all work on account of the great financial depression of the time. This was unfortunate, and could it have been anticipated a few days the heading into the soft material would have been left unopened. As it was now, from being first disturbed and then abandoned, the water was allowed to soften up the black mud in the heading, and, in spite of the bulkhead, a considerable quantity of the material was washed into the tunnel.

By this time some progress had been made with tunnel work from the shaft at Ravenswood, Long Island. Work on this shaft had commenced in June, 1892, and by March, 1893, about 290 feet of tunnel was built, the material met with being a hard seamy gneiss interrupted by seams of soft chlorite about 4 feet thick. At this point, however, a vein of almost liquid chlorite was found by test drills about 2 feet ahead of the face.

These holes were plugged, but as it was necessary to know what was ahead, and as with 100 feet of cover between the tunnel roof and the river bottom it was thought that the condition of affairs could not be very serious, it was decided to continue driving ahead without air pressure, and with a timbered heading. To see what the material would do, several hand-holes were put into the rock-face with the object of blasting out a hole about 2 feet square through the remaining 2 feet of rock, to the chlorite. Before blasting, however, the precaution was taken to build a bulkhead, some 40 feet back from the face. On firing the holes, an inrush of many yards of material took place, which was finally checked by some rock fragments closing the opening through the rock.

Repeated attempts to work a timbered heading in this material proved unsuccessful, and in March, 1903, work was abandoned, and the shaft and tunnel were drowned out. When the stoppage of work in the New York heading, due to financial difficulties, occurred, work in the other tunnel had been at a standstill for five months, except that an airlock and bulkhead had been put in, and a trial hole driven in the face which disclosed the fact that the seams of chlorite and other soft matter was 32 feet thick, and that beyond was a soft white limestone.

When the company were in a position to resume tunnelling operations, it was resolved to employ shields, and as the bulkheads and airlocks were already built in the tunnel it was necessary to design the details of the machines so as to admit of all the parts passing through the airlocks, and it was thought convenient also to make them, as far as was compatible with the necessary stiffness, easy to strip and re-erect, so as to admit of the shields being taken to pieces and re-erected with ease.

Figs. 143 and 144 [1] show the shields as designed by Mr. Aims to meet these requirements. To avoid having the plates of the skin of the usual large size, the length of the skin plate being generally the length of the shield, he divided the

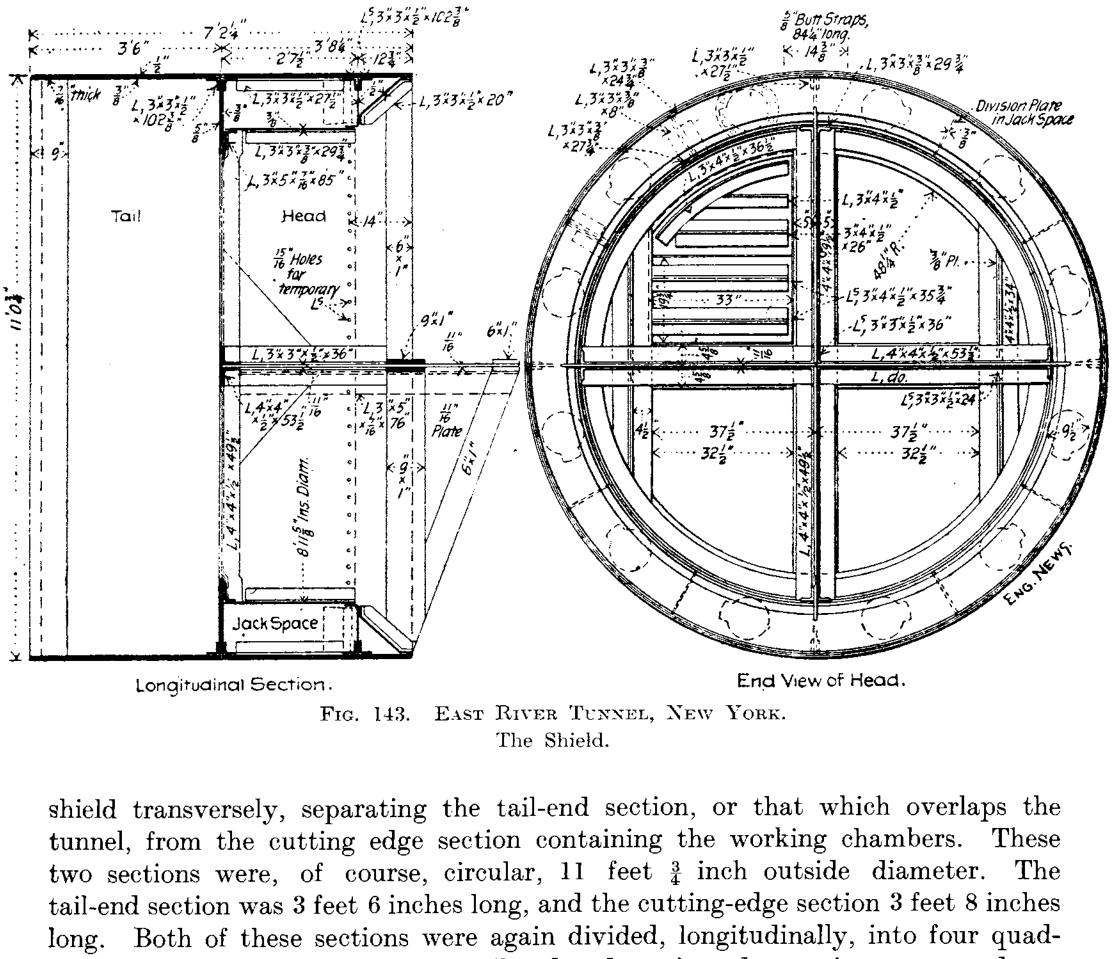


FIG. 143. EAST RIVER TUNNEL, NEW YORK.
The Shield.

shield transversely, separating the tail-end section, or that which overlaps the tunnel, from the cutting edge section containing the working chambers. These two sections were, of course, circular, 11 feet $\frac{3}{4}$ inch outside diameter. The tail-end section was 3 feet 6 inches long, and the cutting-edge section 3 feet 8 inches long. Both of these sections were again divided, longitudinally, into four quadrants. The outside shell, in both tail-end and cutting-edge sections, was made up of one $\frac{1}{2}$-inch and one $\frac{3}{8}$-inch steel plates rivetted together, and, at the four quadrant joints, there were $\frac{1}{2}$-inch butt-straps 12 inches wide running the whole length of the shield and uniting the quadrants and the two sections. The middle diaphragm, separating the cutting-edge and tail-end sections, was made of two plates, one

[1] Reproduced from *Engineering News*, March 1, 1894, by courtesy of the Editor.

rivetted to each of the two sections, and these two plates bolted together with the butt-straps united the sections.

The cutting-edge section contained two stiffeners, one vertical and one horizontal, of the same length as the section.

Within the skin of the front section of the shield was built a circular box girder, the inside flange of which, ⅜ inch thick, had a diameter of 9 feet. In this, in compartments formed by plate gussets and angles, were twelve hydraulic rams.

The cutting edge extended 1 foot beyond the box girder containing the rams, and was stiffened by inclined plates from the flange of the girder to the skin.

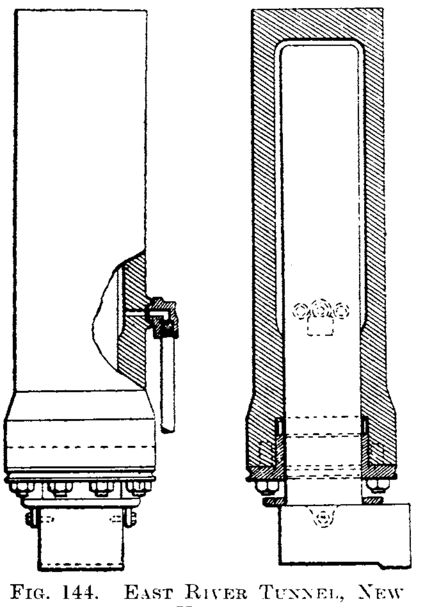


FIG. 144. EAST RIVER TUNNEL, NEW YORK.
The Shield: Hydraulic Rams.

The horizontal stiffener, or platform, in the cutting edge section of the shield, in front of the main diaphragm, had provided a detachable extension in front which extended 2 feet 8 inches in front of the cutting edge, and served the same purpose as the sliding tables on the larger shields used in London Clay tunnelling, namely to hold up the face, and to afford a working area for the miners when taking out the excavation at the top.

To erect this shield the only rivetting necessary was at the four but-strap joints in the tail-end section, where it was necessary to preserve a flush surface on both sides of the outer shell. In the cutting edge part countersunk bolts were used through the butt-straps. About 380 ⅞-inch bolts and 160 rivets were used to erect the shield. Two doors closing each of the four working chambers were hung on the vertical platform, and were provided with fastenings so that the whole face could be easily closed.

This arrangement resembles that adopted for the Greenwich tunnel shield in the later stages of that work (see Figs. 163 and 164).

To drive the shield twelve 5-inch hydraulic jacks were used, designed for a working pressure of 5,000 pounds per square inch, or 600 tons on the whole shield (Fig. 144). These jacks were controlled by two block-valves, one placed on each side of the shield. Each of these block-valves consisted of six independent valves all in one compact casting, each of which had a pressure and exhaust stem. Half-inch pipe was used for connecting each jack with its valve, and 1-inch hydraulic pipe was used for the pressure-main which was connected with the shield block-valves by three swivel-joint connexions. To furnish the pressure, a very compact little pump, was used without an accumulator, the pressure being governed by a steam-regulating valve.

On September 22 work was resumed on the New York side, with a small force of men working days only, to excavate in the rock an enlarged chamber about 15 feet back from the face, in which to erect the shield. This chamber was made circular about 15 feet in diameter and 10 feet long. Back from this, the rock was taken out in a circular form of about 11 feet diameter, for some 14 feet, or enough for about 10 rings of the cast-iron segments which were here erected in the rock, the spaces between being thoroughly grouted with Portland cement. These rings were thus made solid in the rock to withstand the thrust of the shield-jacks upon the lining. The blasting necessary in this work was made as light as possible, but it was not without its effect upon the soft material in the heading, a considerable quantity of the black mud being washed through the bulkhead, while the braces showed signs of a heavy strain from the squeezing of the material. The shield arrived at the works on November 10, and the work of erection was immediately begun. The sections were lowered down the shaft and taken through the airlock to the shield-chamber. On November 17 the shield was all assembled, and rivetting the tail-end sections was commenced. For heating the rivets in the air-chamber a forge was used, with a hood to which was connected at the top a 2-inch pipe with a valve which extended through the air-lock bulkhead. By means of this pipe all the obnoxious gases from the furnace were removed from the air-chamber. After the rivetting was finished, the shield was brought to its right position for line and gradient, and all the machinery of the rams fitted to it ; the length of cast-iron lining already erected was extended to reach under the tail of the shield, and the advance was commenced. Continuous work, in eight-hour shifts, was arranged for.

The shield was advanced until it was necessary to disturb the bulkhead, the remaining bench ahead of the shield being blasted out as the shield progressed.

The most difficult part of the work was then reached, for at the point where the shield entered the soft black mud on top there still remained about 12 feet of hard rock in the bottom, as the dip of this vein was over 40 degrees towards Long Island. Blasting had therefore to be continued in the bottom pockets of the shield after the top had entered the much softened material. As soon as the bulkhead was passed it was with great difficulty that the bottom pockets could be kept clear of the black slush from overhead. The material had become so softened along the rock face that it was almost impossible to confine it, and several rushes of inflowing material occurred, until finally an open connexion with the river was established, and the tunnel was visited by crabs and mussels, together with boulders, old boots and shoes, brick, and tinware direct from the river bottom. Notwithstanding these adverse circumstances the work went on, although in 45 pounds of compressed air, which was now escaping through the heading and causing a very violent ebullition on the river surface. This upward current of air held in check the downward current of water, so that no efforts were made to prevent its escape. On December 13 the shield finally cleared the rock and was now fully entered into the soft black mud. The main difficulty now surmounted, the work progressed more rapidly, and the shield soon reached undisturbed material, a black mud, dry and hard, with occasional lumps like charcoal and numerous nodules of pyrites. Mattocks were used by the men in the working chambers, who would clean out these four compartments to within a foot of the cutting edge. As soon as this was done hydraulic pressure was put upon the jacks, sometimes to the amount of 5,000 pounds per square inch, and the shield forced ahead 16 or 18 inches, enough for another ring of plates, the working chambers again being filled with the displaced material. On December 24 the last of the black mud was passed through, and lying next to it, at an angle of 40 degrees towards Long Island, white decomposed feldspar was found, containing fragments of decomposed quartz charged with sulphuretted hydrogen. An important departure was now made in the method of erecting the cast-iron lining by making the successive rings break joint, instead of having, as had previously been the case in all iron-lined tunnels, the horizontal joints in a continuous line. On January 16, 1894, the end of the soft seam was reached with the shield, and rock was again entered after having passed through 98 feet of soft ground. This rock resembled slightly the rock on Blackwell's Island. It was in a much shattered condition, with many loose heads and small, soft veins. As this material required support in the heading and a permanent lining, and as, in its present condition, there was no assurance that it might not again pass into soft material, shield tunnelling was still continued. Small machine-drills were set up in the four working chambers of the shield upon arms bolted to the vertical platform, and the rock, drilled and blasted, just ahead of the shield. The progress of 4 feet per day was made in this material for a distance of about 65 feet, when solid rock was met with, and the shield was dismantled and removed, the remainder of the work from the New York end of the tunnel being carried out by the ordinary process of drilling and blasting the rock. This was in February, 1904, and in the same month shield work was commenced at the Long Island end of the tunnel, where, however, no special difficulties were met with in passing through the soft seam of green chlorite. For a length of nearly 90 feet the tunnel was lined with cast iron erected under compressed air, the work occupying a month, after which the shield was removed, and the air pressure taken off, the white limestone which was then met with being worked by ordinary methods. At the point where the tunnel passed from this material to the gneiss rock of the New York end, a further soft seam of decomposed chlorite was passed through which necessitated the re-employment of compressed air, and for a distance of 40 feet the tunnel was lined with cast iron, erected, however, without a shield.

The tunnel was completed in July, 1894, two years having been occupied in constructing the entire length of 2,516 feet.

Chapter VII

THE SHIELD IN WATER-BEARING STRATA (continued)

The Vyrnwy Aqueduct Tunnel—Commenced without a Shield, and without Compressed Air—Failure of Operations—Shield and Compressed Air Provided—Description of Shield—Timber Safety Diaphragm or Trap in Tunnel Behind Shield—Second Abandonment of the Works—Reconstruction of the Shield—The "Trap" Diaphragm—Double Airlock used in the Tunnel—The Greenwich Subway—Description of Tunnel—Machinery and Plant—The Caissons—Their Airtight Floors—The Plugs in Tunnel Openings of Caissons—Erection and Rivetting of Caissons—Sinking of Caissons in Compressed Air—Erection of Shield in Caissons—Opening out the Tunnel Face—The Airlock and Bulkhead—Safety Diaphragms in Tunnel—Rate of Progress in Tunnelling—The Shield, Detailed Description—The "Trap" Diaphragm—The Face Rams—Original Method of Working a Failure—Trial of Needles in the Face—A Poled Face Adopted, with Clay Pockets in Front of Cutting Edge—Description of Working—Alteration of Shield Diaphragms—Ventilation of Shield—Cost of Shield, and Working Gang Required—The Lea Tunnel—Shield Chamber and Airlocks—Safety Diaphragms and Vertical Airlock—Details of Shield—The Baker Street and Waterloo Railway—Shafts in River—Details of Shield—Combination of Hood and Shutters—Timbering of the Face—Description of the Method of Working

The Vyrnwy Aqueduct Tunnel under the River Mersey at Fidler's Ferry [1]

AT the same time (1888) that the assisted shield as described previously was employed on the City and South London Railway, another undertaking involving the driving of a tunnel through water-bearing material of an extremely difficult nature was taken in hand, in connexion with the Liverpool water supply from Lake Vyrnwy.

It was a necessary part of this scheme to construct a tunnel to carry the main pipes of the aqueduct under the River Mersey above Liverpool, access to the tunnel, which was of cast iron and 9 feet in internal diameter, being gained by cast-iron lined shafts sunk on either side of the river.

The shafts were originally constructed with a view to placing the tunnel about 100 feet below high water level, it being known that boulder clay was to be found at that depth, and, it was hoped by the engineer, of sufficient tenacity to exclude the water beds which permeated the beds above, and permit of the construction of the tunnel not only without a shield, but without compressed air.

A commencement was made (1888) with the tunnel at the depth mentioned, no shield being used, but compressed air being employed.

When, however, only some 60 feet out of a total length of 805 feet had been constructed after eighteen months' work, the contractor who had undertaken the work withdrew.

[1] Simms' *Practical Tunnelling*, p. 449. *Proc. Inst. C.E.*, vol. cxxiii. pp. 100–105.

The material met with, instead of proving, as was hoped, clay homogeneous in character, was very variable and bad to work in. In spite of the use of compressed air, water made its way into the tunnel, ultimately completely flooding it.

Another contractor having undertaken the work, it was decided, on the advice of Mr. Greathead, to abandon the length of tunnel already constructed and to drive another one at a level of about 50 feet below high water, and to do it under a shield in compressed air, it being known that at that level the material met with would be water-bearing, and of loose open character. This proved only too correct a description of the material met with, with the additional inconvenience that the character of the working face varied constantly even in the length of excavation required for a single ring of the tunnel lining. Clay, coarse ballast, and running sand

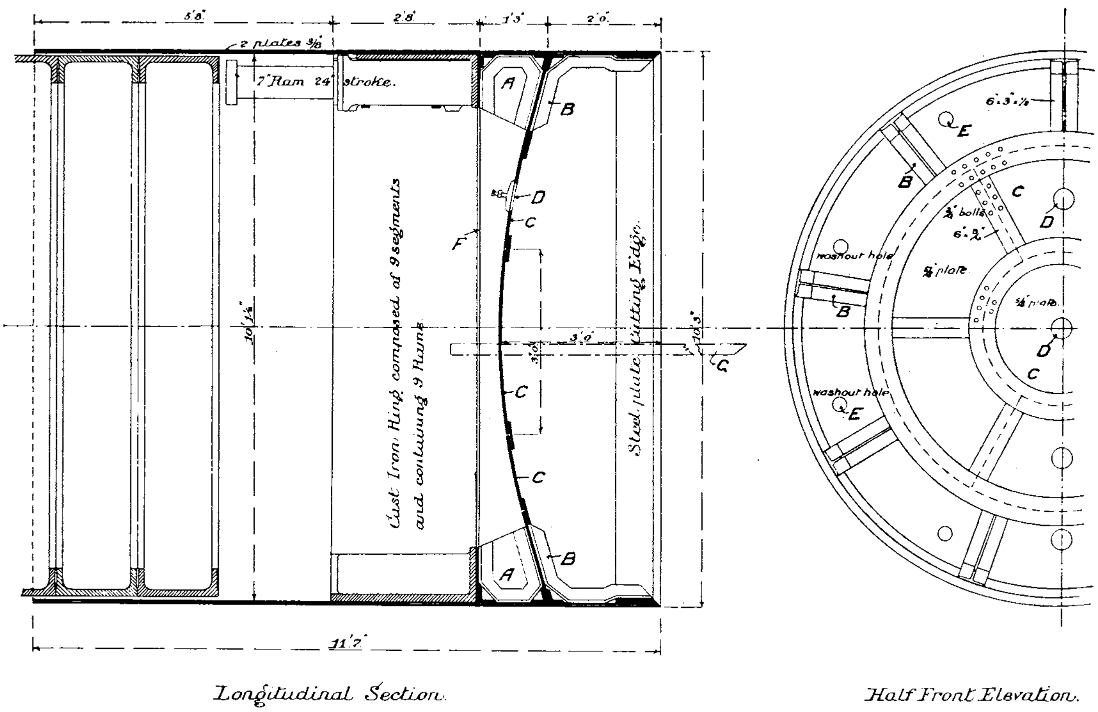


FIG. 145. VYRNWY AQUEDUCT TUNNEL, LIVERPOOL.
The Shield as first constructed.

were all met in turn, and frequently the vertical face of the tunnel work showed bands of them all.

The compressed air arrangements followed the usual lines, but the design of the shield was a departure from the type used at the Tower Subway and on the City and South London Railway. The results obtained with the shield as at first designed were not satisfactory, but some of the features of the original shield are of interest in view of later developments, and the improvements introduced during the progress of the work have been elaborated since, and used in this country in the Greenwich Tunnel under the Thames, and in the subaqueous portion of the Baker Street and Waterloo Railway in London.

The shield as at first designed is shown on Fig. 145, the details of the hydraulic rams, pumps, and pipe connexions being omitted from the drawings.

The outside cylinder or skin consisted of two ⅜-inch steel plates, made to break joint in the ordinary way, its inside diameter being 10 feet 1½ inches, thus having ¾ inch play round the cast-iron lining of the tunnel. At the front the skin was stiffened by a steel plate cutting edge. The total length over all was 11 feet 7 inches.

The front diaphragm, instead of being, as in the Greathead shield, composed of a fixed vertical plate pierced by a rectangular door in the centre, was made of curved plates, some of which were removable, having their concave sides to the front of the shield. This diaphragm, ⅝ inch in thickness, was at its circumference,

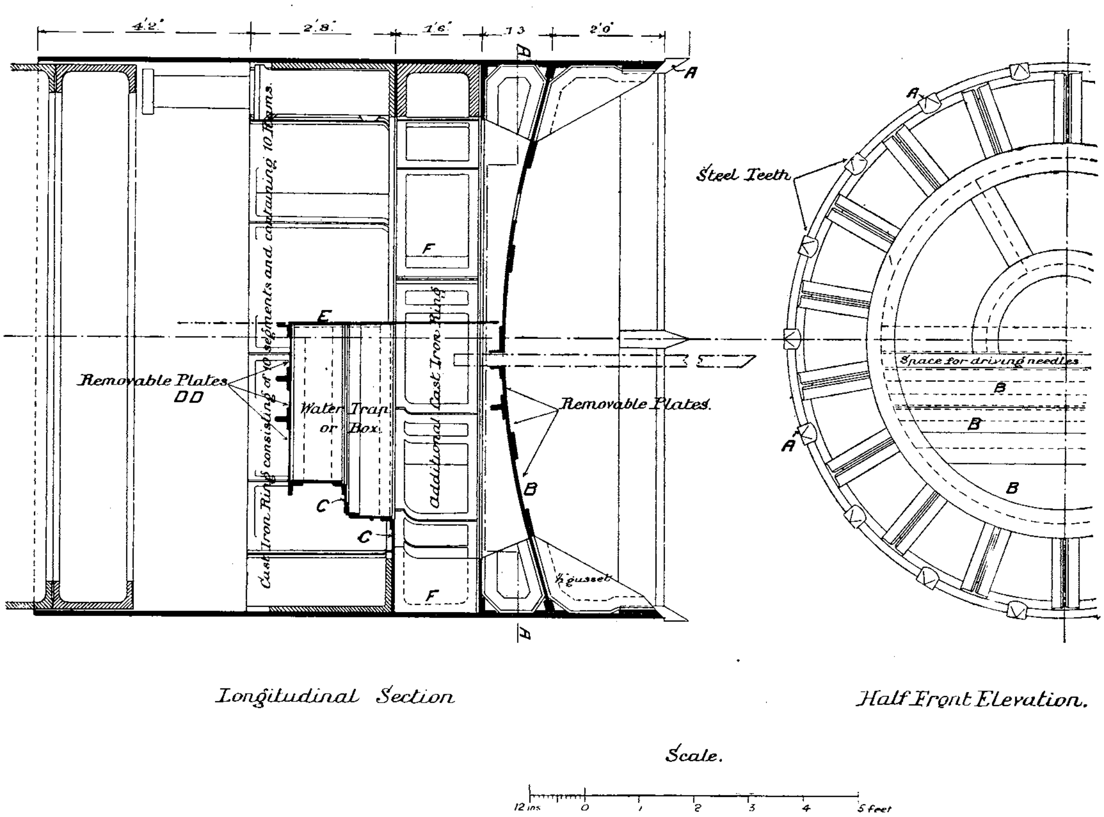


FIG. 146. VYRNWY AQUEDUCT TUNNEL, LIVERPOOL.
The Shield as altered. (For Section on line *A*, *A*, see Fig. 147.)

where it joined the skin, 2 feet from the cutting edge; at its centre on the axis of the shield it was 3 feet from the front.

It was secured to the skin by angle irons, by gussets *A*, *A*, behind, and by T irons, 6 inches by 3 inches by ⅝ inch in front, these latter *B*, *B*, serving also as supporting brackets to the cutting edge. (Fig. 145.)

The outer portion of the diaphragm so attached to the skin was of course irremovable, but the central portion, about 6 feet 6 inches in diameter, was formed of seven separate removable plates *C*, *C*, *C*, joined to each other and the outer portion of the diaphragm by cover strips fastened with ¾ inch bolts. In the diaphragm were hand holes *D*, *D*, and small ones *E*, *E*, through which a hose pipe could be introduced to loosen the material in front by means of water jets. In the lowest of the radial plates, a sluice valve was fitted so that the semifluid material washed down by these jets could be passed out behind the shield.

Immediately behind the gussets A, A, was placed a circular plate F, secured by an angle iron to the skin, and rivetted also to the gussets.

Behind this plate was a cast-iron ring, in nine segments, bolted to each other and to the skin. Each segment formed a cradle for a ram, 7 inches in diameter, which abutted on the front flange of the segment.

The design of the shield is open to criticism, and in actual work the combination of a closed face and the use of water jets failed to justify the inventor.

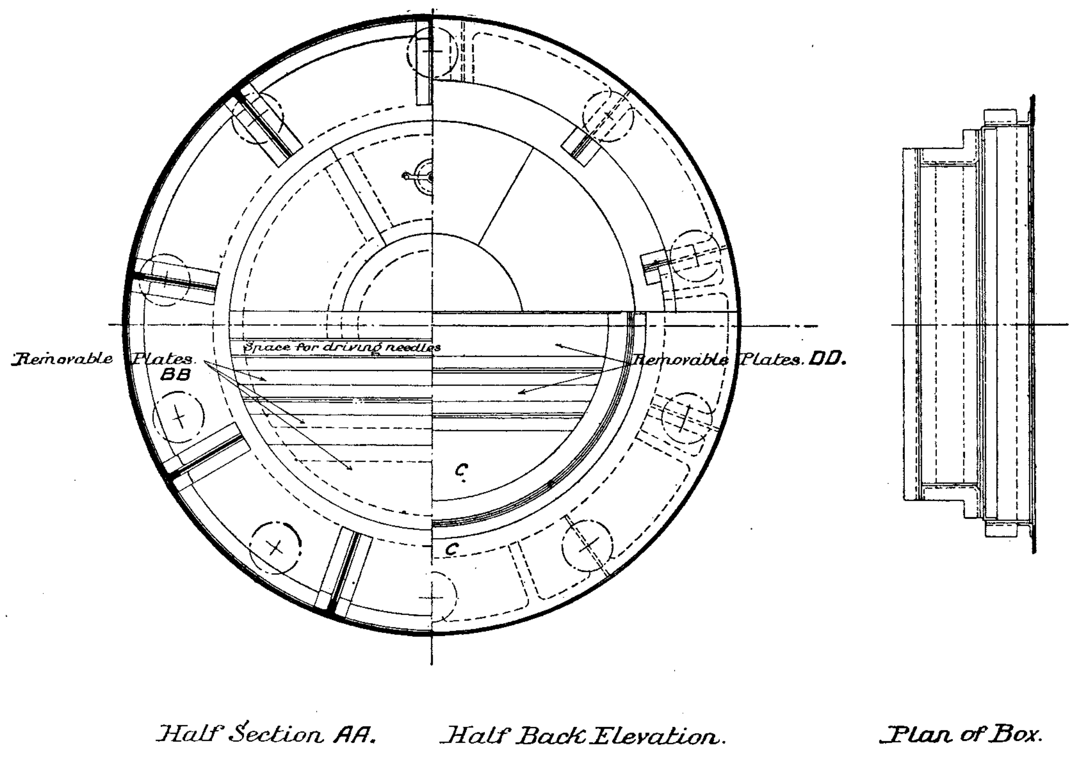


FIG. 147. VYRNWY AQUEDUCT TUNNEL, LIVERPOOL.
The Shield as altered. (For position of Section A, A, see Fig. 146.)

But some features of the shield were an advance on previous machines, and as regards the water-jets it must be noted that Mr. Greathead himself at that time favoured their use in tunnel work, not merely as subsidiary aids, but as a principal method of working in loose ground.

He had in 1874, and later in 1884, taken out patents for shield work on the same principle.

The placing of the front diaphragm of the shield sufficiently far back from the cutting edge to provide a working space in front of it, under the protection of the skin, was a distinct advance. As built, the projecting skin lacked strength, and this was one of the causes of trouble.

The arrangement of the diaphragm by which a larger or smaller opening to the face could be given at will was also an improvement, and in the more modern plan of constructing the diaphragm partly in removable horizontal strips has proved very useful in several cases.

The arrangement of the diaphragm, as actually constructed, with a removable central plate, and radial ones around it was not, however, satisfactory.

When the shield was first put in motion, the method of working attempted was as follows :—

The sluice in the lower removable plate in the diaphragm being opened, water jets were directed on the face through the openings provided for the purpose, the idea being that the water jets would loosen the material of the face, and that the resulting mixture of gravel and slurry would flow out through the sluice valve, when it would be loaded up by the miners, who would thus be working always under the protection of the shield. No timbering or mining work in front of the shield would indeed have been necessary if the water jet scheme had been successful.

It is quite possible that a tunnel in perfectly homogeneous alluvial material might be driven in this manner ; in the actual conditions the effect of the water jets was simply to wash out a channel in front of each jet for a little distance, whence the water found its way to the bottom of the shield, with little or no effect on the material of the face.

After some trial this method of working was abandoned, and excavation was carried on by raking out material through an opening at the bottom of the diaphragm, made by removing altogether the lowest removable radial plate.

Progress was slow, owing to the smallness of the opening, and to the continual falling down of the material above, as that at the level of the opening was removed, which enormously increased the cubical amount of excavation necessary per foot advance of the shield.

To lessen this movement of the face, needles *G* made of channel bars were driven through a groove cut in the diaphragm near the horizontal axis. They were long enough to project some 3 feet into the solid beyond the cutting edge, and were spaced 12 inches apart. (Fig. 145.)

Their use prevented the falling in of the face in a great measure, and some progress was made.

For greater security a timber diaphragm was built in the invert of the tunnel at a little distance behind the shield, its upper edge being a few inches above the top of the bottom opening in the diaphragm of the shield.

A water trap was thus formed, so that in the event of a " blow " in the face, and a consequent inrush of water through the shield, the water coming into the tunnel would be held by the timber diaphragm until it rose over the top of the timber by which time the opening in the shield diaphragm would be under water, and the outrush of air choked.

This simple and ingenious arrangement was designed first by Mr. Greathead in his shield for the Woolwich subway in 1874 (the shield was made but never used),[1] and has been used since with entire success ; indeed, as will be seen, it was the main feature in the alterations subsequently made in the shield under consideration.

When the tunnel had been driven about 180 feet, the contractors abandoned the work, and the engineer, Mr. Deacon, resolved to complete the undertaking himself.

[1] See Fig. 11, page 17.

Acting on the advice of Sir B. Baker, he made an entire alteration in the working of the shield, the details of which were considerably modified at the same time. Figs. 146 and 147 show the shield as altered, or rather transformed, for it had, save the skin and rams, very little in common with the machine shown in Fig. 145.

In the original shield the portion of the skin projecting in front of the diaphragm and forming the cutting edge was not sufficiently stiff, and had buckled in consequence.

The existing gussets were strengthened and new ones added, while the knife of the cutting edge was provided with eighteen teeth *A*, *A*, projecting 6 inches in advance. The effect of these teeth was to immensely reduce the hydraulic power required to move the shield forward.

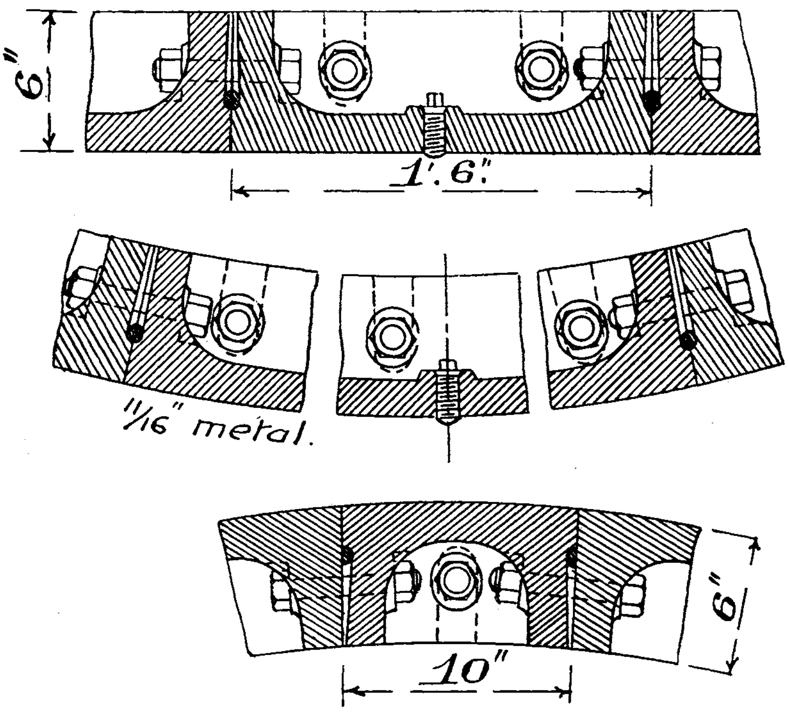


FIG. 148. VYRNWY AQUEDUCT TUNNEL, LIVERPOOL.
Details of Cast Iron Lining of Tunnel.

The principal alteration made, however, was the placing of a water trap on the shield itself instead of the previous makeshift one in the form of a timber diaphragm in the tunnel behind the shield.

To effect this the lower half of the shield diaphragm was removed up to within a few inches of the horizontal axis of the shield, and provision made for closing, if necessary, the semicircular opening so made by removable steel strips *B*, *B*, stiffened with angle irons.

Behind this diaphragm was fixed a second one *C*, *C*, or, rather, this second one was a built frame forming three sides and bottom of a box, of which the fourth side was represented by the lower plates in the front diaphragm. The sides of this box were made of removable plates *D*, *D*, similar in construction to those in the front.

On the top of this box was fitted a sliding lid *E*, which, when closed, completely shut up the face of the shield.

The top of the back plates of the trap was about 6 inches above the bottom of the upper solid half of the front diaphragm. Six inches was therefore the amount of "water-seal," supposing the shield to have no roll to either side.

This arrangement may be described as an application, on a larger scale, of the principles of action which are shown in the ordinary drinking fountain in a bird-cage.

In this, the domed reservoir holds a certain amount of water, which would flow away from the opening at the base, were it not for the air pressure without. In the shield, as in the bird's drinking fountain, the flow of water stops immediately the opening is "sealed" by the water.

In an ordinary shield and also in the "trap" shield when the face is dry, the face where the air pressure and water pressure meet is vertical, and consequently the pressure of air necessary to keep all the face dry must equal the water pressure at the invert of the shield. Immediately a "blow" at the face occurs, and the

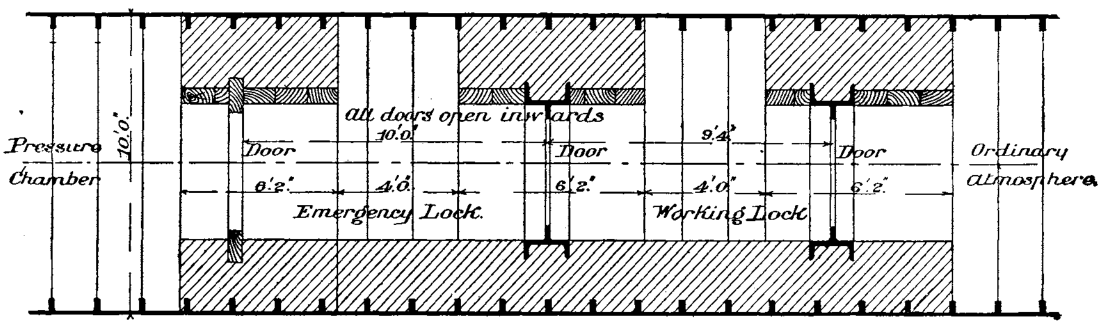


FIG. 149. VYRNWY AQUEDUCT TUNNEL, LIVERPOOL.
Bulkhead with Double Airlock.

"trap" of the shield is closed by water, the vertical face becomes a horizontal one, and one, too, where the hydraulic head is less by the height of the "trap" water level above the invert than the air pressure, thus insuring the holding of the incoming water by the air pressure.

The needles in front of the shield, which had previously been found serviceable, might, it was thought, prove useful again, and the openings for them in the diaphragms were retained.

The number of rams was increased from nine to ten, and consequent on this change, an extra ring of cast-iron segments *F*, *F*, was introduced, partly to better distribute the thrust of the rams, and partly to stiffen the skin of the shield and make room for the water-seal.

The shield as altered proved very well adapted to its work, the miners gaining courage to pass in front of the diaphragm and excavate the face, fixing light timber supports stayed from the cutting edge of the shield, and the construction of the tunnel made good progress; an average speed of 34 feet per week was maintained, the greatest distance bored in any one week being 57 feet.

On several occasions "blows" occurred in the face, but when the miners had time to close the door *E*, no flooding of the tunnel took place, and by increasing the air pressure it was easy to partially dry the material filling the trap and remove it.

When a blow occurred too suddenly for any precautions to be taken, a certain amount of water and sand entered the tunnel. The water-seal, formed as soon as the water from the face rose above the bottom of the front diaphragm, was always effective, and only on one occasion did any appreciable quantity of material find its way into the tunnel.

The history of this shield is a very instructive example of the making of an ineffective machine into an effective one, and it is interesting to compare its evolution with that of the Greenwich Tunnel shield described later in this chapter, as the latter machine was, as at first constructed, an attempt to combine in one machine the good points of the first and second shields of the Vyrnwy Tunnel.

As stated above, the compressed air arrangements followed the usual lines, and do not call for any special description.

One detail, however, may be noted.

The airlock in the tunnel (Fig. 149) did not apparently, as first made, give a sufficient sense of security to the miners, and there was therefore constructed on the pressure side of the working lock a second bulkhead, having in its centre a wooden door opening towards the pressure chamber. The effect of this was practically to double the capacity of the lock, but beyond this there does not seem to be any advantage in the way of additional security, and the double lock has not been employed since.

The Greenwich Subway (1899)

The Greenwich Subway[1] consists of a tunnel under the River Thames, connecting the Isle of Dogs, Poplar, on the north bank with Greenwich on the south. Two shafts 43 feet in external diameter, and respectively 44 and 50 feet deep from ground level to the tunnel entrance contain circular stairways and lifts giving access to the tunnel. These shafts were, during construction, the only means of access to the tunnel works (see Fig. 170).

The tunnel itself is 12 feet 9 inches in external diameter, and is lined with cast iron (see Figs. 30, 31, 32).

From each shaft the tunnel dips towards the centre of the river with a gradient of 1 in 15; the middle portion of the tunnel is on a gradient of 1 in 227, falling towards the Greenwich shore. These gradients were entailed by the advisability, from motives of economy, of limiting the depths of the shafts, and by the necessity of complying with the conditions of the Act authorizing the undertaking, which stipulated that the level of the tunnel should be such as to allow of dredging in the river a channel 500 feet wide and 48 feet deep at high water.

It was arranged to start the tunnel from the northern, or Poplar shaft, and the contractors' yard and general machinery and workshops were laid out, therefore, at this end. The machinery installed for the work was as follows, in addition to the ordinary hoisting machinery in the shaft. There were two large air compressors built by Walkers of Wigan with a capacity, estimating the efficiency at 80 per cent., of 52,000 cubic feet per hour each at any reasonable pressure.

These engines worked with a boiler pressure of 100 pounds, and the high and low pressure cylinders were respectively 18 inches and 24 inches diameter, the

[1] *Proc. Inst. C.E.*, vol. cl. The Author's Paper on *The Greenwich Footway Tunnel.*

length of stroke being 42 in hes. The air cylinders were 24 inches in diameter.

These were for the supply of air to the working chambers in the shafts and tunnel only, and in addition an Ingersoll-Sargeant straight line piston inlet compressor of 40 I.H.P. with an automatic regulator and unloading arrangement was employed, for working the pneumatic rivetters which were largely used in putting together the shafts, for the blast in rivet forges, and for driving sundry small machines in the workshops, for driving the hauling engine within the tunnel, and later for pumping.

Two small steam-driven hydraulic compressors were employed for supplying power to the shield rams. These could work up to a pressure of 3 tons per square inch. The steam cylinders were 8 inches in diameter with 10 inches stroke, the water cylinders being 1 inch in diameter. They were fitted with an automatic unloading device to cut off the steam when the hydraulic pressure rose above the required pressure.

Dynamos driven by small vertical engines were provided for lighting the tunnel and works.

A wash-out pump was provided with the intention of using water from the River Thames to wash down the working face of the tunnel, but was not used. It was, however, employed several times for forcing water outside the shafts when sinking, with a view to lessen the skin friction.

In addition to the ordinary offices, stores, cement shed, and workshops, a set of rooms, properly heated, with proper washing appliances, were provided for the gangs working in compressed air.

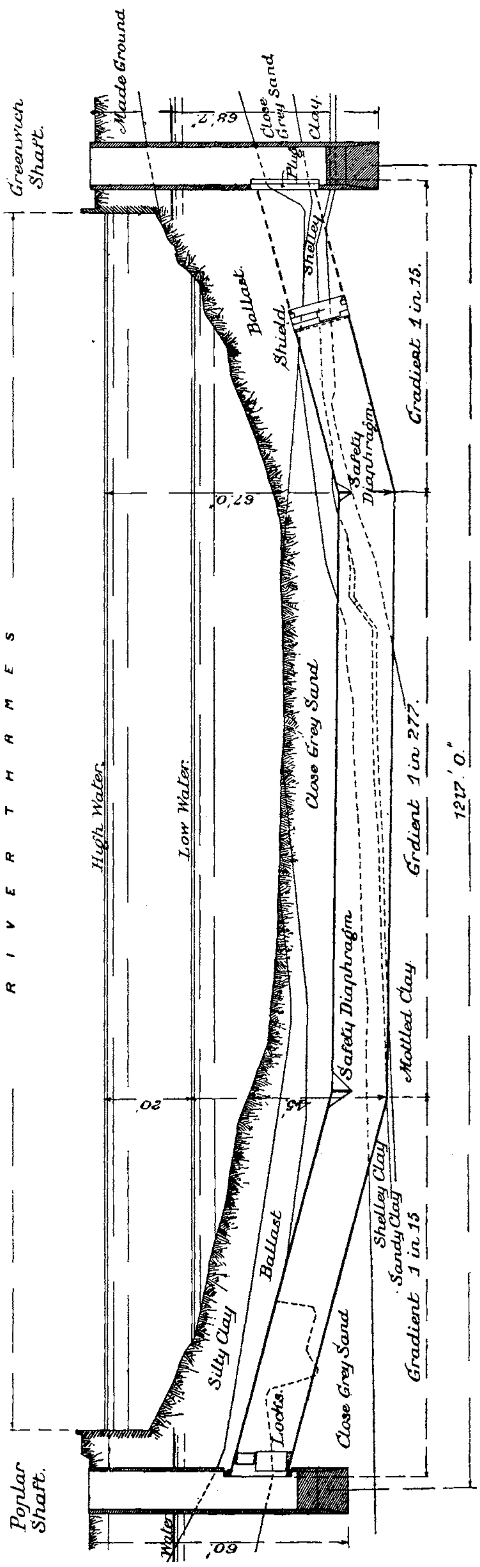


FIG. 150. GREENWICH TUNNEL, LONDON. Longitudinal Section.

A medical lock and medical officer's room were of course required.

The general arrangement of the contractors' yard is shown in Fig. 151.

The two shafts are alike in general construction, and differ only in depth, that on the Poplar shore measuring 60 feet from top to cutting edge, and the Greenwich shaft 66 feet 7 inches.

The caissons (see Figs. 152 and 153) are 35 feet in internal, and 43 feet in external diameter, and are formed with two steel skins, the 4-foot space between which is filled with 6 to 1 Portland-cement concrete. The skins are formed of horizontal rings built up of plates, which are generally about 4 feet 9 inches in depth and vary in thickness from $\frac{5}{8}$ inch at the bottom of the caisson to $\frac{5}{16}$ inch at the top ; the vertical joints in each ring are arranged, wherever possible, to break

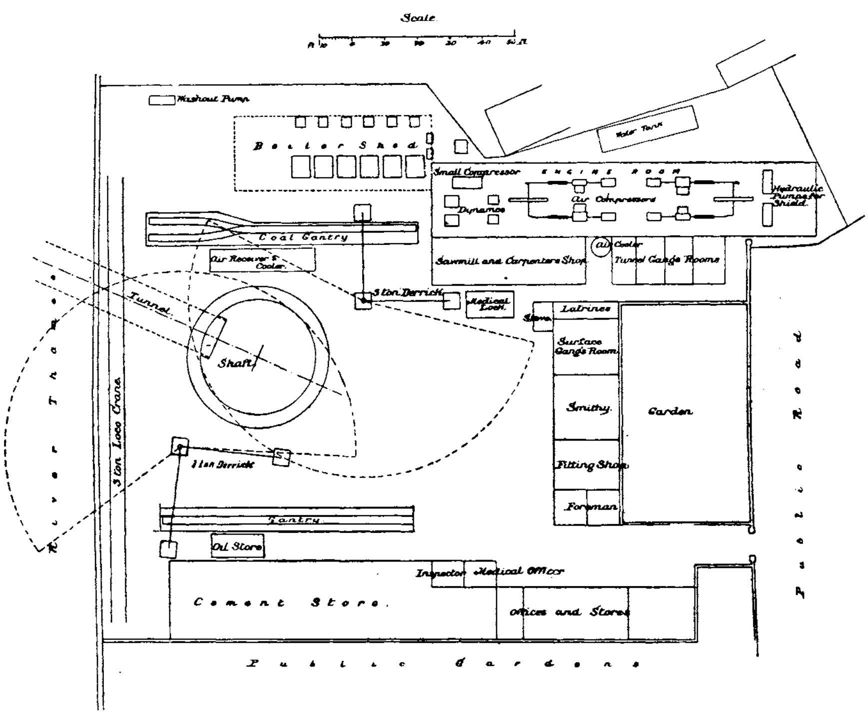


Fig. 151. Greenwich Tunnel, London.
Contractor's Yard.

joint with the rings above and below. The skins are braced together with vertical angle-bar frames and horizontal angle-bracings. At the points where the main girders of the air-tight floors are attached, the webs of which are carried through to the outer skin, vertical plate gussets are fixed in the rings above and below, to resist deformation under the severe stress produced at the ends of the girders by the air-pressure on the floor. Around the tunnel-opening, also, the caisson is strengthened by numerous plate gussets.

The cutting edge is 7 feet in depth, and is formed by inclining the inner skin to meet the outer : at the edge thus formed an extra plate, $\frac{3}{4}$ inch thick, is placed round the outer skin for greater stiffness. The bottom edges of the cutting edge plates are not flush with one another, but each edge is 1 inch above that of the plate outside it, so as to allow of easy caulking. All caulking at this and other parts of the shafts was done by means of pneumatic tools. The cutting edge is further strengthened by forty-eight triangular vertical gussets ½ inch thick. At the top of the inside skin of the cutting edge is fixed round the entire circumference

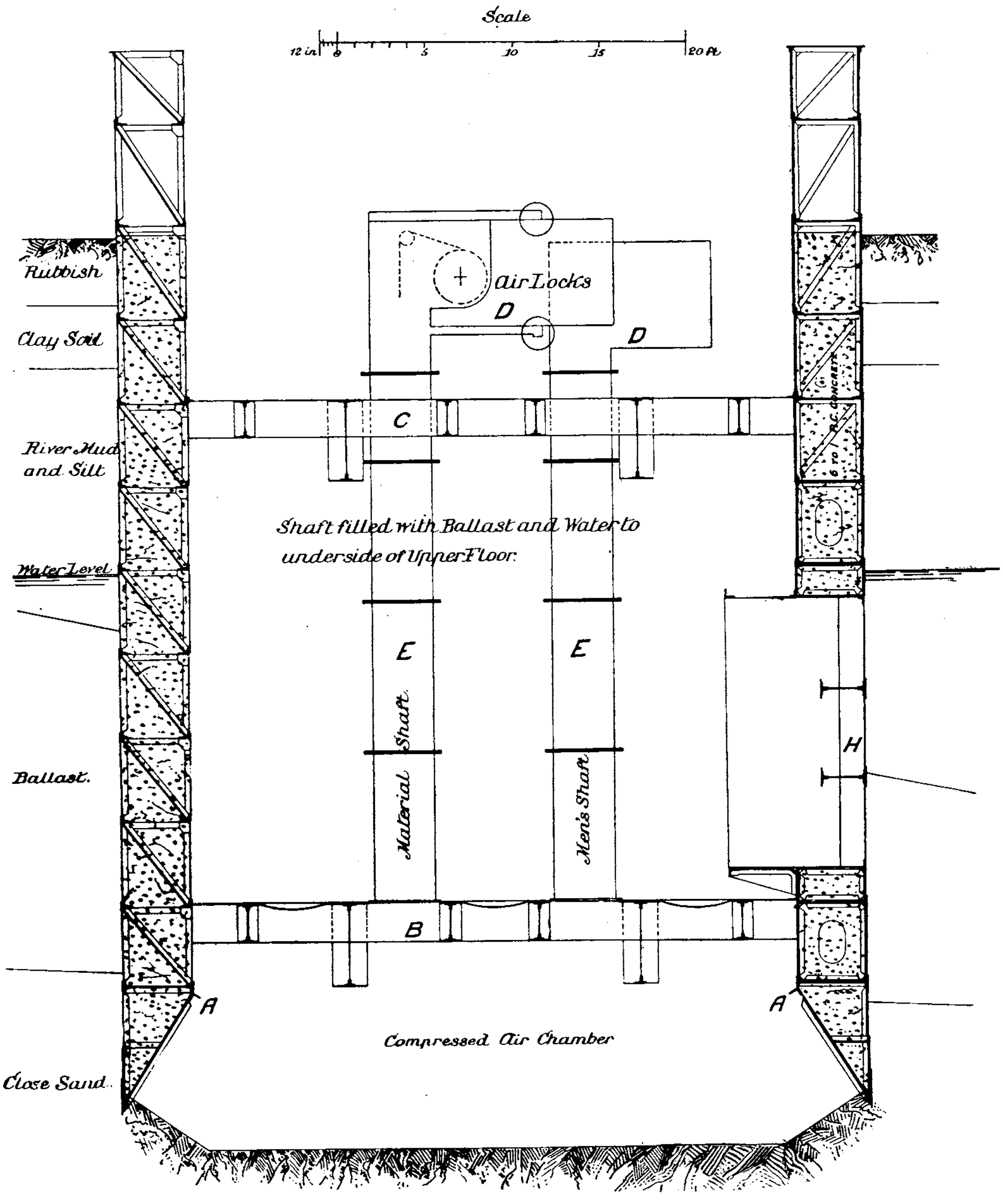


FIG. 152. GREENWICH TUNNEL, LONDON.
Method of sinking Shafts.

an angle-bar *A* (Fig. 152), 6 inches by 6 inches by ¾ inch. It was intended to use this as a bracket under which timbers could be fixed in order to control the sinking of the shaft. In practice, however, all such work was done by timbers fixed under the main girders of the air-tight floor.

The outer skin of the caisson was without the usual batter, but the plates of each ring were inclined outwards towards the top, so that the top edge of every ring touched a vertical cylinder. The caisson was therefore of uniform diameter from top to bottom, excepting for the extra ⅜-inch plate at the cutting edge ; and

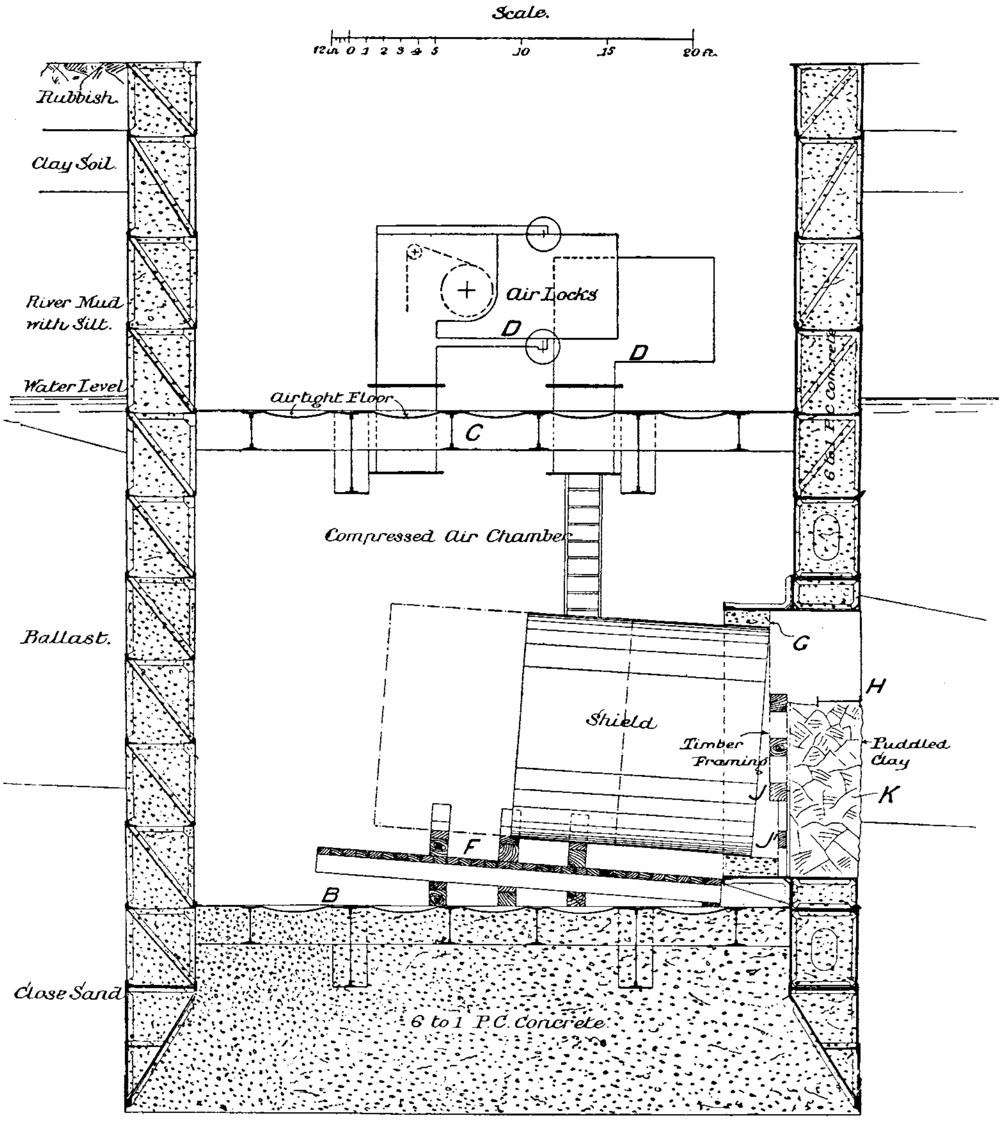


FIG. 153. GREENWICH TUNNEL, LONDON.
Method of removing "Plug" in Shaft to commence Tunnelling.

although the absolute necessity of preventing any spreading during the erection of the successive rings (whereby the caisson would have been made wider at the top than at the bottom) rendered great care necessary in rivetting up the work, still the extra trouble and expense so incurred were more than compensated for by the results obtained in the sinking of the shafts : results which the Author believes were largely due to the absence of taper in the shafts and of consequent settling of the ground around them. Iron rivets were used throughout; and all rivetting, whether gap-rivetters or hand-pistols were used, was done by compressed air power. Three tiers of pipes were fitted through the sides of the caisson, and connected to the wash-out pump, through which water could be pumped to lubricate the outer skin in case of necessity. These, however, were little used.

Each caisson is provided with two air-tight floors, a permanent one *B* fixed below the tunnel-opening and above the cutting edge, and a provisional one *C* fixed, when in use, a few feet above the tunnel-opening. These floors were alike in construction, being formed of two pairs of main girders crossing each other at right angles; the intermediate areas were crossed by small girders and the whole frame was covered by buckled floor-plates bolted to the girders. The provision of two air-tight floors has the advantage that, while a single floor above the tunnel-opening is a necessity for starting the tunnel-shield in water-bearing strata, the use of the lower floor only during the operation of sinking the caisson, while allowing an ample working-chamber underneath for the miners, enables any kentledge used in sinking to be placed near the bottom of the caisson, and so keeps the centre of gravity of the whole structure, when sinking, much lower than is possible with an upper floor only. This lessens materially the tendency of the shaft to tilt over to one side when sinking. Against this advantage must be set the increased cost of the shafts, due to the extra depth required to make room for a floor with girders 4 feet 6 inches in depth, clear of the tunnel-opening above it and the cutting edge below (see also page 185).

The opening in each shaft for the tunnel is 15 feet 3 inches in diameter. During the sinking of the caisson it was closed by a "plug" *H* formed of steel plates (see Figs. 154, 155 and 156), fitted between girders in such a way as to be removable singly when the shaft was sunk to its proper depth and the shield was ready to start. The face-plates of the "plug" were held in place by two girders, which divided the opening into three horizontal strips about 5 feet deep. These areas were again divided vertically by three smaller girders, 5 feet apart. The face-plates were fitted and bolted to the girders in the areas so formed, wood packings being used to facilitate their removal when necessary. Bolts were also used for making up the girders, so that they could be removed in pieces. The girders were bolted to horizontal brackets, fixed on the skin of the circular plug-opening, and themselves removable.

For convenience of removal, the plug was made slightly smaller in diameter than the opening which it was required to fill. It was intended, when the plug was in position, to drive hardwood wedges between it and the shaft plates so as to make a water-tight joint. The contractors, however, preferred to caulk with soft wood, subsequently driving into this thin hardwood wedges, a method of working which proved very successful.

The erection and sinking of the caissons was carried out as follows, the same method being adopted in each shaft :—

All the steelwork used in the caisson was first put together in the builders' yard in sections of not less than four rings at a time, so as to ensure good fitting; and so well was this work performed that, when it was put together again on the site of the shaft, but little adjustment was found necessary. To ensure the caisson being perfectly cylindrical, which was particularly important for the reason already mentioned, the contractors were required to put in the concrete filling between the skins as the erection of the steelwork advanced; that is to say, the concrete filling for each ring was (save in exceptional circumstances, such as frosty weather) always put in to within 2 feet of the top before the rivetting of the next ring was proceeded with. It was therefore necessary to make each ring absolutely correct before going on with the next above, because, the concrete filling once in, no further adjustment was possible. Only in the two top rings, when all danger of the shaft being jammed

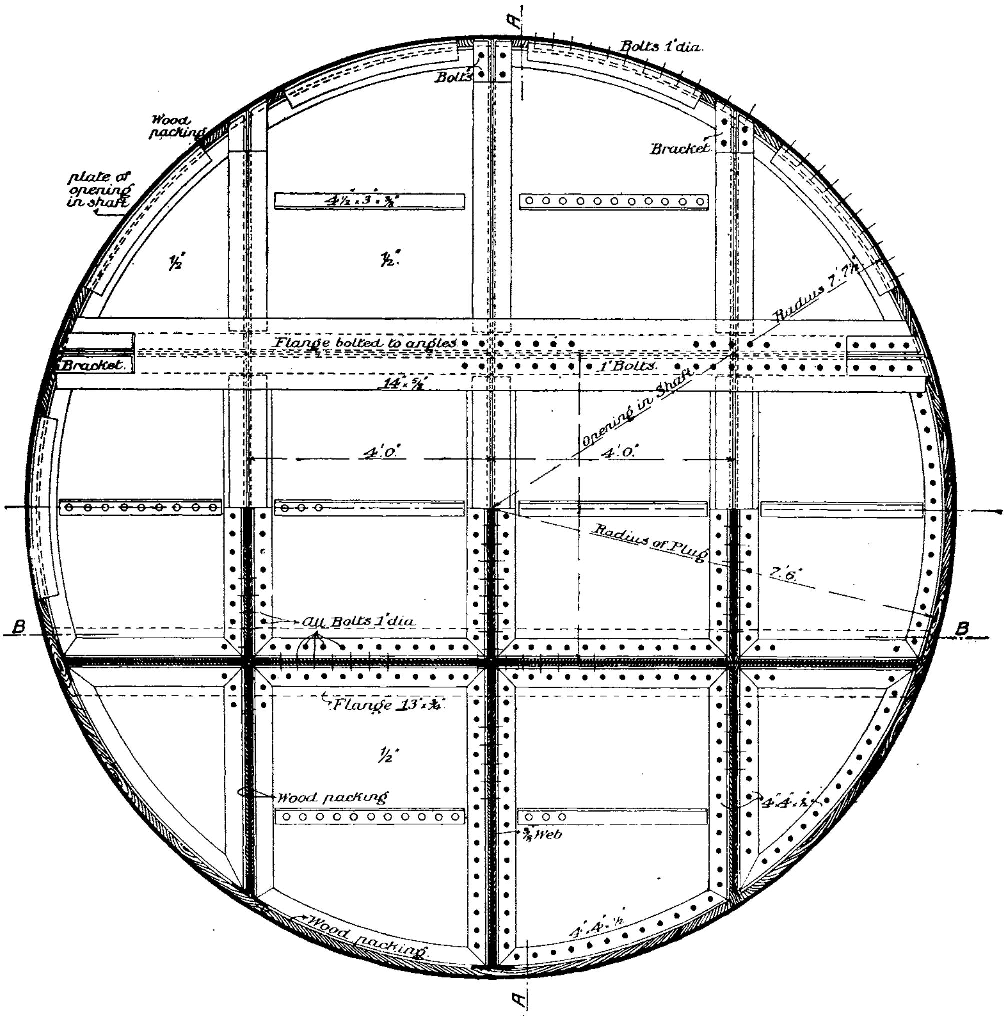


FIG. 154. GREENWICH TUNNEL, LONDON.
Framing or "plug" closing Tunnel opening during operation of sinking Shaft. (For cross sections A, A, and B, B, see Fig. 155.)

in sinking had disappeared, was this procedure departed from. This method of working was also advantageous in ensuring that the concrete filling was tipped only a few feet from the skip. As soon as the cutting edge and the lower air-tight floor with the ring surrounding it were rivetted up, and the concrete filling was in place, the blocks on which the caisson had stood were removed and the sinking was commenced.

The erection of the northern or Poplar caisson was commenced on September

26, 1899, and by March 13, 1900, one-half was erected and the cutting edge was sunk to a depth of 24 feet 6 inches below ground level, when the quantity of water met with prevented further progress, and sinking was stopped until the arrangements for working in compressed air could be completed. So far the sinking of the caisson had been done in the open, the material inside the shaft being removed in the ordinary way, and the lowering of the structure being controlled by foot-blocks under the cutting edge. No kentledge was required at this stage, the shaft going down easily when released, and being never more than a few inches out of level. The material passed through was mainly river-mud and silty clay; but at 22 feet below the surface ballast was found, through which, as already stated, water found its way from the river, the water in the caisson rising and falling with the tide.

Up to this time the girders only of the lower floor *B* had been fixed in place, the floor plates being left off so as to allow of the removal of the material excavated,

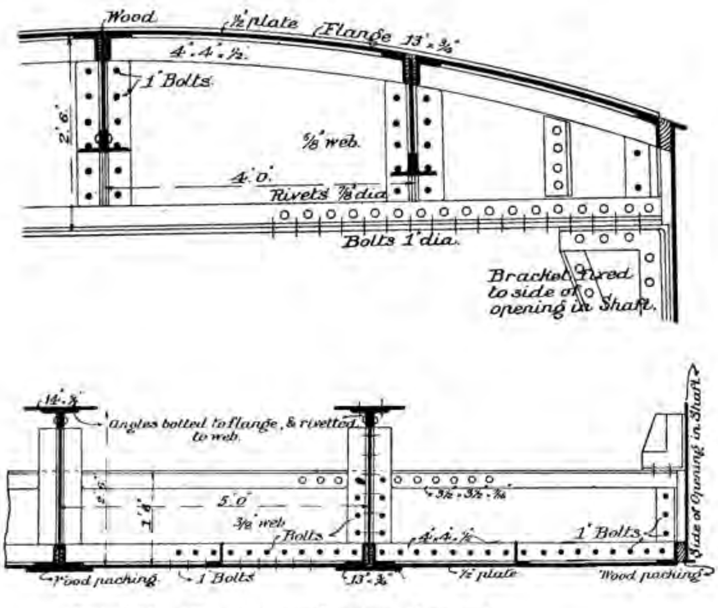


FIG. 155. GREENWICH TUNNEL, LONDON.
Details of Plug. Sections on lines *A*, *A*, and *B*, *B*, Fig. 154.

while the girders of the upper floor *C*, save for the ends of the webs, which were built into the caisson, were not put in. When the water became too deep to continue work in the open, the bottom floor-plates were fixed on the lower girders, and the upper floor-girders were erected in position (see Fig. 152).

On these upper girders were fixed two airlocks *D*, *D*, the one for men, the other for material, from which shafts *E*, *E*, 3 feet 6 inches in diameter,[1] were carried down through the lower floor, thus giving access to the working-chamber below it. On May 2, 1900, the work of sinking the caisson was resumed under compressed air, the erection of the steelwork of the caisson having in the meantime been completed to within 15 feet of the total height. The remaining rings were erected during the time the shaft was sinking.

[1] For details of the material lock, see Figs. 131, 132, and 133.

The method of sinking the caissons under compressed air was as follows. Starting usually with the ground-level in the pressure- or working-chamber about 1 foot 6 inches above the bottom of the cutting edge, the miners excavated daily to a depth of about 1 foot below it, leaving all round the cutting edge a berme between 1 foot and 2 feet in width. The amount of excavation was limited by the number of skips which could be passed through the vertical airlock in a given time; and in practice it was found that four men working in the pressure-chamber could keep the skips filled as fast as they could be returned empty. Daily, generally during the breakfast-hour of the morning shift, when the men were out of the caisson, the air pressure in the working-chamber was lowered until the caisson commenced to move. No further reduction of pressure was then made, and the movement of the caisson was gradually stopped by the tapered cutting edge burying itself anew to a depth of 1 foot to 2 feet below the general level of the excavation. The air pressure was then again raised sufficiently to dry the bottom of the shaft, and the same process of excavating and sinking was repeated. It was found possible to carry on simultaneously the different operations of plating and rivetting the skins, putting in the concrete filling, and sinking the shaft; and by careful organization it rarely happened that one operation interfered with or delayed another. It will be seen from the Table giving details of the sinking operations that the daily progress under compressed air was singularly uniform.

The strata met with 3·00 feet below Ordnance datum, or about 20 feet below ground-level, were water-bearing. The top surface of the ballast, which was found on the north side of the caisson about 22 feet below ground level, sloped rapidly southward, and some difficulty was expected in keeping the cutting edge level on that account. As a matter of fact, for a few days the error of level of the caisson amounted to 6½ inches, being the largest amount of tilt recorded; but this was put right, and subsequently the caisson, though sinking at an average rate of 1 foot 3 inches per day, was never more than 1¾ inch out of level. Below the ballast, at about 41 feet below ground-level, was found a bed of close grey sand, at times almost as tough as soft sandstone. It was noticed that the skin-friction of the caisson, which, when the lower portion was in the ballast, had been generally 4·5 cwt. to 4·7 cwt. per square foot, became less as the cutting edge sank deeper into the sand; and the last observations, taken when the caisson was nearly down to the required level, gave a skin-friction of just under 3·8 cwt. per square foot. The probable explanation is that, owing to the consistency of the sand, most of the air escaping from the pressure-chamber passed up close to the outside of the caisson and so made an air lubricant for it. The lubricating-pipes which were provided in the caisson were used on a few occasions, but without appreciable results, perhaps owing to the choking of the pipes by the dirty water used, but more probably owing to the air that escaped from below driving away the water from the caisson as soon as it left the pipes.

The total weight of kentledge put into the caisson was only 921 tons, which, with the weight of the steel and concrete in the structure, made finally a total weight of 2,560 tons. By the provision of an air-tight floor at the bottom of the shaft, the contractors were enabled to provide the necessary kentledge by tipping the ballast as it came up through the airlocks into the shaft below, and by running in water from a pipe above. As stated above, the sinking of the Poplar shaft under compressed air was commenced on May 2, 1900. It was sunk to the required depth by the 31st of the same month. The Table shows the daily progress from

May 10 onward, with the loads on the caisson, pressure, etc., from the commencement of work under compressed air until the shaft was sunk to the required level.

TABLE SHOWING RATE OF SINKING OF THE POPLAR SHAFT.

Date.	Depth of Cutting Edge below Surface.	Cutting Edge out of Level.	Depth sunk each time of lowering.	Load on Shaft, including Kentledge.	Air-Pressure.	Remarks.
1900. May.	Feet.	Inch.	Feet.	Tons.	Lbs. per Sq. Inch.	
2	24·80	½	—	1,346	6	Pressure put on. Cutting edge in ballast at north side.
7	27·50	6½	2·70	1,362	6	Skin-friction 4 cwt. per foot.
10	28·60	1⅜	1·10	1,412	6	
11	29·60	1¾	1·00	1,457	8	
12	31·83	⅞	2·23	1,618	8	
13	33·70	1¾	1·87	1,826	8	Skin-friction 4·7 cwt. per foot.
14	35·80	1⅜	2·10	1,943	8–10	
15	37·26	⅞	1·46	2,114	10	Skin-friction 4·75 cwt. per foot.
16	39·16	⅝	1·90	2,257	10–11	
17	39·96	⅝	0·80	2,371	11–12	
18	41·50	⅞	1·54	2,371	11–12	Cutting edge in close grey sand.
19	42·50	1	1·00	2,371	10–11	Skin-friction 4·6 cwt. per foot.
20	43·60	1	1·10	2,371	10	
21	44·75	½	1·15	2,421	10	
22	46·42	1⅛	1·67	2,421	10½–13	
23	48·31	⅞	1·89	2,421	11–13	Lubricating-pipes in use.
24	49·46	⅞	1·15	2,421	13	
25	49·82	¾	0·36	2,421	14	
26	51·80	⅜	1·98	2,449	15	
27	53·35	⅝	1·55	2,477	15½	
28	55·20	⅝	1·85	2,505	16	
29	57·13	⅝	1·93	2,533	16½	
30	58·55	½	1·42	2,561	16	
31	60·30	—	1·75	2,561	20	Skin-friction 3·8 cwt. per foot.

It will be seen from this Table that from May 10 to 31, a period of twenty-two days, the depth sunk daily varied but little, only twice falling below 1 foot and twice exceeding 2 feet. When sunk to the proper depth the caisson was exactly plumb. As the Greenwich caisson was sunk in a similar manner, and with the same uniform speed and accuracy, the use of vertical sides to the caisson, and of an air-tight floor near to the cutting edge during sinking, would appear to be justified. The vertical sides of the caisson prevented, as far as could be seen, any disturbance of the surrounding ground during the operation of sinking; at least no cracks were visible on the surface more than 2 or 3 feet away, and those which appeared within that distance were slight. When the plug of the tunnel-opening was removed, and the shield was pushed forward into the solid ground, no previous movement of the strata was perceptible. The steadiness of the caisson when in motion was no doubt due in part to the slight disturbance of the surrounding ground; but the lowness of the centre of gravity of the structure, due to placing the kentledge near the bottom of the shaft, probably also accounted largely for the ease with which it was controlled.

From the experience gained in recent years it appears probable that in sinking a shaft or caisson through different beds, of varying resistance, it is best to make the caisson with an uniform or nearly uniform external diameter. Perhaps for shafts from 50 to 100 feet in depth, the most satisfactory arrangement would be to have a cutting edge of about 7 feet in length of one diameter, and then above that length to make the remainder of the shaft 1 inch less in diameter. But there is little doubt but that a caisson should have its sides practically parallel.

As soon as the Poplar shaft had been sunk to the required depth, the working-chamber under the air-tight floor *B* was filled with 6 to 1 Portland-cement concrete to the level of the underside of the floor-girders ; and when that had set, pressure was taken off, and the floor-plates were removed. Concrete was then filled in between the girders to just below the floor-level, and the plates were replaced, grout being afterwards forced beneath them under pressure, through holes provided for the purpose. The floor thus made has proved to be absolutely water-tight, no leakage having been observed in the three years during which the tunnel has been open to traffic. The material for the shield was then lowered through the upper floor-girders, the airlocks and tubes being moved for the purpose, and the shield was erected on a timber cradle *F* laid on the lower floor. (The position of the shield during erection is shown in Fig. 153.) A ring of concrete *G* was then built inside the tunnel-hood, leaving an opening large enough to admit of the passage of the shield. Behind the shield some temporary tunnel-rings were built, extending to the skin of the caisson, for the shield to push against. This done, the upper floor-plates were fixed on the girders already in position, the airlocks were replaced, and air pressure was again applied. The actual removal of the "plug" *H* was carried out as follows. Across the plug-opening, at a distance of 4 feet from the steel plug, and about 5 feet from the invert of the plug-opening, a 12 inch by 12 inch timber *J* was fixed, bearing on the concrete ring previously referred to, which was itself secured by rails bolted to the circular hood. Below it was placed a 12 inch by 6 inch timber J^1, similarly bearing against the concrete ; and close poling was then built in front of the joists, forming a diaphragm from the invert of the plug-opening to above the level of the lower girder of the plug. The lower plates of the plug were then removed one by one, and the space between the solid ground so exposed and the timber diaphragm was filled with well-plugged clay *K*. The lower girder was then removed, the bottom edges of the plates above it being held by stretchers to the 12 inch by 12 inch timber. Two similar timbers were then fixed above the first, and close poling was placed in front of them, thus raising the timber diaphragm to the level of the second girder of the plug ; the plates below were in turn removed, and the exposed face was supported by clay filling as before. In this way all the steel plug was removed, and in its place the tunnel-opening was closed by a timber diaphragm and some 4 feet of clay in front of it. The shield was pushed forward until it touched the timber diaphragm, which was subsequently cut out to allow of its passage.

The cast-iron lining of the tunnel has been already described in chapter III. The type of joint used proved entirely satisfactory, and after being three years in charge of the completed tunnel the Author can state that the leakage observed is the smallest on record for a subaqueous tunnel of this length.

The whole of the tunnelling was done under compressed air. The vertical airlocks in the Poplar shaft continued in use until 142 feet of the tunnel had been constructed, and then a bulkhead, with a horizontal lock and an emergency-lock above it, was built in the tunnel close to the shaft, and the upper air-tight floor and locks were removed and transferred to the Greenwich shaft.

The bulkhead consisted of two thicknesses of brickwork in cement separated by a cement grouting of 9 inches; the total thickness being 8 feet 3 inches. On

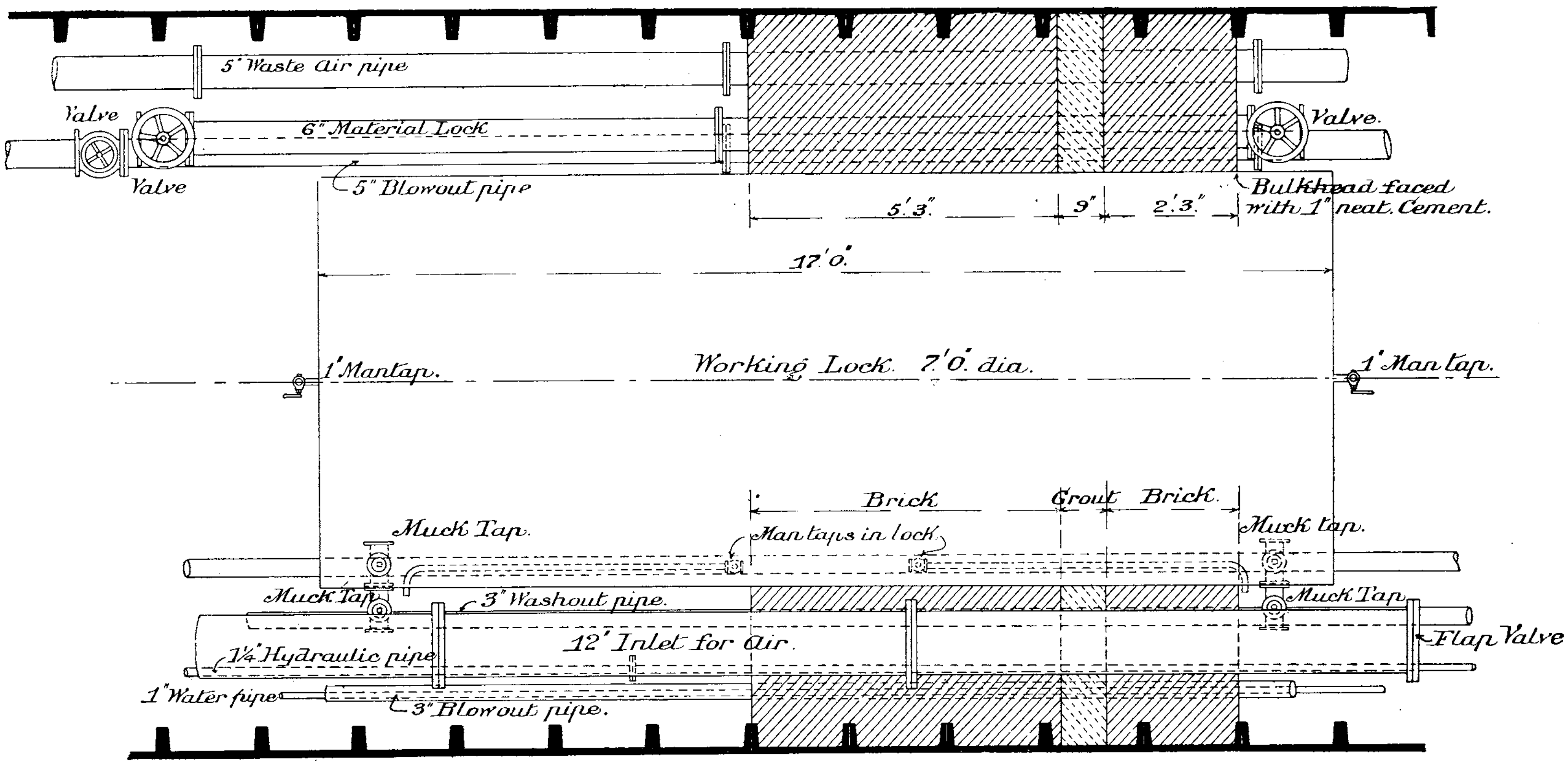


FIG. 156. GREENWICH TUNNEL, LONDON.
Bulkhead and Airlock: horizontal Section.

the inner or pressure side of the bulkhead, a coating of neat cement, 1 inch thick, was laid.

The use of brick rather than concrete for bulkheads is preferable by reason of the greater ease with which the latter can be removed when the bulkhead is no longer required.

Figs. 155 and 156 show the arrangement of the locks and pipes in the bulkhead. The main or working lock was supplemented by a second or emergency lock, built in to the bulkhead above the other, so that in the event of the lower part of the tunnel becoming flooded, a means of egress would be left for the miners.

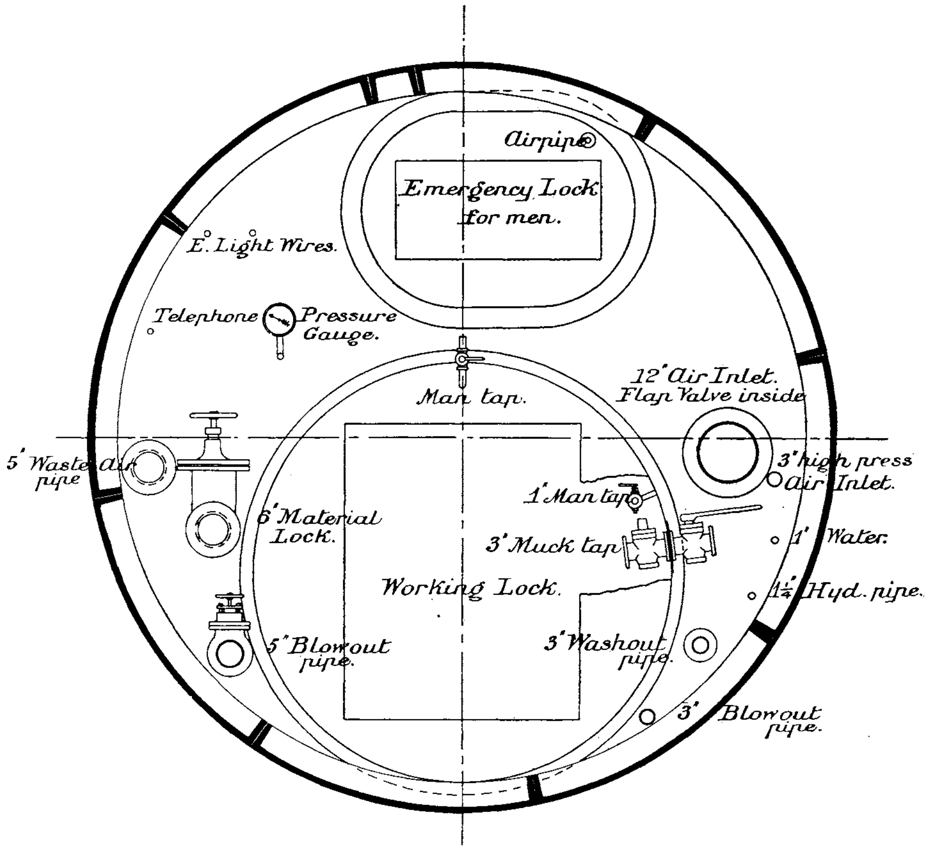


FIG. 156A. GREENWICH TUNNEL, LONDON.
Bulkhead and Airlocks: Outside Elevation.

The arrangement of the pipes built in the bulkhead is a fair example of the requirements of a work of this kind. For the passage into the air chamber of rails, timbers, pipes and generally of material of small bulk in proportion to length, a material lock, 18 feet long, and 6 inches in diameter, was provided. This lock was simply a flanged pipe, having at either side of the bulkhead a sliding air-tight valve.

The main air inlet was 12 inches in diameter, and terminated, on the inner or pressure side of the bulkhead, in a flap valve. (To this pipe was afterwards attached the purifying apparatus described in chapter II.) This pipe received the compressed air from the compressors, the cooling reservoir or tank being fixed about midway between the compressors and the tunnel. The fact that this inlet pipe delivered the air immediately inside the bulkhead ensured that, as the waste air pipe and the various "blow-out" pipes were carried forward as the shield, the air of the whole length of the tunnel was continually renewed.

The waste air pipe, which was always carried forward with the shield, had its outside end carried sufficiently far from the lock to prevent the noise of the escaping air interfering with the secure working of the lock, and the other exhaust pipes known as "blow-out" pipes discharged into the well of the shaft, whence the water was pumped by a Smith Vaile force pump to the surface of the ground.

An air pipe 3 inches in diameter conveyed air at a pressure of about 100 pounds to the face for working the grouting machine, and also the winding engine fixed in the roof of the tunnel immediately within the bulkhead.

For the working of the lock 1 inch valves for passing workmen, and 3 inch valves for material were used.

The bulkhead was placed in the very entrance of the tunnel, close to the Poplar shaft, in which a lift was fixed, so that the miners, in leaving the pressure chamber, were conveyed without delay or exertion on their part to the surface.

Safety diaphragms of the character figured on page 260, were used in this tunnel, and one was fixed at the foot of each of the gradients from the shafts as soon as the shield commenced the ascent on the Greenwich side. It is clear from an inspection of the longitudinal section of the tunnel that, in case of a "blow" when the shield was, say, halfway up the incline, the working pressure at the face being less than that required at the lower part of the tunnel, there would be no escape for the men at the face, unless a refuge was provided for them much nearer than the main airlock.

Such a refuge was provided by the two diaphragms in the positions shown in Fig. 150, as they formed, with the roof of the tunnel, an air space, into which the miners could, on an emergency, climb, until help could come from outside.

With the object of removing the water in the lower part of the tunnel in case of a blow of this character, two "blow-out" pipes were provided at Greenwich, the one being carried forward as usual with the shield, the other being stopped when its aperture had reached the lowest part of the tunnel, so that whenever any water entered the tunnel, an exit was provided for it at the lowest point of the invert.

The time occupied in driving the tunnel was from September 19, 1900, to May 31, 1901, or about eight and a half months, the monthly progress being as under :—

1900.	September	nil
,,	October	48 feet 0 inches
,,	November	50 ,, 0 ,,
,,	December	101 ,, 8 ,,
1901.	January	168 ,, 4 ,,
,,	February	195 ,, 0 ,,
,,	March	260 ,, 0 ,,
,,	April	218 ,, 0 ,,
,,	May	141 ,, 8 ,,

From February 22 to May 1 a daily advance of 10 feet was made without exception.

No difficulty was experienced in making the junction with the Greenwich shaft, the only precaution taken being the driving of steel needles from inside the shaft round the top of the steel plug, so as to form a hood over the shield when it reached the shaft, thereby preventing any fall of the ground above while the plug was being removed.

The pressure in the Greenwich shaft was, of course, when the shield was approaching closely to it, maintained at the same height as the air pressure in the tunnel.

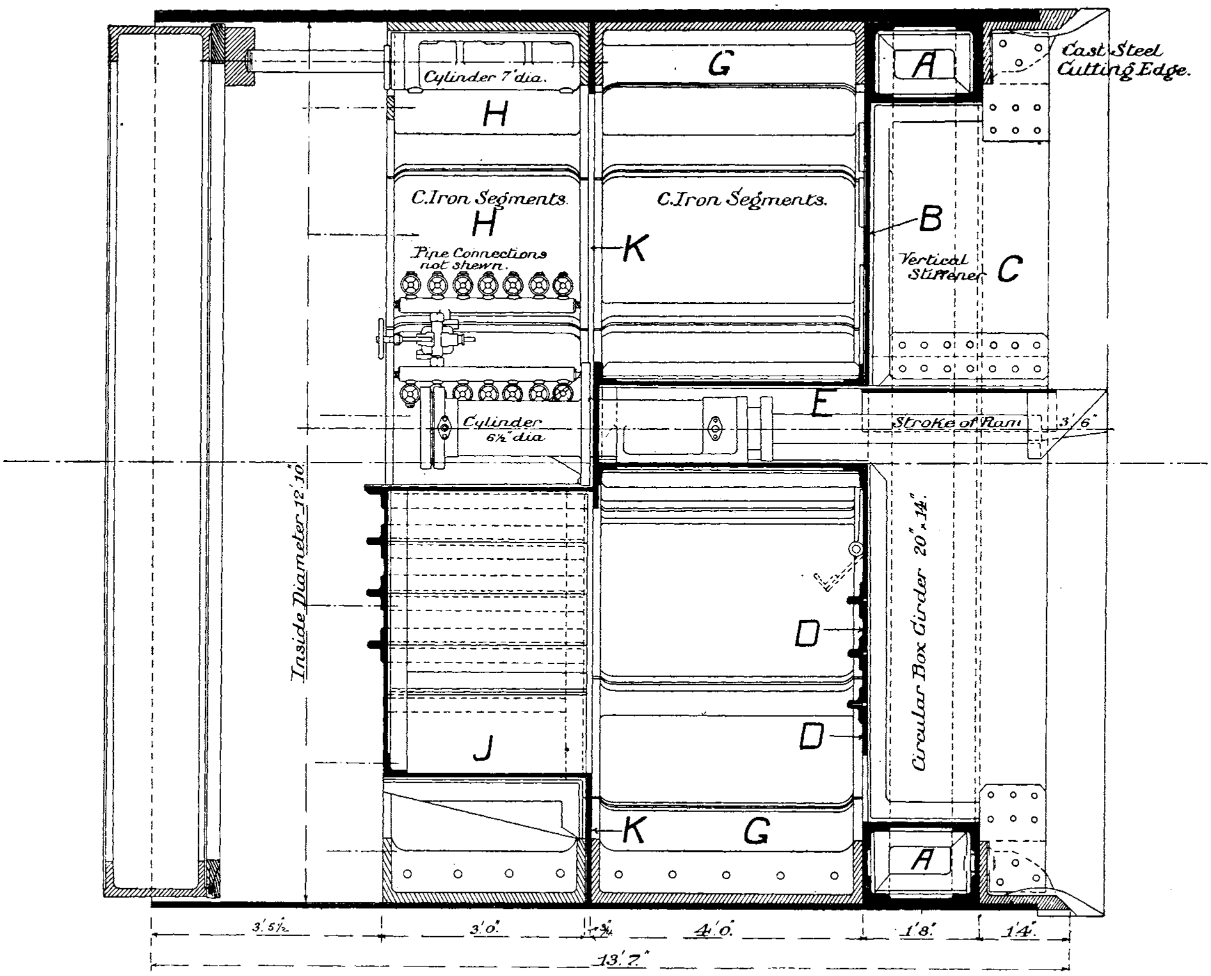


FIG. 157. GREENWICH TUNNEL, LONDON.
The Shield: Longitudinal Section.

The shield was designed on the lines of the modified Mersey Tunnel shield (see Figs. 146 and 147), and is an interesting example of how a shield, designed on lines which had previously given good results, was modified to suit improved methods of working developed as the tunnel advanced.

The external diameter of the tunnel, 12 feet 9 inches, rendered any horizontal division of the shield unnecessary, as the difference in hydrostatic pressure between the top and bottom of the shield was comparatively small.

It was determined therefore to use a shield, as said above, in general character resembling the Mersey Tunnel shield as altered by Sir B. Baker, adding to the design, however, face rams of a peculiar character instead of the provisional needles which had been then employed, and certain other novelties were introduced.

The "trap" or "box" arrangement of the diaphragms had proved so useful at the Mersey Tunnel[1] that it was reproduced at Greenwich with but small modifications, and the other details of the shield were worked out in subordination to this central idea.

The shield as first designed is shown in Figs. 157, 158, 159, and 160.

It consists of an outer cylindrical skin, 1 inch in thickness, in seven strips, each joint having a 1 inch cover over it. To prevent the cover-plates from stripping when the shield is in motion, the cast steel cutting edge is thickened in front of the covers (see Fig. 158).

The cutting edge is of cast steel, formed in thirteen segments, with close-fitting machined joints, each segment having cast on it two teeth, projecting 6 inches beyond the general line of the cutting edge. These teeth, which, as has been previously mentioned when treating of the Mersey Tunnel shield, were originally suggested by the effective action of similar projections on the grab buckets of a dredging crane, proved very useful when working in ballast. The outside of the teeth, except when these came in front of one of the cover strips of the skin, projected 1 inch beyond the general circumference of the cutting edge.

In coarse ballast this projection is distinctly advantageous, but it is not suited to the system described by Mr. Haigh in the *Proc. Inst. C.E.*, vol. cxxxix., p. 25, by which a skin or coating of clay originally placed ahead of the cutting edge is left as the shield advances on the outside of the shield, and remains to form a more or less continuous seal to retain the air at the tail of the skin.

Immediately behind the cutting edge is placed a circular box girder *A*, 1 foot 8 inches wide by 1 foot 2 inches deep, formed of plates and angle irons, and rivetted to the cylindrical skin of the shield, while it is bolted to the cutting edge in front and the cast-iron segments behind it.

A circular girder of this kind gives great stiffness to the shield, and it was with this idea it was put in on the first place. Immediately behind it is a continuous plate diaphragm *B*, covering nearly one-half the sectional area of the shield, and further strengthened by the horizontal plates forming the top and bottom of the face rams' boxes, *E*, *E*, the front of the shield being thus made very rigid. The cutting edge and skin of the shield projected 3 feet beyond the vertical diaphragm, and the circular girder stiffened this projection infinitely better than gussets would have done.

In fact, the combination of built circular girders to give stiffness with an actual cutting of cast steel in front is, perhaps, in small shields, a better arrangement than a built cutting edge of plates and gussets; the latter arrangement, however carefully put together, being always liable to buckle if hard material, or gravel containing large single blocks, is met with.

In case of crippling it is much easier to remove and renew a damaged segment than to cut out and make good a crippled plate-cutting edge.

In this shield further rigidity is given to the front by a vertical stiffener *C*, 2 feet 8 inches in width and ¾ inch thick, bolted to the cutting edge and the circular box girder at top and bottom.

[1] See page 228.

The diaphragm *B*, which forms the front portion of the "water trap," the main feature of the shield, is pierced with numerous holes, some covered with thick glass for observation, others smaller for inserting bars or water jets, and two large rectangular ones, primarily intended for giving access to the upper face, in case of necessity.

No use was made of them; the idea of washing out the material in front by means of water jets was never put into practice, and the use of bars for loosening the face was soon found to be impracticable.

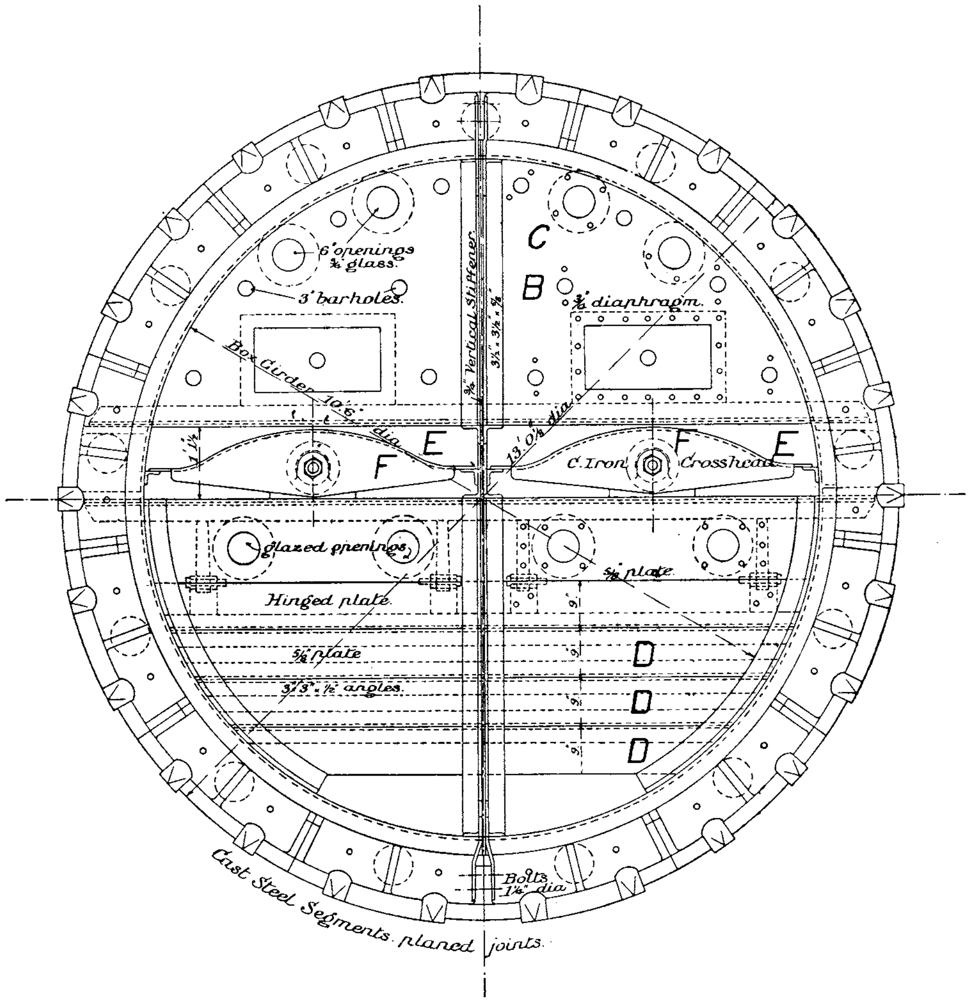


FIG. 158. GREENWICH TUNNEL, LONDON.
The Shield: Front Elevation.

In suggesting the use of water jets for loosening the face, the designers of the shield only followed earlier inventors who had patented shields for use with water jets. No attempt, however, was made to use them at Greenwich.

This diaphragm or curtain, ¾ inch thick, closed entirely the upper half of the shield and extended downward (below the boxes containing the face rams) 1 foot 3 inches below the horizontal axis of the shield.

Below this level were removable curtain plates *D, D,* of $\frac{5}{8}$ inch plate, stiffened with 3 inch by 3 inch by $\frac{1}{2}$ inch angle irons, by means of which, when all were in position, the front aperture of the shield could be almost completely closed.

These lower curtain plates were never used in actual practice, but it will be seen that, by providing a means of varying the depth of the front diaphragm, it was possible, in combination with a similar arrangement in the back diaphragm, to vary, to a very large extent, the amount of "water-seal" or trap formed by the

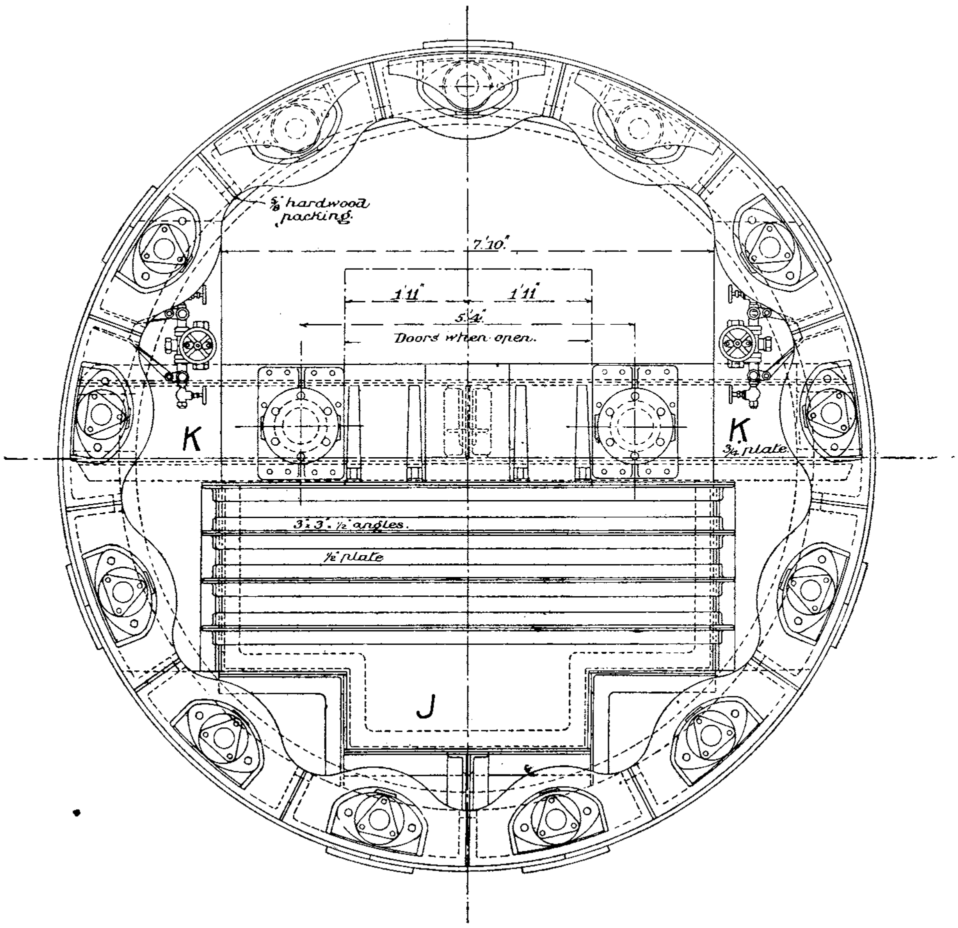


FIG. 159. GREENWICH TUNNEL, LONDON.
The Shield: Back Elevation.

difference of level between the bottom of the front, and the top of the back, diaphragm.

It is advisable to be able to vary the amount of "water-seal" or difference of level of the plates for another practical reason. All circular shields after travelling some distance revolve on their axis, and it may well happen (as indeed happened at Greenwich) that a difference in level between the bottom of the front diaphragm, and the top of the back one, which was quite sufficient when the shield started, may practically disappear after tunnelling a few hundred yards.

The boxes *E, E,* containing the face rams, although they appear to destroy the continuity of the front diaphragm, really form part of it, for although their front end is open to allow of the movement of the face rams, the rear end is closed. The plates forming the top and bottom of these boxes were ⅝ inch thick, and served as horizontal stiffeners to the shield.

At each end, these stiffeners were secured to castings having special ribs cast on them, and forming part of a cast-iron ring *G*, which stiffened the shield between the front diaphragm plate, and the diaphragm to which was attached the "trap" or "box" forming, with the front diaphragm, the water-seal.

These castings were bolted together with hardwood packings at the joints.

In the boxes were placed the face rams, which were of a peculiar design.

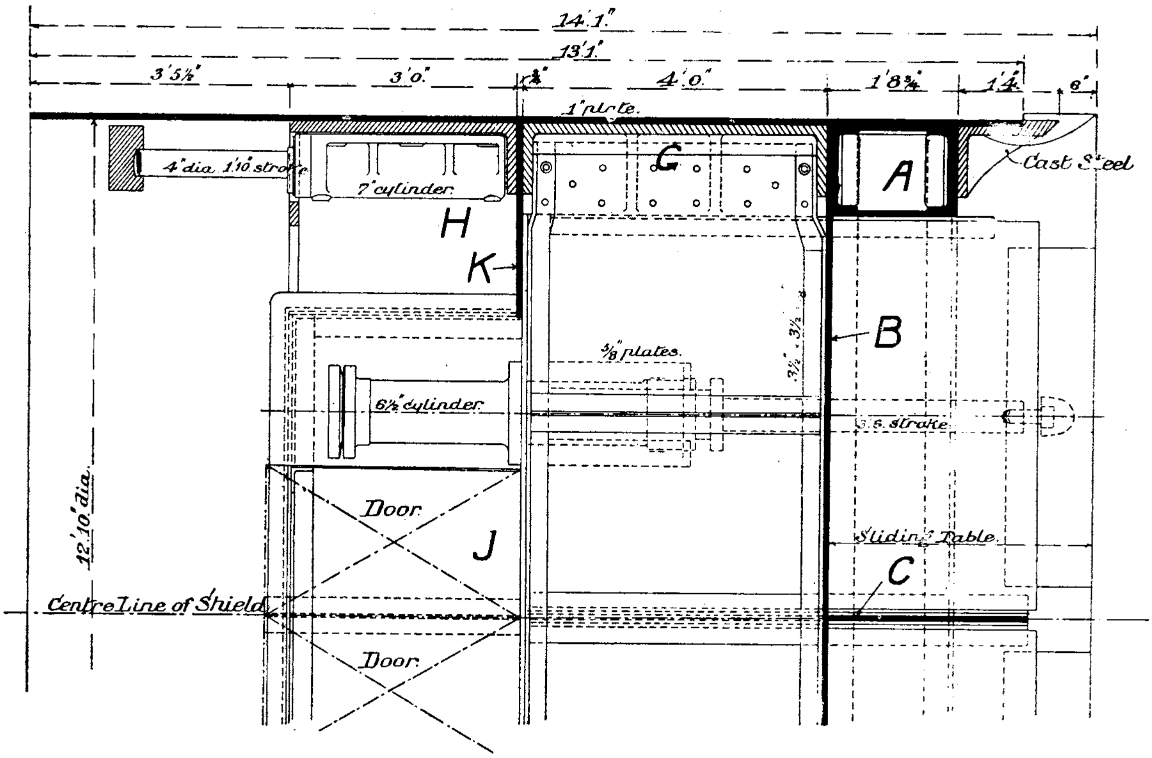


FIG. 160. GREENWICH TUNNEL, LONDON.
The Shield: Half Sectional Plan.

The cylinder and piston were of the conventional type, but the rams had the peculiarity that to the curved cast-iron heads (*F*, in Fig. 158) were attached curved tables, the edges of which slid on angle irons fixed to the framework of the shield.

The idea was taken from the way in which, at the Mersey Tunnel (Vyrnwy Aqueduct), iron needles, passed through holes in the front diaphragm, had held up the material in the upper part of the face while the miners excavated at the bottom.

But in practice the tables were found useless, and were soon removed.

The ram head shaped with a cutting edge also was found of no assistance.

The most serious objection, however, to the face rams as first erected was that, when extended to the full extent of the cylinders, the front of the ram head was only in a line with the cutting edge of the shield. This, for working in loose material, was a very grave defect ; face rams, except for working in London Clay, should be capable of more extension forward.

Immediately to the rear of the boxes containing the front rams, and secured between the cast-iron segments *G*, *G*, and the ram castings *H*, *H* (one ram only is shown in Fig. 157), were plates *K*, *K*, which formed, with the back plate of the face ram boxes, a useful stiffening to the shield, and a frame to which the "trap" or "box" of the shield was secured. Above the face ram boxes, the plates *K*, *K*, as shown in Figs. 157 and 160, left ample working space.

The trap or box *J* is shown clearly in Figs. 137 and 139, and was made of plates ½ inch thick, the upper portion being formed of removable strips similar to those already described as being at the bottom of the front diaphragm. This box was also provided with a lid in two sections, but owing to the projection behind of the two face ram cylinders, the lids or doors only extended over about one-half the surface of the box, thus considerably hampering the work of clearing out excavated material from the face (see Fig. 160).

Around and above this box were fixed inside the skin of the shield thirteen segments *H*, *H*, forming a cast-iron ring, to which were attached the main rams of the shield.

Beyond them the skin of the shield extended some 3 feet 6 inches, the stroke of the rams being about 1 foot 10 inches.

These cylinders are shown in Figs. 165 and 166 ; they were 7 inches in diameter, and, with hydraulic compressors working at 1½ tons per square inch, they exert a total pressure of 750 tons. The hydraulic pressure for working the shield rams was supplied by two compressors placed in the engine room in the contractors' yard on the surface, capable of compressing up to 3 tons per square inch.

The shield, constructed as described, on starting from the shaft sunk for the purpose, commenced tunnelling through open water-bearing ballast, the material for dealing with which the arrangements of the shield were especially designed.

The general scheme of working was to excavate the lower part of the face under the shelter of the face rams or tables, and then having removed a length below, to withdraw the rams, and allow the material above them to fall down, assisting the process, if necessary, by water jets, when the shield could advance again into the face, and the operation be repeated.

After some trial of this system, it was abandoned, it being found that the sliding tables of the front rams were ineffective for the purpose for which they were designed. So far from acting as temporary supports to the material in the upper face of shield, and by their withdrawal allowing it to fall and leave a loose area into which the shield could advance, it was found that the actual result of advancing the tables into the ballast in front of the front diaphragm was to pack the ballast above the tables and against the front diaphragm, thus practically giving the shield a solid face to push against.

The use of the face rams was discontinued, and in their place "needles," formed of small rolled joists, were tried, openings in the front diaphragm, immediately above the face ram boxes, being made for the purpose. Some success attended this method of working, which had, at an earlier date, given good results in the Mersey Tunnel ; but the rate of progress was very slow, and ultimately the use of the sliding tables on the face rams was abandoned, the face rams themselves were lengthened, and utilized for supporting the face by means of soldiers sustaining ordinary close poling.

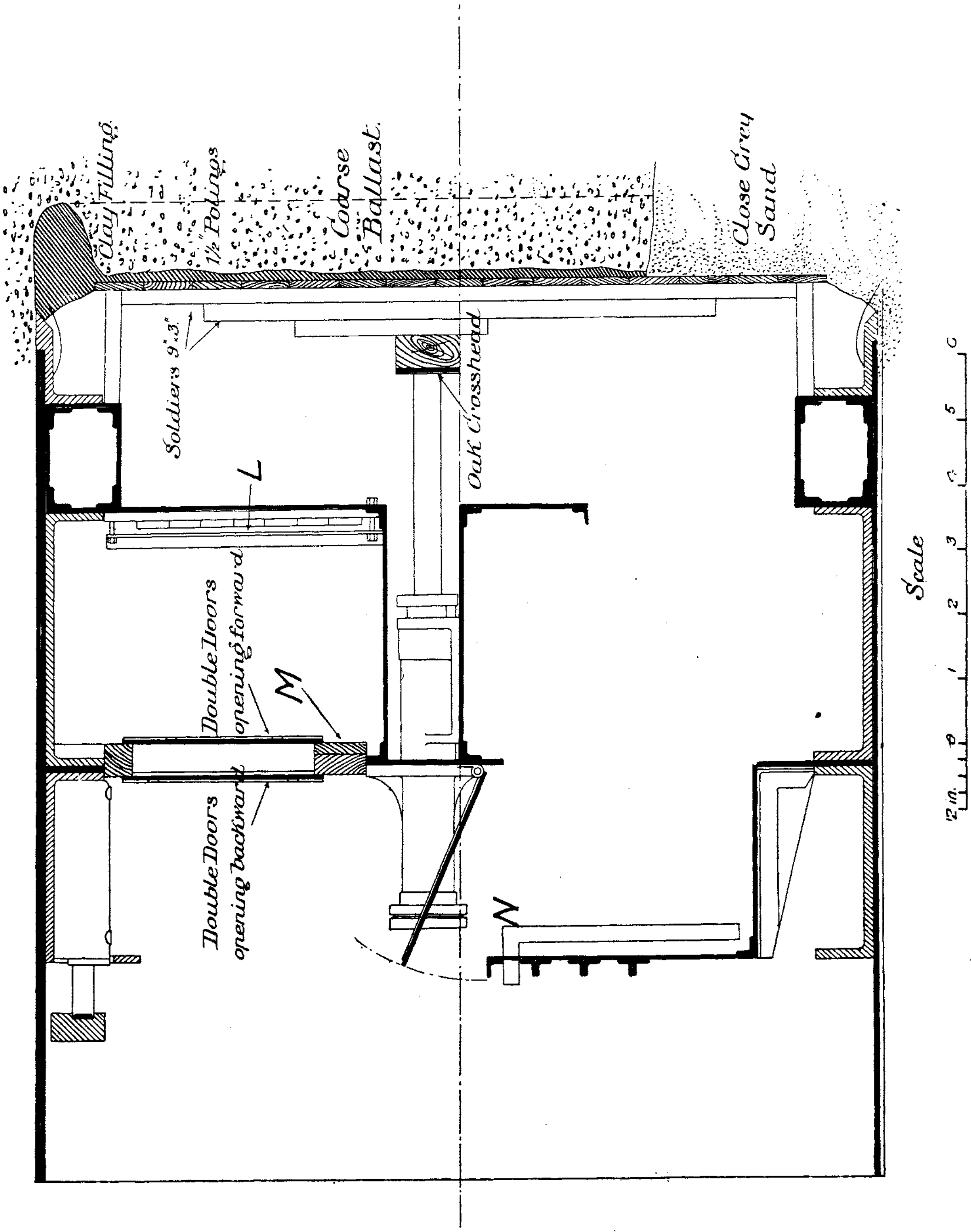


FIG. 161. GREENWICH TUNNEL, LONDON.
Method of Working the Shield in Ballast. Shield ready to advance.

This gave satisfactory results from the first, and subsequently the method of working was improved by excavating in front of the cutting edge, and filling the circular channel so made with clay, thus forming an airtight medium in which the cutting edge passed when the shield was advancing.

This was done by Brunel in the Thames Tunnel,[1] in that case to keep the water out, as compressed air was not used in his great work ; and in recent times on the Baker Street and Waterloo [2] and Waterloo and City [3] Railways, with the object of preventing the compressed air used in the tunnel from escaping, and facilitating the entry of the cutting edge into the ballast. The use of the clay

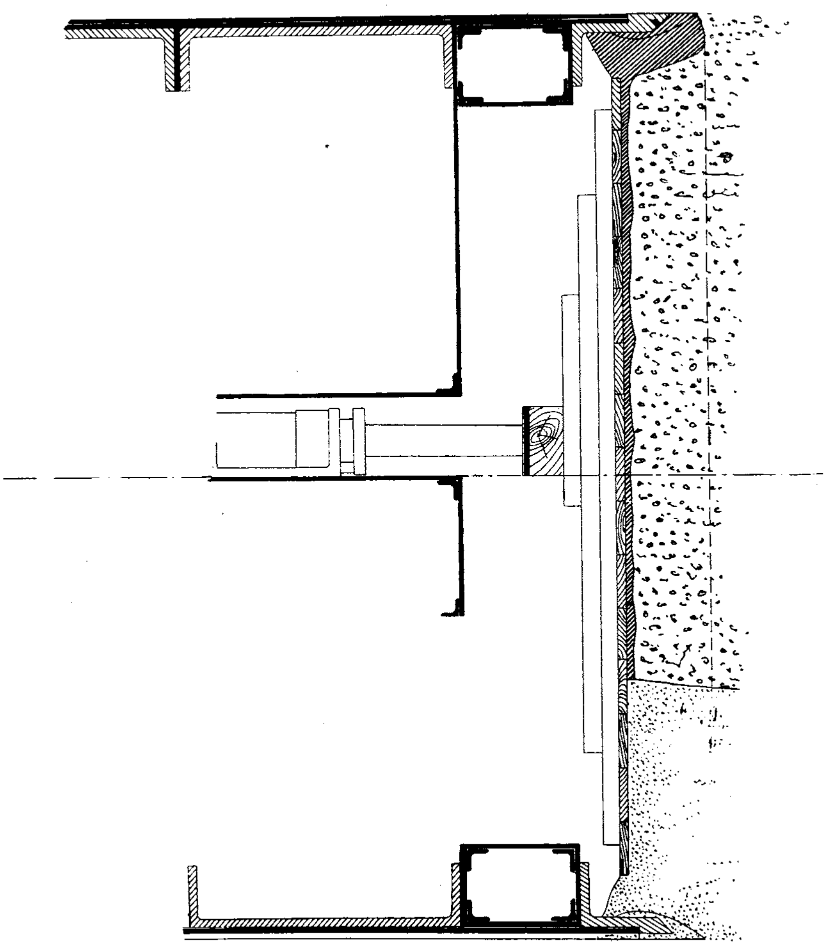
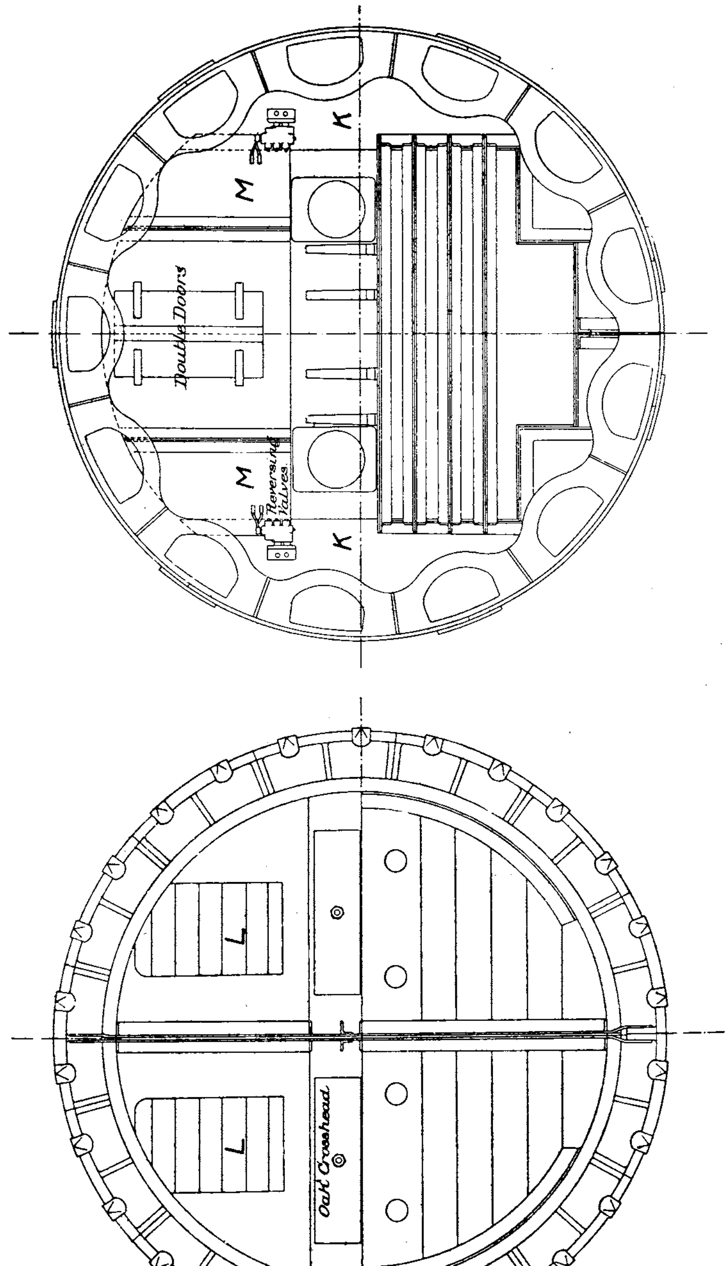


FIG. 162. GREENWICH TUNNEL, LONDON.
Method of Working the Shield in Ballast. Shield at end of Stroke.

annular space round the cutting edge on the tunnels of the two Waterloo Railways had apparently one advantage over the system employed at Greenwich Tunnel. The clay pockets in these cases were excavated a little wide of the shield, and the cutting edge being a continuous plate with a bevelled front edge, it made, as the

[1] *Weales' Quarterly*, vol. v. (1846).
[2] See page 269, and *Proc. Inst. C.E.*, vol. cl., p. 25.
[3] See page 140, and *Proc. Inst. C.E.*, vol. cxxxix.

shield advanced, a clean cut into the clay, and so leaving outside the shield a skin of that material which remained in a more or less complete state, not merely



Figs. 163 and 164. Greenwich Tunnel, London.
Altered arrangements of Shield: front and back Elevations.

round the advancing shield, but also round the tunnel behind it. This it was claimed decreased the escape of air at the tail of the shield.

At Greenwich, the clay pockets were taken out the bare size of the shield, and on this account, and also because the teeth on the cutting projecting outside the skin of the shield broke up the clay more than a smooth cutting edge would have done, no continuous clay envelope was found outside the tunnel at the rear of the shield.

Figs. 161 and 162 show this method of working, which differs mainly from previous work of the same kind in the use made of the face rams.

Beginning at the top of the shield, the ballast was removed around the cutting edge low enough to fix the first poling boards, which in the first instance were held in position by short timbers stretched from the frame of the shield, and similarly all the face, or so much of it as was in ballast, was poled, each poling being temporarily supported in the same way.

The poling boards did not extend the full width of the face, but were in two lengths, thus limiting, when the ground was bad, the face exposed in fixing each poling board to one-half of the face at that level. Clay was placed in pockets opened in front of the cutting edge, and doubtless lessened considerably the work of the shield rams, but the provision of teeth on the cutting edge was found, as in the Mersey shield, useful in this respect. When all the face was poled, the face rams of the shield were brought into action, and by means of soldiers, took the pressure of the face, the short timbers or " clogs " which had previously held each poling being knocked out. When once the pressure of the face was taken by the face rams, the shield was pushed forward, and as the cutting edge passed beyond the polings, the face rams were allowed to draw back at the same rate as the shield advanced, so that while the latter was moving forward, and so allowing space behind for the erection of a new ring of the tunnel lining, the poled face remained unaltered in position. The position of the shield at the end of the forward movement just described is shown in Fig. 162, the position before moving being shown in Fig. 161.

This system of working answered admirably when working in open ballast with very little sand.

The material met with for a considerable length of the tunnel made the shield work comparatively easy, and the " trap " arrangement was consequently practically abandoned, two doors being cut in the upper front diaphragm, which could be closed when necessary by short timbers dropped into vertical guides on either side of the openings (see *L*, *L*, Figs. 161 and 163).

Towards the conclusion of the work, however, the tunnel was again made through open ballast on an upward gradient of 1 in 15, and having in view the fact that the larger portion of the tunnel already built was lower than the shield, and that consequently any blow at the face, unless checked by the shield, must result in the flooding of the tunnel, and consequent imprisonment of all working at the face, a considerable change was made in the arrangements of the shield.

The alterations made are shown in Figs. 161, 163 and 164, and were mainly in the direction of improving the means of exit for the men working in the face in the event of an inrush of water.

As before mentioned, doors which could be closed by short poling boards had been previously cut in the front diaphragm.

These were left open, the polings being kept in readiness if required.

A second closed diaphragm was formed at the rear end of the face ram box, by fixing to the plates *K*,*K* of Figs. 157 and 159, and the end of the face ram boxes a frame

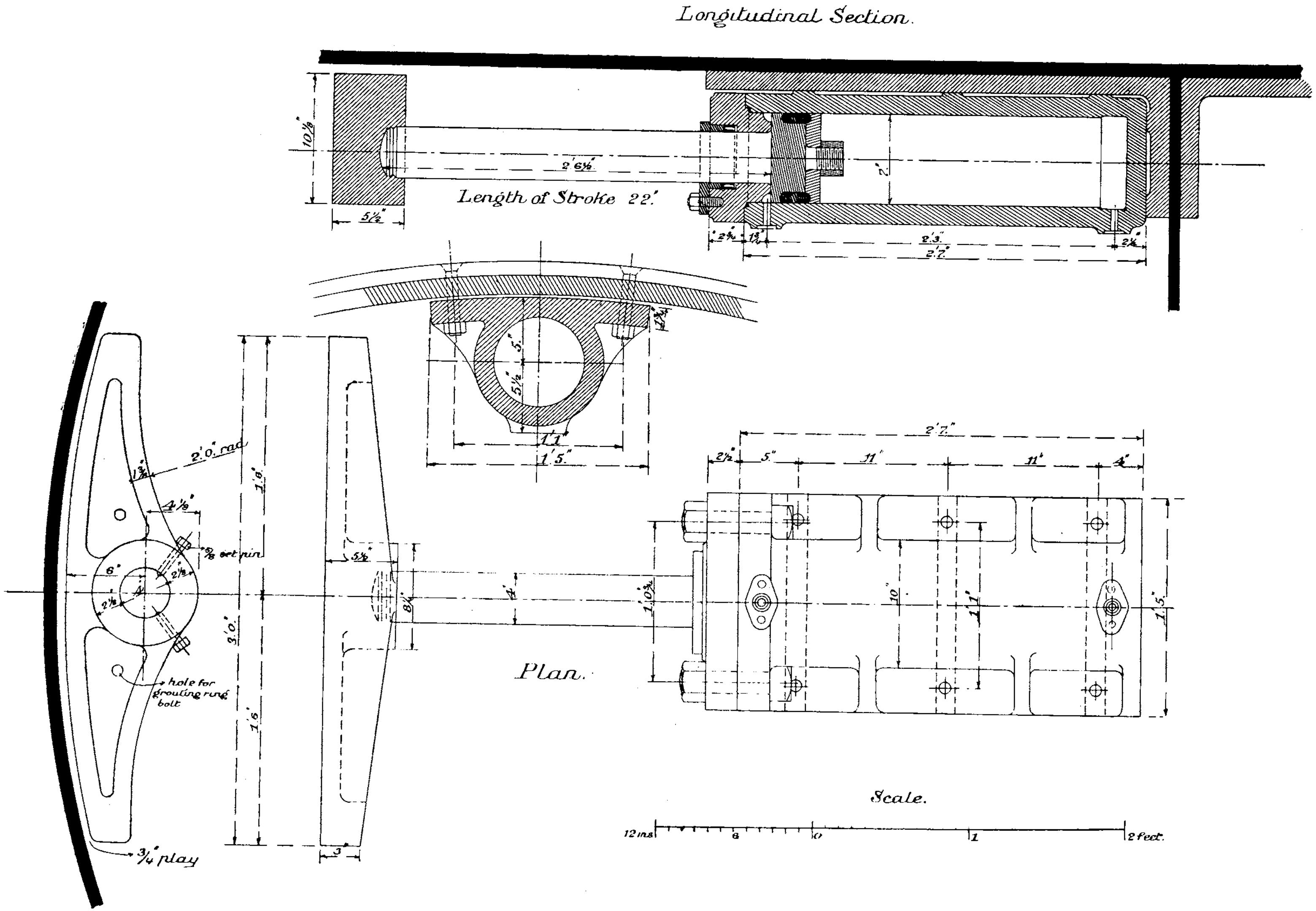


Fig. 165. Greenwich Tunnel, London. The Shield: Details of Hydraulic Rams.

of wood and iron M, M, which completely closed the upper part of the shield, except for an opening about 3 feet 3 inches by 2 feet. This opening was provided with two double doors, the front ones opening towards the face, and the back ones to the rear of the shield. The front pair of doors were held closed by a short stretcher to the front diaphragm, which could be easily knocked away, when the rush of air outwards, which a "blow" would have occasioned, would make the doors fly open.

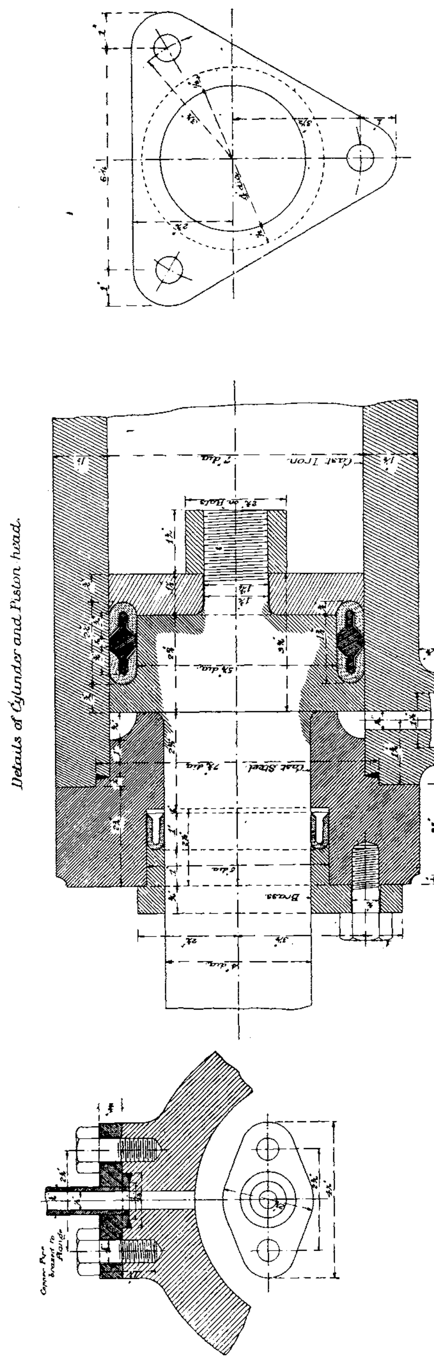


FIG. 166. GREENWICH TUNNEL, LONDON.
The Shield: Details of Hydraulic Rams.

The doors to the rear of the new diaphragm were kept open. In the event of any "blow" occurring in the face, and a consequent fall of the ballast blocking the ordinary means of egress through the trap, the men working in the upper part of the face could escape through these doors, and it was found, on the few occasions where small "blows" did occur, that the knowledge of a means of escape thus provided did embolden the men to endeavour to make things safe in the face before leaving instead of rushing out of the shield in a panic.

With this arrangement of the shield an advance of 5 feet, or three rings of the cast-iron lining of the tunnel, was made daily in a face consisting almost entirely of open ballast.

During the construction of the tunnel, the face gave way on several occasions, and the trap or box arrangement of the shield proved satisfactory each time. The front of the shield filled, of course, with gravel and water, but at no time did any great quantity of water pass over the trap into the tunnel.

From the construction of the shield it will be seen that the men working at the face were shut up in a very small chamber, and, in consequence, in spite of the flow of air through the trap, it was found that the atmosphere in the lower part of the shield was always more charged with carbonic acid than that in the open tunnel immediately behind the shield. On some occasions, when the amount of CO_2 at the invert of the tunnel immediately behind the shield was 0·1 per cent., there was 0·2 per cent. at the invert of the front of the shield.

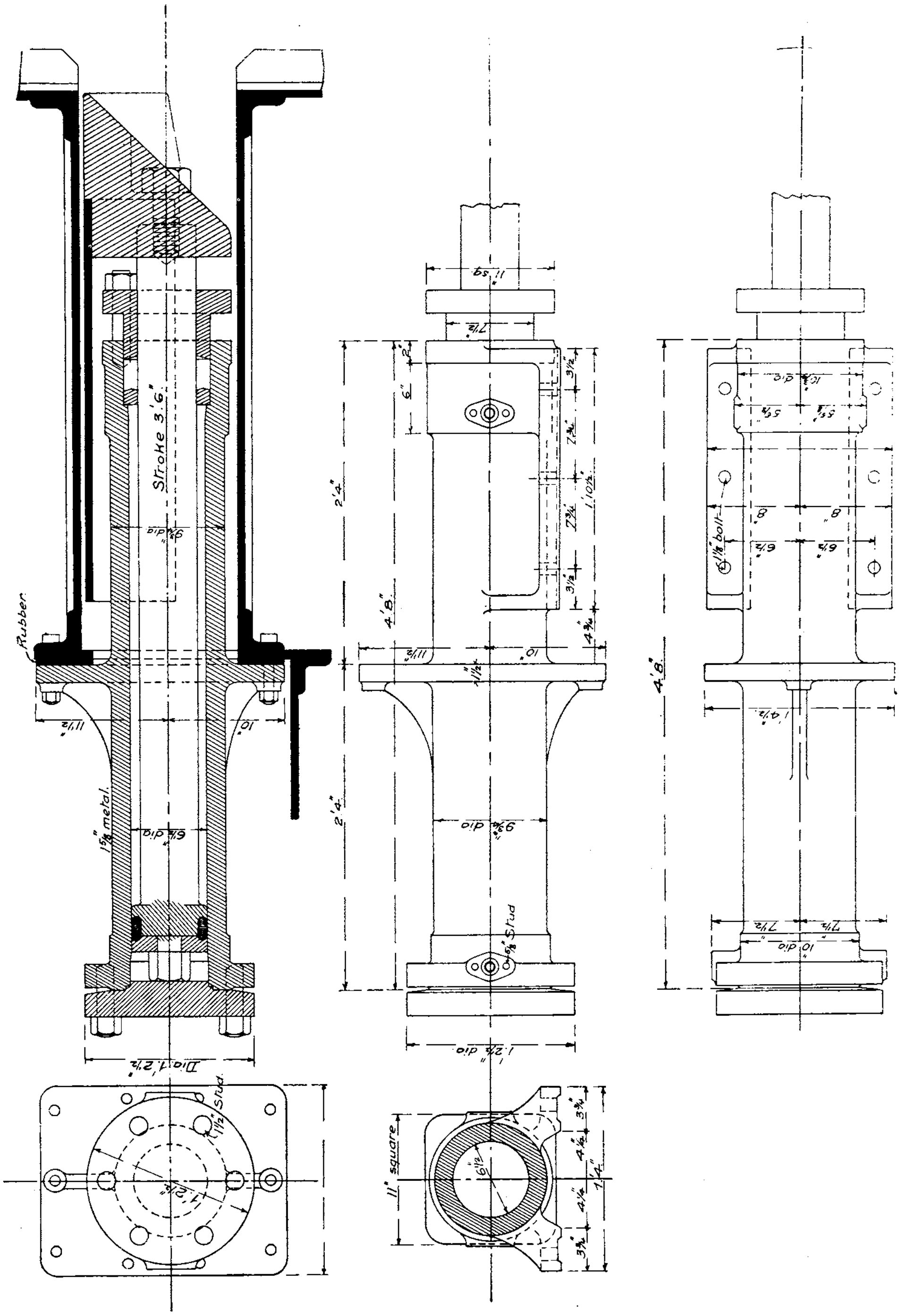


FIG. 167. GREENWICH TUNNEL, LONDON.
The Shield: Details of Hydraulic Face Rams.

A simple arrangement, by which the ordinary blow-out pipe of the tunnel was utilized to remove the vitiated air in the shield, proved very effective, a reduction of 30 per cent. in the amount of CO_2 in the shield being measured by analysis after using the blow-out pipe for a few minutes.[1]

A pipe *N* (see Fig. 161) of 3 inches diameter was inserted in the trap, one end of it reaching to the bottom, the other projecting a few inches through the vertical back, of the trap. On this projecting end, the blow-out pipe of the tunnel, when not in use for blowing water out of the invert, was placed.

By this arrangement the opening of the valve of the blow-out pipe drew out the air from the bottom of the shield face, and, as said above, a noticeable improvement of the air in the working chamber was effected thereby.[2]

The shield as modified proved an efficient machine for working in water-bearing strata, but the experience gained with it suggests several structural improvements, which, in another tunnel of approximately the same diameter, might be usefully carried out.

The combination of the built ring with cast steel segments forming the cutting edge was very satisfactory, but the length of the front chamber so made might well be increased from 3 feet to 4 feet. This would give more room for work, and the increase in the length of the shield, an important matter when curves have to be negotiated, could be compensated for by reductions elsewhere.

Such an increase in the front of the shield should be made in the invert as well as in the crown.

The front diaphragm could well be made without any observation holes, but instead be constructed in hinged segments and the whole bolted, not rivetted, to a circular plate introduced behind the cutting edge circular box girder.

The distance between the front diaphragm and the trap opening was unnecessarily great, owing to the sliding tables of the face rams having to be withdrawn within the line of the front diaphragm. The front rams, if unprovided with sliding tables, need only, when drawn back, be within the shelter of the cutting edge, and consequently their cylinders could be correspondingly advanced towards the cutting edge, and their extension behind the front diaphragm reduced, which reduction would enable the "trap" to be brought nearer to the front diaphragm.

For an actual application of this idea, see the drawing of the Lea Tunnel (Fig. 171).

Among the smaller improvements made in the shield was the substitution of Berry's two-way valves for the ordinary ones usually fitted to the shield rams.

They gave good results, and were incomparably better as regards compactness.

Details of the shield rams and of the face rams are shown in Figs. 165, 166 and 167.

The first cost of a shield of this character is about £1,700, but the repairing charges are small, and when the Greenwich tunnel was completed, the shield was, for practical purposes, as good as ever.

The labour necessary to work the shield was as under, the wages put down to each man being those on which the piece-work prices were based, for as usual all the work was done by contracting with the shield gang, a progressive bonus being paid on the number of rings put in weekly over a certain number.

[1] *Proc. Inst. C.E.*, vol. cl., pp. 20 and 22.
[2] For compressed air experiments in this tunnel, see p. 45.

The shield gang consisted of—

1 ganger	at 12*s.*	per	shift	of 8	hours
2 miners	,, 10*s.*	,,	,,		,,
2 miners' labourers	,, 9*s.*	,,	,,		,,
5 labourers	,, 8*s.*	,,	,,		,,
1 shield driver	,, 8*s.*	,,	,,		,,
1 locksman	,, 8*s.*	,,	,,		,,

These were all the men inside the airlock, and the cost of their labour, including bonus, varied from £10 per foot run of tunnel when only one ring per day was erected to about £4 5*s.* when three were daily put in.

The charges for air compressors, hoisting apparatus, lighting, and pumping vary so much with the local conditions that any attempt to specify them would be misleading.

At the Greenwich tunnel the first cost of the machinery and general contractors' equipment amounted to nearly £20,000, but much of this expenditure was, as is usually the case, spread over other work than the part now under consideration.

A further development of the shield described above is illustrated by the machine used in the Lea Tunnel.

The Lea Tunnel Shield (1900)

In the year 1900 it was decided to enlarge the outfall sewers of the London Main Drainage system on the north side of the Thames, and this necessitated tunnelling under the River Lea at a point near Abbey Mills Pumping Station, where the Lea flows in three channels. It was decided to make the new sewer, 11 feet 6 inches in internal diameter, by means of a shield, the sewer itself to be of cast iron lined with masonry. The character of the ground at the sewer level was reported

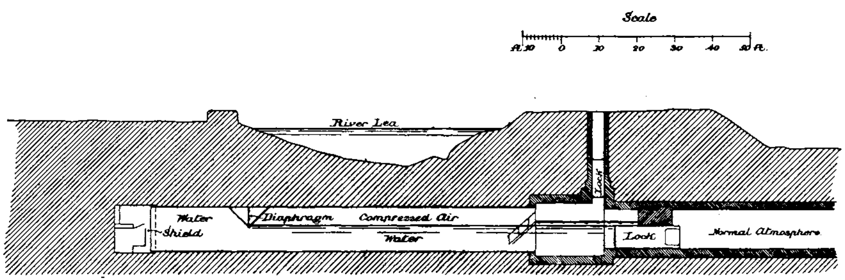


FIG. 168. THE LEA TUNNEL, LONDON.
Longitudinal Section.

to be open water-bearing ballast above and clay below at the commencement, gradually changing to a full face of clay. In actual fact the material described in the trial holes as clay proved to be for the greater part of the tunnel merely peat, but when the shield was designed, it was planned with the object of making it equally useful either with compressed air and a protected face or with ordinary atmospheric pressure and an open face of clay or other impermeable material.

The tunnel was made and the sewer built, but partly owing to insufficient air-compressing power, and partly owing to ignorant handling on the part of those entrusted with the work, the shield was never used as it should have been, and as the Greenwich Tunnel Shield actually was being used at the time, but the tunnelling was carried on rather on the lines of the "assisted shield" method referred to in a previous chapter.

The arrangements made for building a tunnel under compressed air were in general of the same character as in other works of the like nature, but some modifications were introduced, due to the special circumstances of the case.

The shield chamber, in which the shield was erected, was made in brickwork, a length of the ordinary brick sewer being built of slightly larger diameter to permit

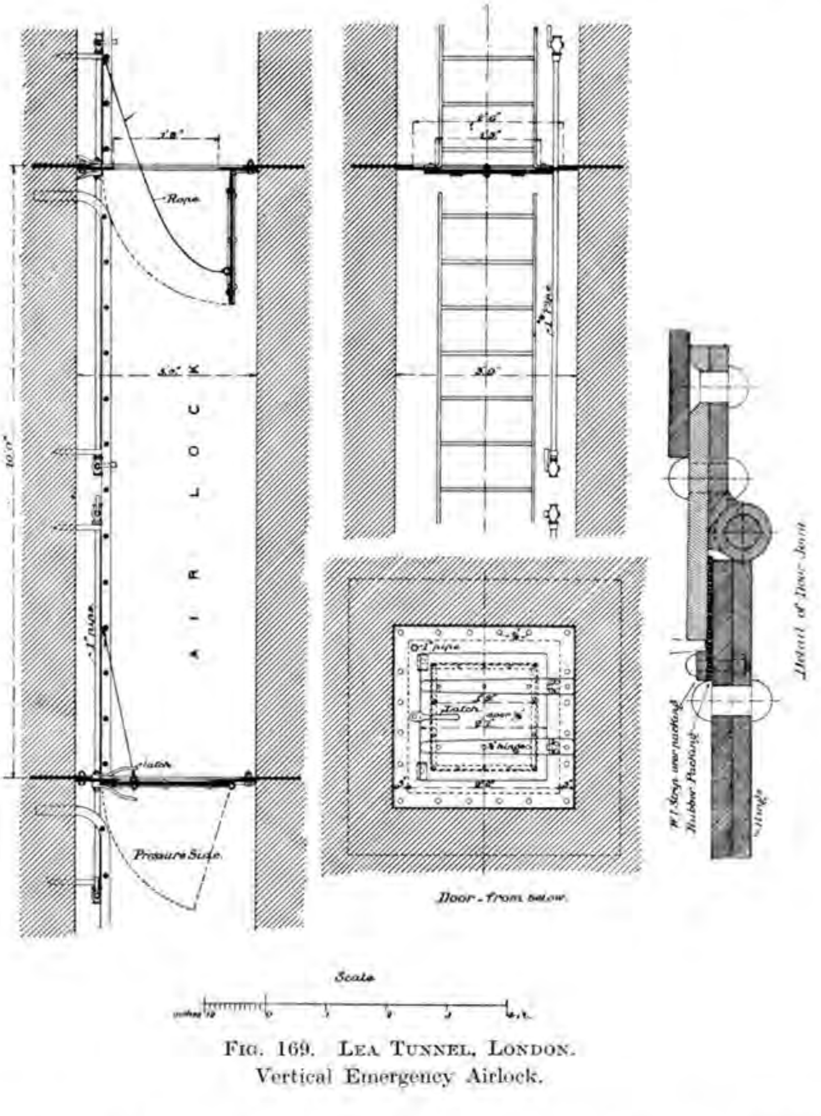


FIG. 169. LEA TUNNEL, LONDON.
Vertical Emergency Airlock.

of the erection of the shield within it (see Fig. 168). The shield was erected in the open, the forward end of the chamber where the iron tunnel was to commence being close timbered during the process.

When the shield was erected, a brickhead with airlock *A* (Figs. 15 and 16) was built behind it, and work under compressed air proceeded in the ordinary way.

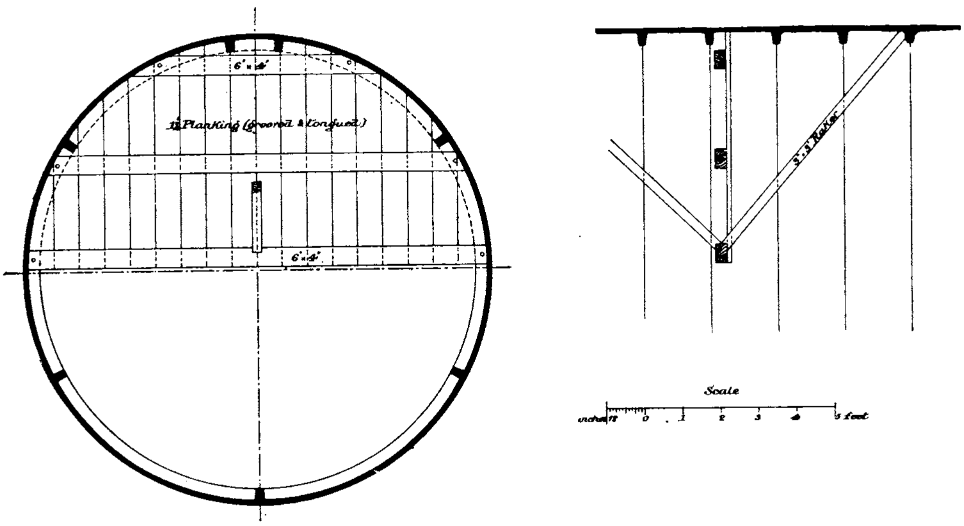


FIG. 170. LEA TUNNEL, LONDON.
Timber Safety Diaphragm of Screen in Tunnel.

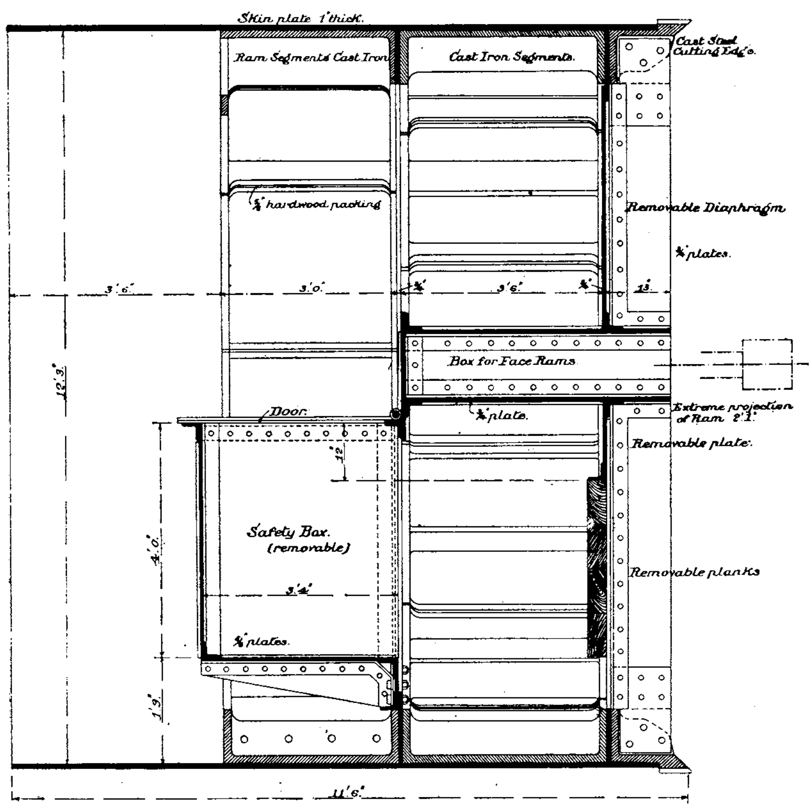


FIG. 171. LEA TUNNEL, LONDON.
The Shield: Longitudinal Section.

It was necessary to provide, at the point where the shield chamber was erected, a ventilating shaft for the sewer when finished, and the Author, who had charge of the work for Sir A. R. Binnie, fitted in this shaft an emergency lock, by which the miners in case of a "blow" in the face which blocked the main airlock could escape. To increase the conditions of safety, a safety diaphragm of similar character to those employed at Blackwall and at Greenwich was employed. In a small tunnel like the one under consideration, the diaphragm could be made of wood, and little labour was expended on it, save in making a caulked joint with the iron lining

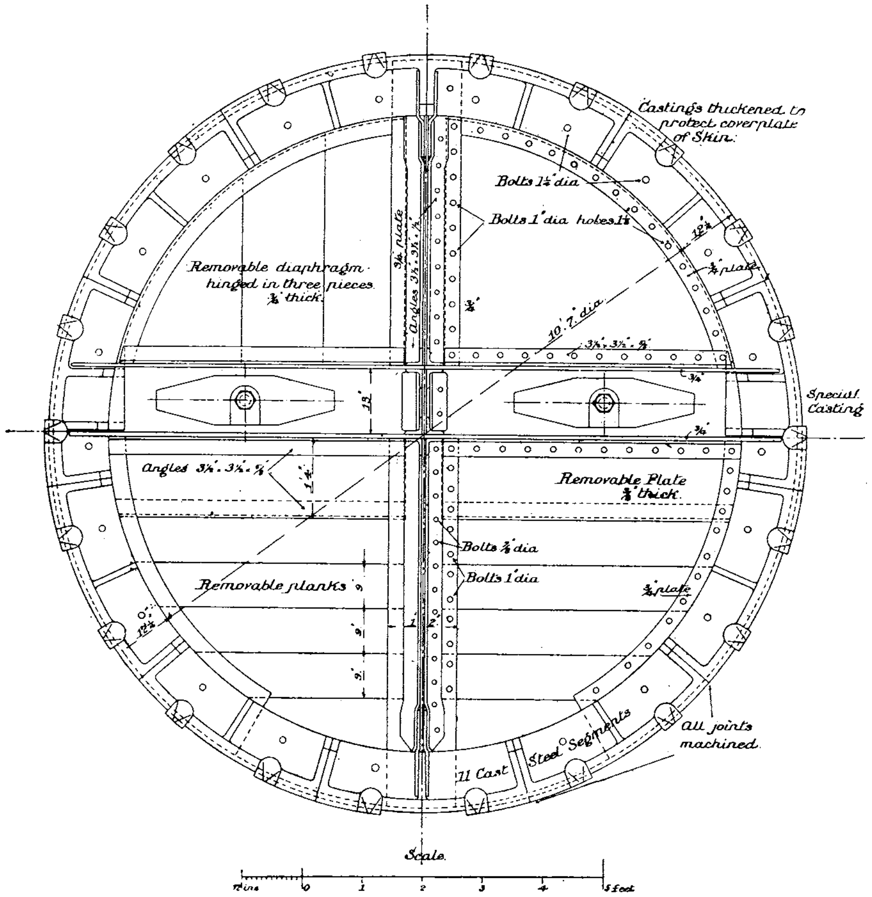


FIG. 172. LEA TUNNEL, LONDON.
The Shield: Front Elevation.

of the tunnel. The boards composing the diaphragm were tongued and grooved. Fig. 168 shows the arrangement adopted, by which it is evident that, could the miners after a "blow" at the face escape behind the diaphragm, they would be in a space where the air was sealed in, and where they would at any rate have temporary protection until they could make their way out through the vertical airlock. The details of the diaphragm are shown in Fig. 170.

The airlock shown in detail in Fig. 169 was of the simplest character, the two ends being formed of $\frac{1}{2}$-inch plates built into the brickwork of the ventilating shaft, in which plate openings for the lock doors were cut. When the compressed air work was finished, the doors and fittings were removed, and the end plates left in.

In general character the shield resembled the Greenwich Tunnel shield and the Baker Street and Waterloo subaqueous shield in its "trap" construction, but certain modifications were introduced, which may be briefly indicated.

Figs. 171, 172, 173 and 174 show how nearly the general arrangement of the shield resembles that of the Greenwich Tunnel, with the important difference that the whole of the internal framing of the shield, with the exception of the vertical

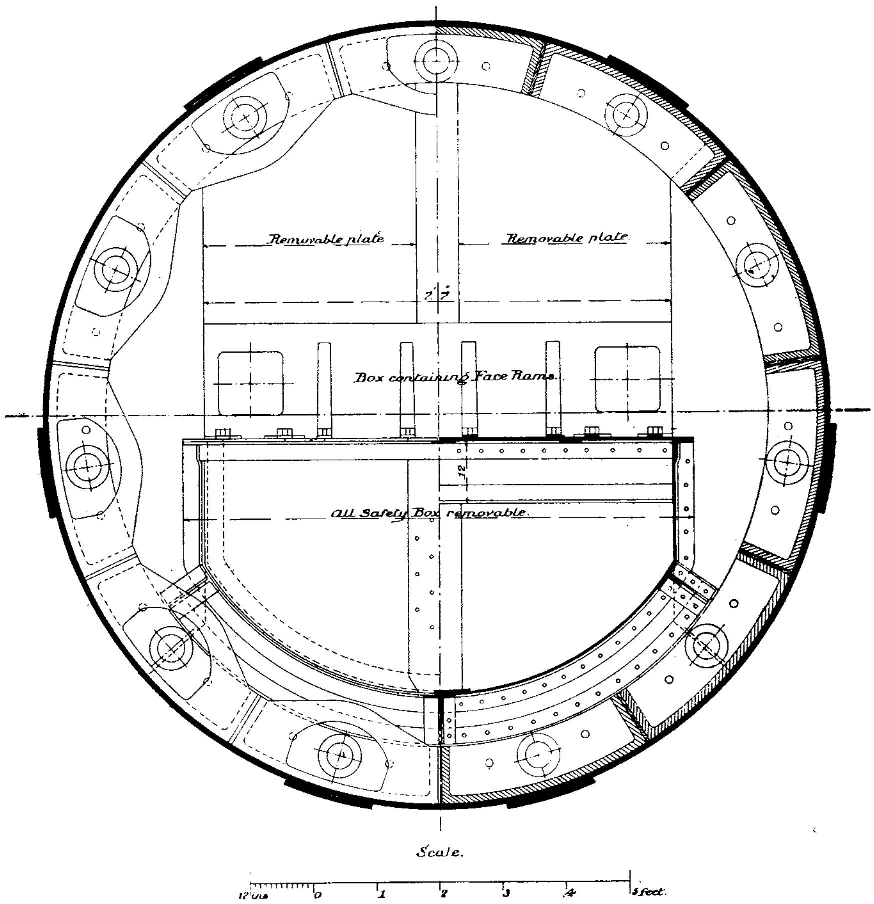


Fig. 173. Lea Tunnel, London.
The Shield: half back elevation and half section through Safety Box.

stiffener, and the horizontal plates of the box containing the face rams, could be easily removed, and replaced, as the character of the face varied.

The characteristic parts of the "trap" or "box" shield, the front air-tight upper diaphragm, and the back diaphragm shaped like a box and provided with lids, could be removed with ease, leaving a shield with an open nearly circular face divided by vertical and horizontal girders.

This is shown in Fig. 173, giving a half back elevation and half sectional elevation of the shield.

The face rams were arranged so that, when extended, they were well in advance of the cutting edge of the shield, a modification made as a result of the working

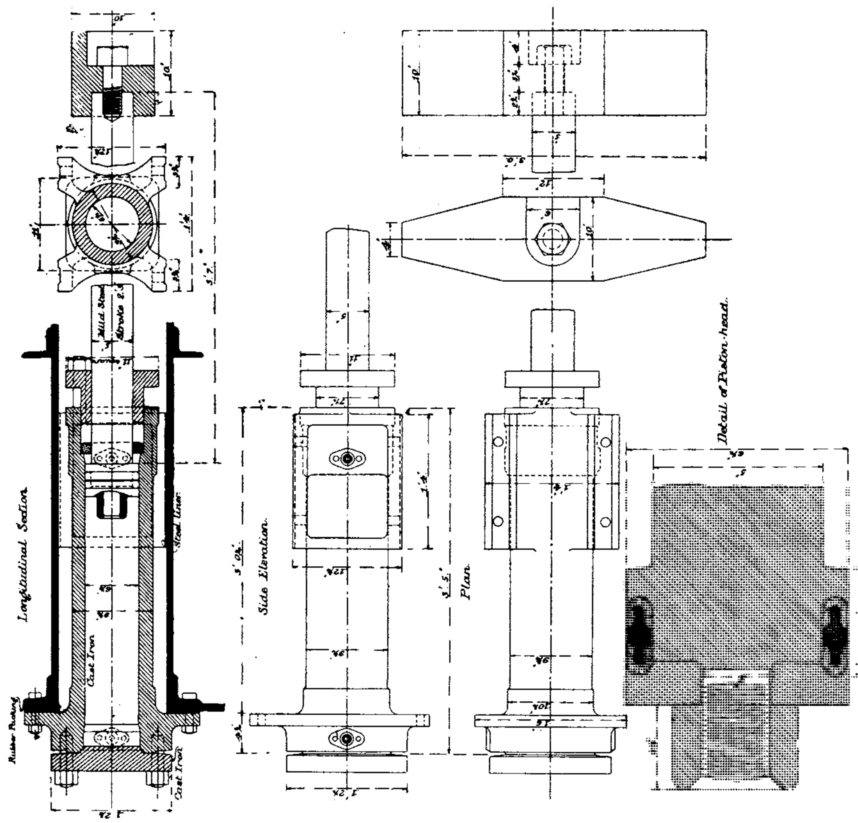


FIG. 175. LEA TUNNEL, LONDON.
The Shield: Details of Face Rams.

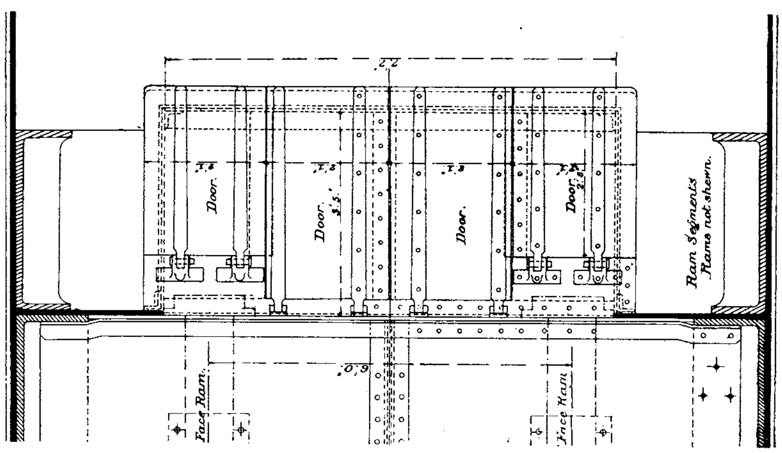


FIG. 174. LEA TUNNEL, LONDON.
The Shield: part Plan.

of the Greenwich shield, and by thus advancing them they were placed nearly clear of the doors or covers of the "trap," so enabling a larger width to be opened for working purposes, as shown in Fig. 174. (Compare Fig. 160 of the Greenwich shield.) An improvement was also made in the attachment to the frame of these face rams. They were secured to the horizontal plates above and below them by bolts passing through the plates, so that it was possible to remove the bolts, and so detach the rams, without having to timber in front of the shield (see Fig. 175). On the other hand, the circular-built girder of the Greenwich shield was omitted, and the cast steel cutting edge bolted directly to the plates to which the removable front diaphragm was attached. It was found that the reduction in the distance from the front of the cutting edge to the front diaphragm was an error ; the working area in front of the diaphragm should be at least 3 feet as in the Greenwich Tunnel, and, as suggested in the description of that work, could well be made 4 feet.

Quite apart from the greater freedom for working in the wider chamber, the miners in it feel, in some degree, a greater sense of security than when between a working face and a diaphragm only 18 inches apart. The feeling is not defensible on any logical ground, but it undoubtedly exists, and the men's prejudices must be reckoned with in making the arrangements of a shield.

The front diaphragm of the shield was made, as regards the portion above the face ram boxes, in folding sections, but this arrangement in the actual circumstances of the work, was never tested. In fact, as said above, the shield was never fairly tested ; one of the modifications made on previous designs was, however, distinctly satisfactory, namely, the making the face rams with a longer stroke, or rather with a stroke reaching further beyond the cutting edge of the shield.

The rams used with this shield were the same as those of the Greenwich shield.

The Baker Street and Waterloo Railway River Shield.[1]

At the same time that the two tunnels under the Thames at Greenwich and the River Lea, just described, were in progress, two tunnels, forming part of the Baker Street and Waterloo Railway, were in course of construction under the Thames at Charing Cross, the conditions of the work and the methods employed being in many respects identical.

The head of water to be dealt with was approximately the same ; the open ballast through which all the tunnels were driven was of the same character ; the shields were all of the "trap" or "box" type ; the tunnels were nearly identical in size, and the methods of timbering the face were on much the same lines.

But in details, there were in the Baker Street and Waterloo tunnels sufficient variations to make a separate description necessary, and the shield in particular is interesting, as, like the one at Greenwich, it was altered in its frontal construction after the commencement of actual tunnelling work, the original design, which was modelled on one previously used successfully, failing to cope with the conditions of the work.

The Baker Street and Waterloo Railway Tunnels are, with the exception of a portion of the length under the River Thames, constructed entirely in London Clay, and their construction, therefore, for the greater part of their length, is identical with similar work described in chapter IV.

For the tunnels under the river, special temporary shafts were sunk in the river itself, from which the shields were started, and which were removed when

[1] *Proc. Inst. E.C.*, vol. cl. Haigh on Subaqueous Tunnelling through the Thames Gravel.

the work was finished. This arrangement effected a notable economy in the work; all the material for the construction of, or excavated from, the tunnels was water-borne (see Fig. 176).

The timber stage from which all the tunnelling operations were constructed was 370 feet long and 50 feet wide, and held all the workshops, machinery, stores, etc., necessary for the work.

The boiler power provided amounted to 300 nominal horse-power, the air compressors being, in addition to a portable Slee engine for grouting purposes, three in number, with double acting air cylinders, 26 inches in diameter, and 30 inch stroke, and running up to sixty revolutions per minute.

These would give, assuming an efficiency of 80 per cent., about 140,000 cubic feet of free air per hour.

From the stage cast-iron lined shafts, 16 feet in diameter, were sunk (to a depth of about 50 feet) into the London Clay, and below them again brick shield chambers were constructed by underpinning. The cast-iron lining consisted of six rings, each 8 feet in depth, having six segments to a ring. The joints were machined, and the pieces were put together with red lead and hemp-yarn. A 2-foot cutting edge, with bevelled vertical flanges and sharpened edge, was used to sink the cylinder. Six rings and the cutting edge made up the 50-foot length of iron cylinder, reaching about 10 feet into the London Clay. Below this

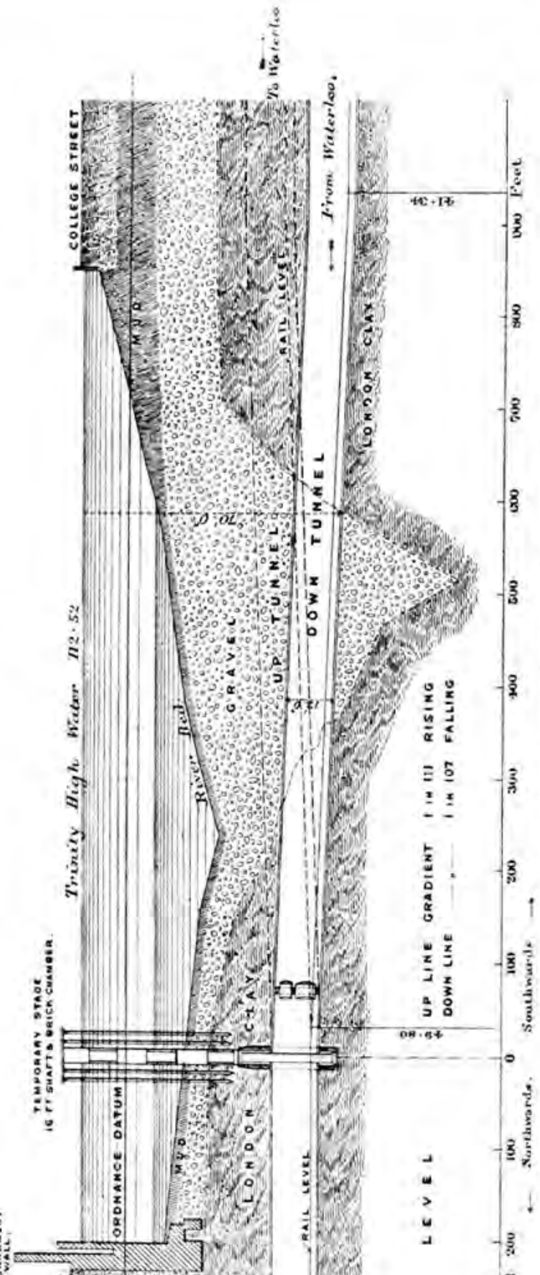


Fig. 176. Baker Street and Waterloo Railway, London.
Longitudinal Sections of Tunnels under the River Thames.

the brick chamber extended downwards a further distance of 22 feet. To prepare for sinking the cylinder, a timber platform was erected, somewhat above the level of low water, and on it the cutting edge was put and bolted together. The two succeeding rings were then built above, and the length was slung by chains, and held by union screws from timber balks across the opening in the stage-decking. The platform below was next removed, and the 18 feet of cylinder was lowered through the mud, the grab being used within, until, on its taking a bearing, the screws could be detached, when another two rings were built. Including the weight of the cylinder, a load of 106 tons, equivalent to about $2\frac{1}{2}$ cwt. per square foot of

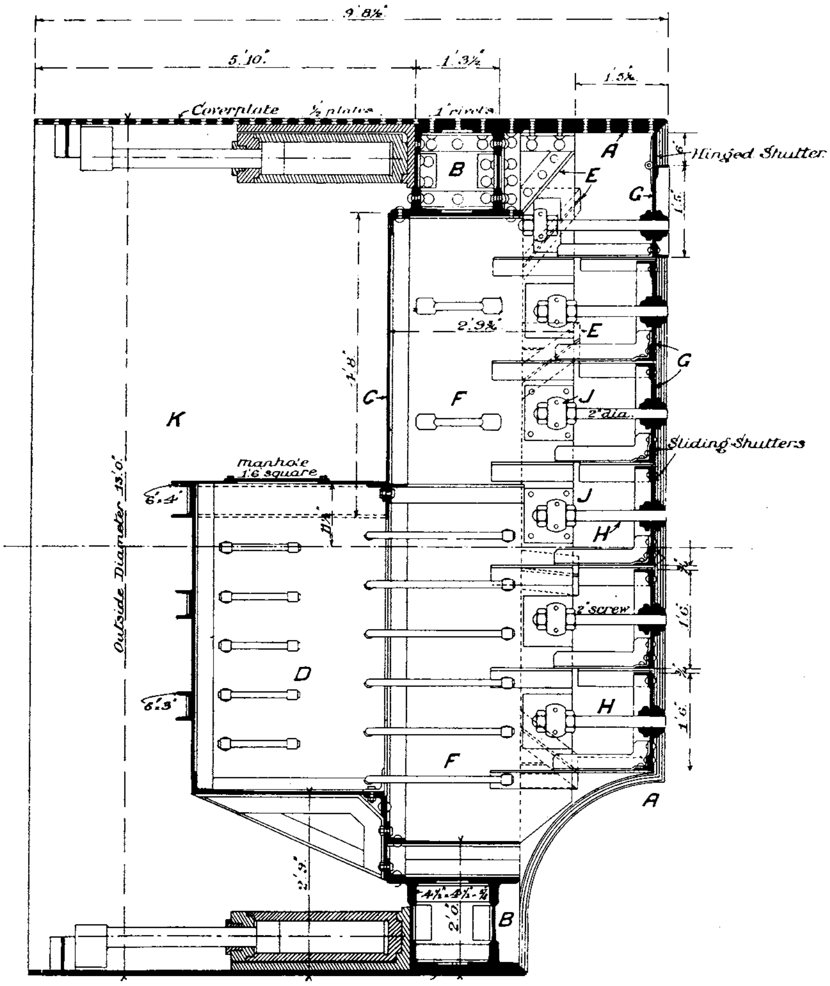


FIG. 177. BAKER STREET AND WATERLOO RAILWAY, LONDON.
The Shield for Subaqueous Work: Longitudinal Cross Section.

maximum surface exposed to friction, sufficed to sink the remaining 6 feet to the required level for underpinning the cylinder with the brick walls, 23 inches thick, for the enlarged chamber below. In carrying down the brickwork, spaces were left for eyes, in which five-ringed brindled brickwork in 2 to 1 Portland-cement mortar was afterwards built, forming complete circles through which the tunnelling-shields were to be driven, the work above being propped in the meantime. Each leg of succeeding rings of brickwork was built under the junction of two legs of its predecessor. Inverts were made of 15-inch Portland-cement concrete, dished about 6 inches.

As the shafts were sunk well into the clay, compressed air was not required in starting the shields from the shafts. They were erected in the brick chambers, and when ready to start, were driven into the clay through the eyes provided for that purpose, and a short length of tunnel built before the airlocks were put in, and compressed air-work started.

These tunnels indeed were driven under the Thames for the greater part of the distance in London Clay, but for a part of their length they passed through a bed of open ballast extending upwards to the river, containing very little sand, and being, of course, charged with water, the high tide level being some 70 feet above the tunnel invert at its lowest level.

The shield employed was, therefore, designed to work under these conditions.

As originally constructed it is shown in Figs. 177 and 178.

The cutting edge *A* was formed of four plates, $\frac{1}{2}$ inch thick, and cut at the face to a bevelled edge, and was shaped into a " hood " of similar pattern to that devised for the Waterloo and City Railway shield. The plates of the cutting edge were riveted together with 1-inch rivets at 6 inches pitch. The segmental plates break joint, and over the six joints of the outermost plate are cover plates, which are extended back over the joints of the single $\frac{1}{2}$-inch plate forming the tail of the shield. Like that shield too it was stiffened with a circular box girder *B*, to the rear of which was attached the front diaphragm *C*, and the base of the back diaphragm or box *D*.

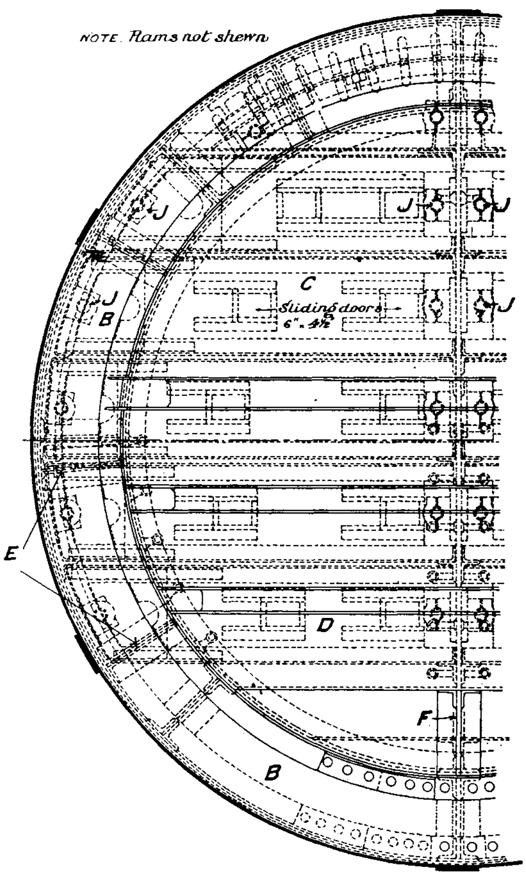


FIG. 178. BAKER STREET AND WATERLOO RAILWAY, LONDON.

The Shield for Subaqueous Work: Half Back Elevation.

The cutting edge projected at the top 4 feet 3 inches in front of this front diaphragm, and is stiffened by gussets *E*, *E*, attached to the box girder.

The shield is further stiffened by a vertical central framing *F* of $\frac{3}{4}$-inch plate, 2 feet $9\frac{3}{4}$ inches wide, similar to that of the Greenwich shield.

The box or trap *D* did not vary in essentials from those used elsewhere, and proved satisfactory, for though no serious collapse of the face occurred throughout the whole period of work, the occurrence of a few small blows from time to time demonstrated that the four men at work between the diaphragm and the face had time to escape through the trap, and that, on filling, the trap sealed automatically, maintaining an unstable equilibrium, until the sand, which followed from the face, filled the trap, and extended with a sloping surface from the lip of the diaphragm to the face at the cutting-edge soffit. It was possible to remove this sand subsequently, by opening carefully under the edge of the diaphragm, until a miner could gain access to the face, and set protecting timber. The top of the trap was provided with a plate with a manhole through it, and a covering lid which could be screwed down in case of need. Round iron foot- and hand-bars were fixed up the curved sides of the trap and inside the circular girder.

But the attempt to do away with timber work in the face by fitting the shield with sliding shutters was an innovation in a shield of this size.

These shutters *G*, *G*, were intended to cover the whole working face of the shield to within 3 feet of the invert. They were held in place by screws *H*, *H*, *H*, which worked in bearings *J*, *J*, *J*, fixed to the skin of the shield and to the vertical frame *F*. Each shutter was in two independent parts, one on either side of the central vertical stiffener, so that in bad ground one-half of the face could be worked down at a time and so minimise the risk of a blow.

It was intended that by operating these screws the shield could be driven forward, while at the same time the face of the ballast could be sustained by the shutters, which would be made to give way as the shield advanced. The Blackwall Tunnel and the Hudson River tunnel shields had been fitted with similar shutters, and the arrangement had proved in both cases perfectly satisfactory. These shields, however, were of much larger diameter, and in the case of the Baker Street and Waterloo shield, it was soon found that it was impossible to work the shutters at the top of the shield advantageously, owing to the limited space available, and the decision to abandon their use was no doubt also influenced by the fact that, for a shield of this size, an advance by means of shutters successively worked meant a very slow rate of progress, as compared with even the most elaborate system of timbering.

The cast steel ring composed of eight segments, which carries the hydraulic rams, was of the usual pattern, but the disposition of the rams was uncommon. They were fourteen in all, and of this number eight were clustered together at the lower part of the shield, and the remaining six distributed in pairs at the crown and sides (see Fig. 179). The number of rams is in excess of that provided previously in shields of the same size; the Mersey (Vyrnwy) Tunnel shield had nine only, and the Greenwich shield thirteen, this being a much heavier shield than either of the others.

In ordinary conditions of work, the four lowest rams were not brought into use, at all, and of the remaining ten, those, never exceeding six in number at once, were employed which the guiding of the shield required.

The rams and connexions were tested for a working pressure of 2,400 pounds per square inch. The hydraulic pressure was supplied by an intensifier fed by water from an hydraulic power company's mains, nominally at 800 pounds per square inch. In this intensifier a 7-inch cylinder compressed the water in communication with the rams by two 3-inch plungers to an actual pressure of 2,400 pounds per square inch. The average working pressure in the rams was 1,300 pounds per square inch.

The tail or skin *K* of the shield behind the circular-built girder consisted of six ½-inch plates butt jointed, the joints being covered with covers 8 inches wide and ½ inch thick.

The weight of the shield was $29\frac{1}{2}$ tons.

The shield had hardly got to work in bad material when the shutters in front were found to be inconvenient, and were removed, and recourse was had to timbering ahead of the shield, somewhat in the manner already described in the case of other tunnels, but with two important variations.

The use of clay pockets in front of the cutting edge, which had proved so satisfactory in the Waterloo and City Railway, was adopted, and, by the employment of steel tubes or rakers passing through holes in the vertical diaphragm of the shield, the use of the timber rakers, such as were used on the City and South London, and Glasgow District, Railways in similar conditions, and the use of which entirely destroyed the protective character of the shield, was done away with.

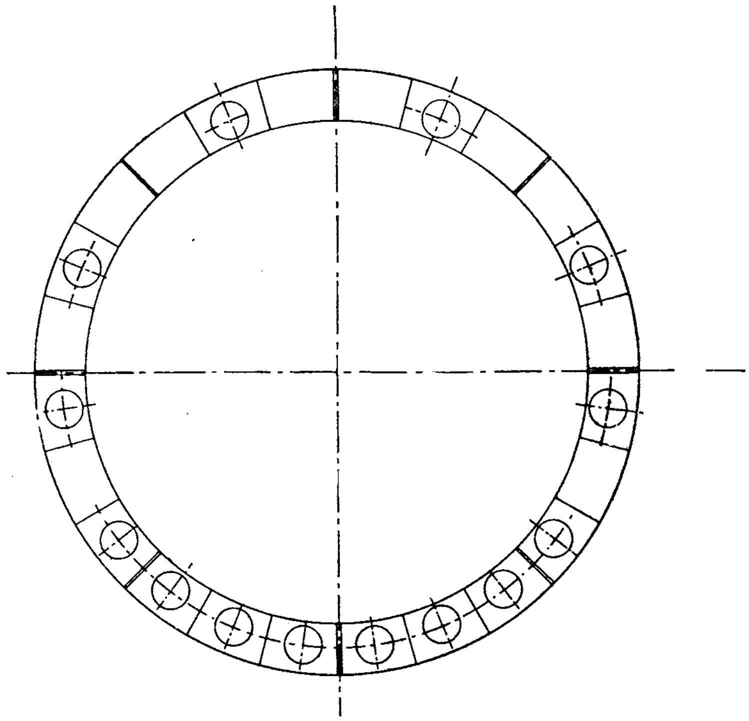


FIG. 179. BAKER STREET AND WATERLOO RAILWAY, LONDON.
Shield for Subaqueous Work: arrangement of Rams and Segments.

The timbering of the face varied a little as to the arrangement of the polings, according to the varying nature of the face. Figs. 180 and 181 show the poling used in a full face of ballast, and also the steel rakers, and their relation to the shield, which appears stripped of the protective shutters in front.

Two pairs of steel struts *L*, *L*, were fitted, constructed of steel tubes, $5\frac{1}{2}$ inches diameter and 7 feet 6 inches long. These tubes were closed at each end by screw plugs, that at the forward end making a flush end with the tube, so as to give a solid bearing against the walings *P*, *P*, of the face, that at the rear being made to receive an adjustable head *M*, *M*, by which the strut could be tightened against the transoms or byatts *N*, *N*. These struts passed through the diaphragms of the shield in holes *O*, *O*, cut for the purpose, and made partially air-tight by leather sleeves fitted on the pressure side of the diaphragms.

The byatts were secured to the sides of the tunnel, and held tight by chogs between the flanges of the tunnel segments.

The face polings were each 9 inches by 3 inches held up by soldiers *R*, *R*, 9 inches by 6 inches, the whole face being carefully plastered with pugged clay.

The use of pugged clay in pockets in front and outside of the cutting edge was efficacious not merely in making an air-tight annular space into which the shield could easily enter, but also in forming, as the shield went forward, an air-seal at the joint of the shield and the last tunnel ring erected.

The rate of working was usually about 5 feet per day of twenty-four hours, a fair advance in open ballast.

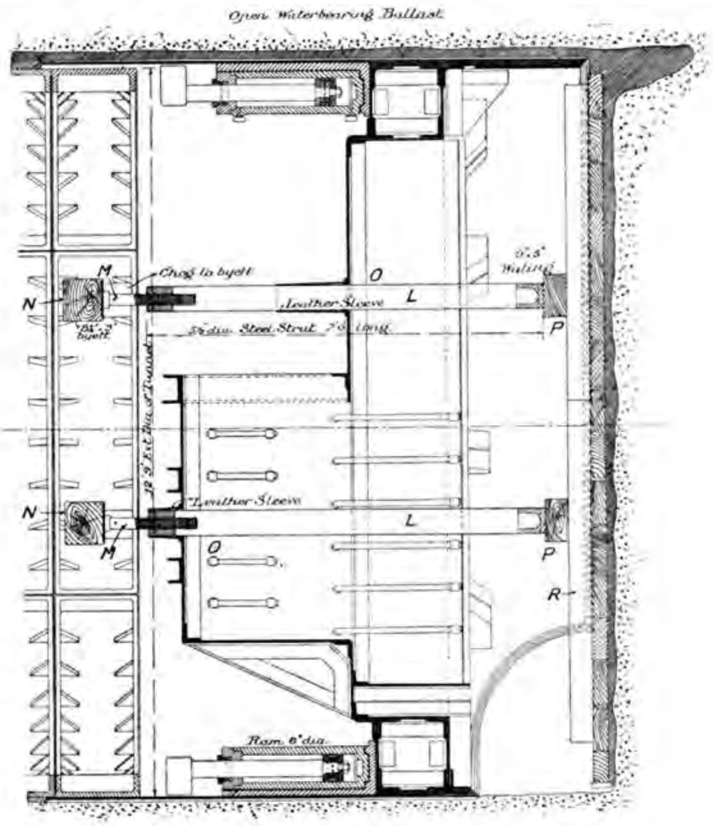


FIG. 180. BAKER STREET AND WATERLOO RAILWAY.
The Shield for Subaqueous Work: Method of Using.

The work of driving the west or down tunnel under the river was commenced on March 19, 1900, work on the east or up tunnel being postponed until the first was built.

When started from the shaft, the shield was without any of the protective fittings, as there was over the tunnel a cover of clay 17 feet thick, and the river bed was 7 feet above the clay.

Driving under ordinary atmospheric conditions was continued until April 2, when the advance was suspended in order to build the bulkhead wall with airlocks behind the shield. At that time there was still 15 feet of clay above the crown of the tunnel. A bulkhead, 8 feet thick, of wire-cut gault bricks and Portland-cement mortar, grouted with neat cement by air pressure through iron pipes built in for the purpose, formed the air-tight diaphragm. Besides the working-lock 5 feet 9 inches in diameter and 13 feet 6 inches long, there was an emergency-lock above it 3 feet 9 inches in diameter, and of course the necessary pipes and electric wires were built in the brickwork of the bulkhead.

The shield was re-started on May 2 after one month's interval. On the 21st, when the clay showed a change in quality, the shield was stopped, and the fountain trap at the back was attached. The cover of clay at the cutting edge was then

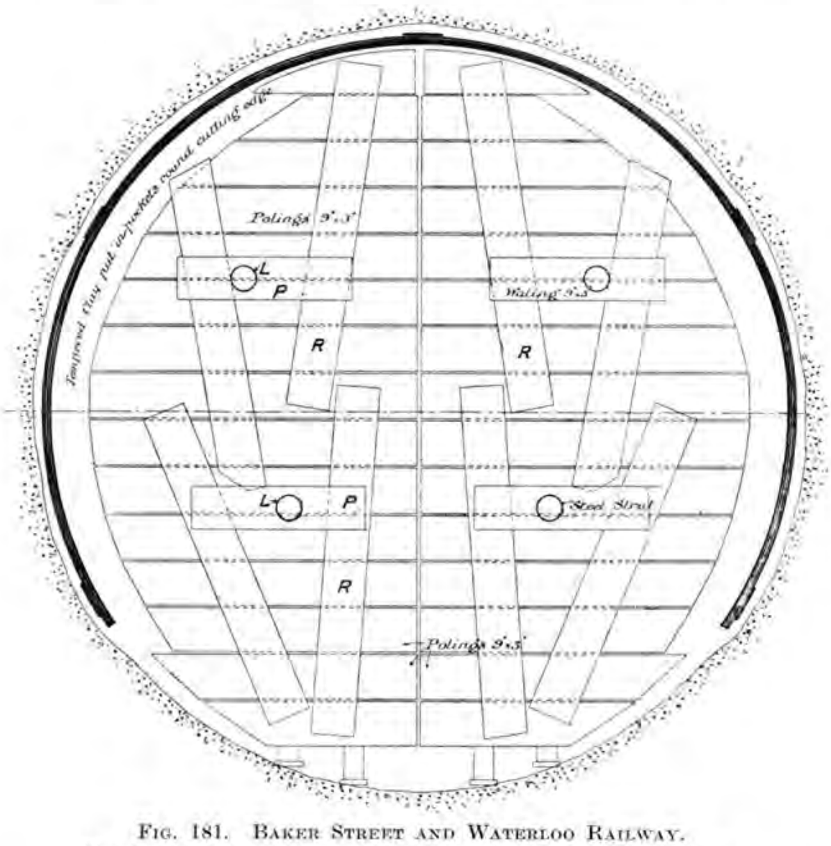


FIG. 181. BAKER STREET AND WATERLOO RAILWAY.
The Shield for Subaqueous Work: the Timbering of the Face.

5 feet, and the depth below the river-bed 18 feet. Hitherto a box heading, with 6-foot timbers for head and side trees resting on sills, had been worked in advance of the shield to a distance of about 7 feet. This was now stopped. Auger-borings were being made in the length each time the shield was driven forward, extending to 5 feet above and in advance of the cutting edge ; they were also made in advance of the box heading. On May 23 the lock-doors were closed, and an air pressure of 10 pounds per square inch was maintained. After building-in the locks and re-starting the shield, one engine had been running and blowing air into the tunnel in readiness for closing the door at any time.

On beginning compressed air work the labour-shifts were altered from two

12-hour to three 8-hour gangs. On June 6 the cutting edge entered the gravel at the soffit. For about three days previously there had been practically no thickness of clay cover; and the vertical face at its upper part was poled up and down, middled by a waling, and the top of the length was guarded by a few boards. When ready for driving, the short stretchers against the shield were struck, after substituting a waling low enough to be held by the hollow steel struts which passed through the diaphragm-plate, and were blocked against a byatt 9 inches by $8\frac{1}{2}$ inches, secured in the flanges of the last-built ring of tunnel. As soon as the thickness of the clay cover above the cutting edge had diminished to only 2 or 3 inches, hand holes or pockets were opened, in advance of the face and in front of the cutting edge, reaching a few inches above it, and rather more than one length in advance, into which well-tempered clay was put, precisely as employed on the Waterloo and City Railway tunnels; a series of such pockets formed finally a continuous portion of an annular bed of soft clay, into which the cutting edge could easily enter. The circumferential length of this annular bed grew as the amount of ballast face increased, until it extended round the whole hood; thus forming, as the shield advanced, an air-seal at its tail where the last tunnel-ring had been built, and affording a clear space for the grout to enter around the tunnel. As the ballast face grew downward a second row of poling-boards was introduced below, with a middle waling 9 inches by 4 inches; the two walings were held by soldiers 11 inches by 6 inches, and by the upper pair of steel struts, when the shield was being driven.

On June 16 the special 18-inch lining-rings were first employed. There was then 15 inches of ballast at the face, and a cover of 22 feet to the bed of the river. When the ballast extended down 3 feet 6 inches, which was the length of the upper polings, it was found desirable to substitute horizontal planks for the vertical upper polings, which exposed too high a portion of the face on removal; two sets of vertical polings continued to be used against the clay below. Each of the three uppermost widths under the hood consisted of two pieces, while a few below them were long planks across the whole face.

From June 21 to 27 the top pair of iron shutters was used, but they were then abandoned and horizontal timbers, in two halves across the face, were substituted. When the face-planking came into use as far down as the lower pair of steel struts, the planks were held by soldiers and walings against the steel struts, the arrangement of the timber varying to suit the changes in level of the ballast. The face was set forward to a position varying between 2 feet 2 inches and 2 feet 6 inches beyond the front edge of the vertical girder. The whole of the gravel portion of the face was thickly plastered with pugged clay, against which the planks were set.

On July 15 there was a full face of ballast. On the 21st a run of water filled the fountain trap. On August 20 and 21 blows occurred, filling the trap with water, followed by ballast which choked itself in the shield. The four men at the face escaped safely under the diaphragm-plate, and were able subsequently to attack the face again by getting into one half-section of it at a time, the vertical girder forming a divisional guard exactly adapted to the circumstances. On both the latter occasions it was the uppermost planks which were blown in. It is probable that on August 20 more timber than a single width of board was removed simultaneously for setting forward; the rule was one width only. After the second of these two blows the space of the five uppermost planks was found exposed, the blow occurring when the lower portion of the face, at about floor-level, was being set forward.

On September 14 the last blow occurred, which filled the fountain trap with ballast. This also was successfully dealt with, but involved delay.

On September 21 a good deal of water was let into the tunnel from deficiency of air pressure; but only near the face was the rail-road awash. From this time until getting completely into the clay the ballast was coarse and open, and the air escaped so readily through it that difficulty was experienced in keeping up the requisite pressure. The blow-off valve of the air-receiver was regulated automatically by a float on the river, which carried a vertical board having an inclined channel-bar groove attached to it. The groove constrained a roller, which moved horizontally as the board rose and fell with the tide, and varied by its movement

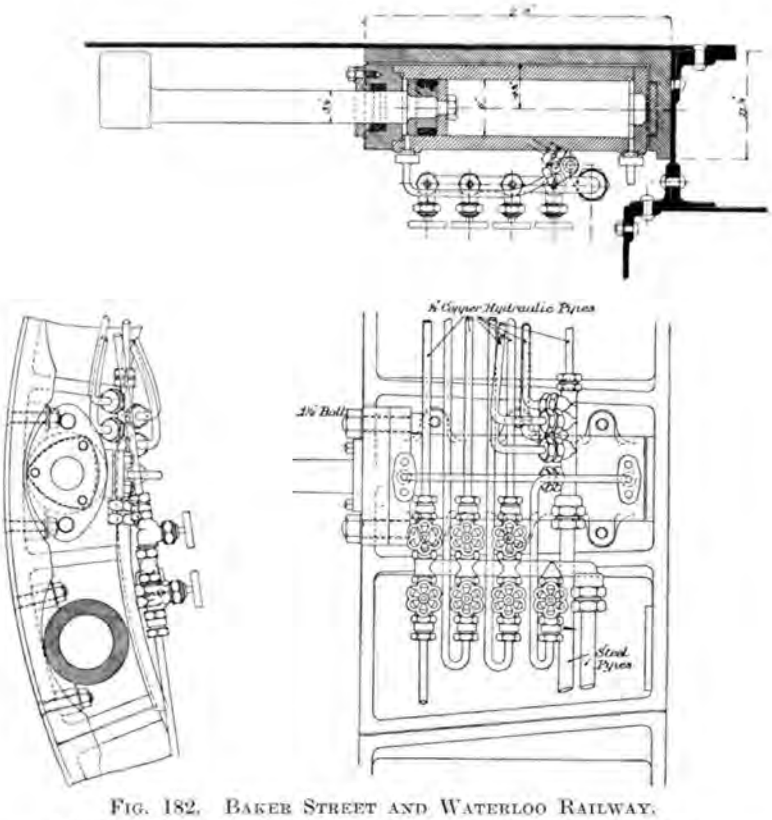


FIG. 182. BAKER STREET AND WATERLOO RAILWAY.
Dalrymple Hay's Hooded Shield. Details of Hydraulic Ram.

the position of the fulcrum of the loaded valve-lever, thus varying the pressure according to the hydraulic head.

On September 27 the tunnel re-entered the London Clay at the invert, and on October 6 a full face of clay was again obtained. During straightforward work, normal progress with a ballast face was three 18-inch rings per day of twenty-four hours.

On October 8 the use of ordinary 20-inch rings was resumed, and a box heading was again begun, driven as low as possible. On the 24th, at low tide, all the compressed air was let out to test water-tightness. There were droppers through bolt-holes and some joints as the tide rose. Air-pressure was then restored, in order to fix grummets on bolts and to recaulk some joints. On October 27, 1900, the air pressure was finally dispensed with.

The construction of the second or east tunnel closely followed the procedure already described as successful in the west tunnel, and the work was completed without incident.

The details of the shield ram is shown in Fig. 182.

NOTE.—In 1885–6 a Swedish engineer named Lindmark constructed a small tunnel in Stockholm, in which he employed a system of face plates supported by struts from removable iron centres, which, though it can hardly be considered as shieldwork in the sense in which the term is used in this book, was, in a measure, a casing or protection advanced in front of the tunnel which was moved forward as the work advanced, and may be briefly described.

The tunnel was of concrete with an arched roof, straight side walls, and an invert, the inside dimensions being: height, 12 feet 3 inches; and width, 13 feet 6 inches. The ground passed through was very bad, gravel with water being the material commonly met with. The method employed for supporting the face was to support it by struts from moveable centres, on which the concrete tunnel roof rested. The face itself was covered by small plates of iron about 12 inches square, overlapping at their edges and locking into each other by T bolts. These plates were held up to the face by a light iron centre and cross framing. As each plate was detachable, it was possible to remove the top ones, excavate in front of them, and reset the plates forward of the rest; and by working downwards, to gradually advance the whole face.

This method proved fairly satisfactory for some time, a daily advance of from 2 to 3 feet being made, but after a time the amount of water met with became unmanageable, and machinery for freezing the face was installed, which, in conjunction with an iron face plate, enabled the work to be carried to a successful conclusion. The work is described in the *Engineer* of April 9, 1886.

Chapter VIII

THE SHIELD IN MASONRY TUNNELS

The Use of a Roof Shield in Masonry Tunnels—The Collecteur de Clichy "Extra Muros"—The Chagnaud Shield—Detailed Description—The Conveyor—Method of Working the Shield—The Centres for the Masonry Arch—General Working Results—The Collecteur de Clichy "Intra Muros"—Details of the Shield—And of the Conveyor—The Centres for the Masonry—The Lagging—Method of Working—General Working Results—The Siphon de l'Oise—The Shield Similar to the East River Machine—The Airlock—The Concrete Lining to the Tunnel—Details of the Iron Centres and Casing—Method of Driving the Shield and Compacting the Concrete Lining—Concrete Lining Compared with Cast Iron—The Paris Extension of the Orleans Railway—Double Line Masonry Tunnel—Method of Working with Advance Headings for the Sidewalls—Details of the Shield—Description of the Working—The Centres for the Masonry—General Remarks

THE shields described in the preceding chapters, with the exception of Brunel's and the experimental Beach Shield,[1] have worked under one condition common to them all, namely, that the excavation carried out under their shelter was immediately and permanently protected by a lining of cast iron, capable of rapid construction, and of being made almost entirely water-tight, without the employment of skilled, and consequently expensive, labour.

In tunnels constructed in water-bearing strata, under, or in the proximity of, large rivers, cast iron, by reason of its ease of erection, and the smaller cross sectional area of excavation required for it as compared with brickwork, will probably always be a more satisfactory lining to tunnels than brickwork; in England especially, where the price of cast metal is low, and the cost of tunnel brickwork, and particularly its cost in labour, high, an iron-lined tunnel compares, in cost, not too unfavourably with a brick one of similar internal area, particularly if the increased risk of settlement in the latter form of construction, as compared with the former, be taken into account.

But in France, where the cost of cast iron is higher, the difference in cost of the two methods of construction is greater, and after the first employment of the Greathead shield in the Siphons of Clichy and of the Pont de la Concorde, in both of which compressed air was employed, French engineers departed from the model previously adopted, and have since constructed all tunnels built under a shield in masonry instead of iron, and have also abandoned, except in one case, the circular form of the shield in favour of the type now known as the "roof shield," or "carapace." It is true that all these later works have been built under conditions which did not require compressed air. Their example has been followed in the United States, and the tunnel lately driven under the Harbour at Boston is lined with concrete, a roof shield being employed in its construction, in conjunction with compressed air.

[1] See page 14.

The roof shield is, as its name implies, a protection for the upper portion of the tunnel only, and, although its form and the method of erection of the brick or concrete arch behind it vary considerably in different tunnels, the manner of its use may conveniently be divided into two classes; namely, the mode of working, in which the upper portion or arch of the tunnel above the springings is first built under a shield, the footings and invert being constructed afterwards by underpinning, and secondly the driving in the first place of two ordinary timber headings in which the side walls of the tunnel are first constructed, and then, on these side-walls as bases, a shield employed to excavate the roof.

To either of these methods, one objection is obvious, as compared with the original system of tunnelling under shield as set forth by Greathead.

The great merit of his system is that, in a period to be measured almost by minutes, the excavation for a tunnel is begun, finished, and the permanent lining put in, the chances of settlement of the ground above being thereby reduced to a minimum.

With a roof shield, the excavation is attacked in three, or sometimes in four sections (the roof, two side walls and invert), and in two of these, the excavation made must stand on timber long enough to build in the masonry, while in all of them green masonry must take the earth pressure before it is ready for it.

These objections would be fatal in the case of a tunnel in water-bearing ballast, but in the case of large tunnels constructed in dry material, the reduction in cost, due to the use of brick instead of cast-iron lining, and the increased rate of travel of a roof shield of, say, 30 feet horizontal width over a circular one of similar internal road capacity, make the newer method very attractive.

Up to the present, no tunnelling has been carried out in England with a roof shield, but in Paris, and in the United States, very extensive works have been, and are now being, executed by this means.

The Collecteur de Clichy (1895–9)[1]

The first example of tunnelling in recent years with a shield, the tunnel lining being composed of masonry, is the main sewer belonging to the sewage system of Paris, known as the "Collecteur de Clichy." This main sewer extends from the Place de la Trinité beneath the Rue de Clichy, and the Avenue de Clichy (at the end of which it crosses the old fortifications of Paris), and then follows the Boulevard National to the River Seine in the suburb of Clichy, where is situated one of the main pumping stations of the city drainage system (Fig. 222). The engineer in charge of the work was M. Alphonse Legouëz, who is well known as the author of the standard French work in this class of tunnelling, *L'Emploi du Bouclier dans la Construction des Souterrains*, Paris, 1897.

The construction of this sewer was carried out in two sections, the one comprising the length outside the fortifications of Paris, the other the part within the city. These sections corresponded, as it happened, almost exactly with the natural divisions of the work, that outside the walls of Paris ("extra-muros") being for the most part at a comparatively small depth below the ground level, the cover being never more than 10 feet, and often scarcely 2 feet, over the crown of the sewer, while the portion within the walls ("intra muros") was for the greater part of its length many feet underground.

[1] Legouëz, *Emploi du Bouclier*, p. 305, and *Genie Civile*, April 26, 1896.

Collecteur de Clichy " extra muros "

The portion outside the walls was commenced first in 1895, a roof shield being employed, and later (1896) the city length was taken in hand, with a shield completely enclosing the elliptical barrel of the sewer. Throughout its entire length the sewer was lined with masonry.

The cross section of the sewer is shown in Fig. 183. Its internal horizontal diameter is 19 feet 8 inches,[1] and the vertical diameter 16 feet 5 inches ; in the lower half of the ellipse, however, are constructed two gangways, each about 3 feet wide, leaving a waterway of 13 feet. The thickness of the masonry varies from 16 inches at the crown to 2 feet at the springing line and 18 inches at the invert.

An uniform gradient of 1 in 2,000 was maintained throughout (see Fig. 184).

The portion outside the walls under the Boulevard National, a crowded thoroughfare, with a double line of tramways along it, was offered to tender, with the condition that the work should be carried out without interference with the road traffic above.

This condition could hardly be fulfilled, if the ordinary system of constructing a shallow tunnel by cut and cover work were adopted, and the old system tunnelling by successive timbered lengths with a cover of, in places, only 2 feet, would have been almost impossible without serious interference with the road traffic.

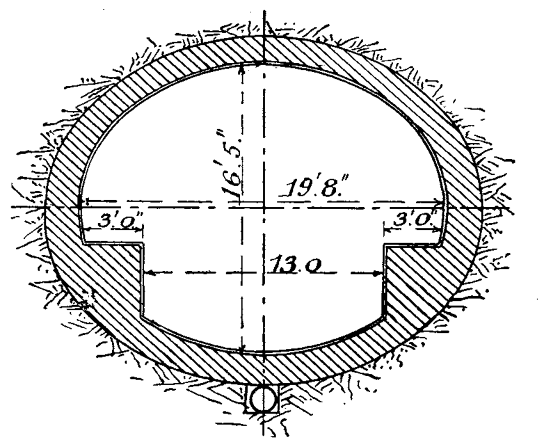


FIG. 183. MAIN SEWER AT CLICHY, PARIS. Cross Section of the finished Sewer.

The shield system was, therefore, adopted by the contractor, who was successful in obtaining the work of constructing the part " extra muros " about 5,750 feet in length at the price of 1,016 francs per metre lineal or, say, £38 14*s*. per lineal yard. As in each yard of the sewer there were 41 yards of excavation and 13½ yards of cement concrete, the price does not appear excessive.

For this the contractor undertook, as a contingency on his contract, to maintain, at all times during the construction of the sewer, the street traffic unimpeded and uninterrupted above over the full width of the road, under a penalty of £20 per day whenever the traffic was interfered with.

He employed a shield of his own invention, named after him the Chagnaud shield, and designed with two principal objects, namely, to afford, in the case where the cover to the tunnel was very slight, a broad support for the roadway above, and, in the second place, to permit of the erection behind the shield of a masonry tunnel. The broad roof he obtained by advancing the cutting edge at the crown of the shield considerably in advance of the base, and so forming an increased protection for the workmen.

The masonry tunnel ring was made possible by an ingenious modification of previous practice. All shields used to that date pushed, in moving forward, against the cast-iron lining already erected, but this could obviously not be done in the

[1] A short length within the walls was some 3 feet 4 inches less in horizontal diameter.

case of a tunnel lining composed of masonry concrete or brickwork, which requires a considerable period to set. M. Chagnaud solved the difficulty by making the rams bear, not on the concrete tunnel, but on the centres supporting it. These centres, some thirty in number, and about 3 feet 3 inches apart, were braced together, and, by their own weight, and that of the completed tunnel and superincumbent centre above, formed a sufficiently solid abutment to take the thrust of the shield rams.

In the shape of the shield also M. Chagnaud was the first to depart from the circular form hitherto employed.

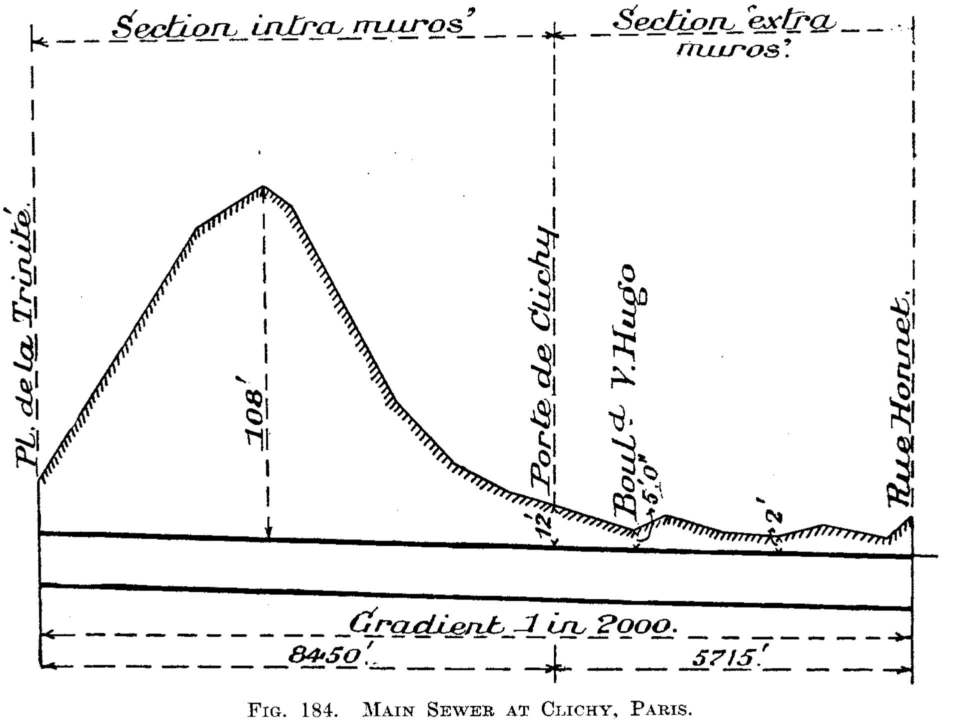


FIG. 184. MAIN SEWER AT CLICHY, PARIS.
Longitudinal Section (bottom).

The shield had its roof elliptical to suit the arch of the sewer, but this roof or skin was cut short at about the springing line of the arch, and the bottom of the shield was formed by horizontal girders on approximately the major axis of the ellipse of the roof.

The whole structure moved forward on rollers, which in turn were on a bed formed of timbers extended forward in short lengths as the shield moved forward.

The shield was only designed to enable the upper half of the sewer to be constructed under it, and the lower portion was afterward finished in sections by underpinning the roof arch in the ordinary manner.

This double series of excavations is of course the weak point of the roof shield method of tunnelling, and it was perhaps fortunate for the inventor of the new type of shield that the material passed through was of a loose sandy nature, making the work of excavation a rapid one, and thus lessening the chances of settlement.

The general arrangement of the shield and its complementary parts is shown in Figs. 185 and 186.[1]

It was practically a framed roof, the envelope or skin *A*, to use the usual English phrase for the covering of the shield, being composed of plates about ½ inch (0·55 inch) thick, the joints of these plates being at right angles to the axis of the shield, and covered inside with ½-inch plates. The skin was semi-elliptical in shape, the major axis being 23 feet 9 inches long, and the semi-minor axis 9 feet 8 inches, to suit the extrados of the arch of Fig. 183. This skin projected at the crown 6 feet 11 inches beyond its base to form a hood *i* to shelter the miners at work at the face. Originally this overhang was only 3 feet 11 inches, but later it was extended, the additional gussets *L* fixed to support the extended front being

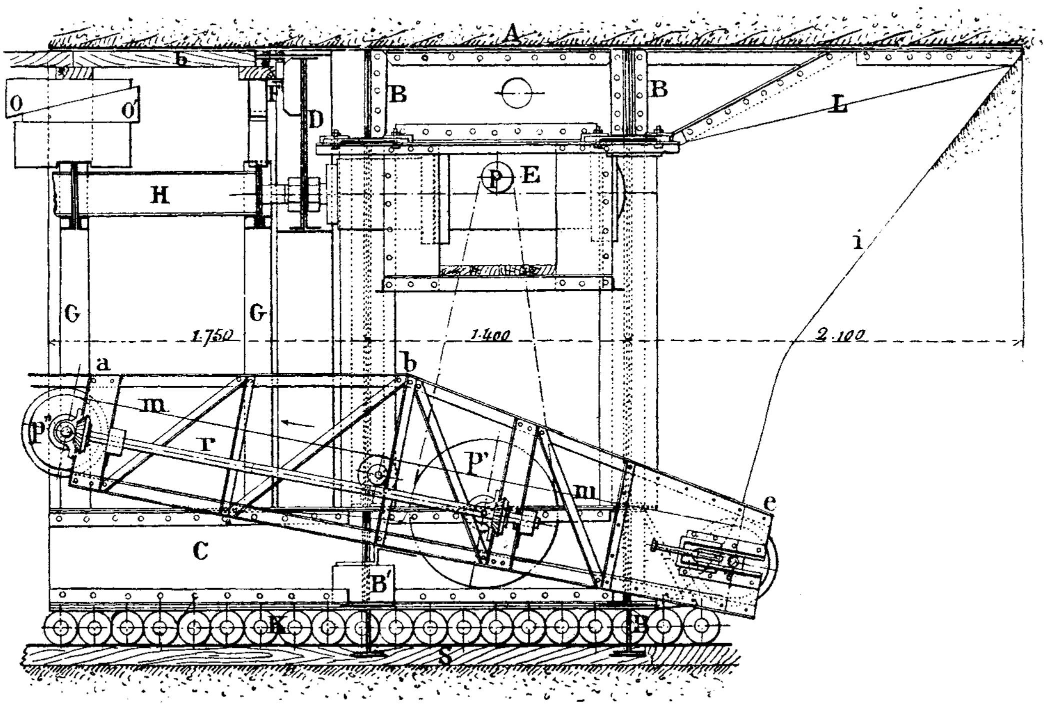


FIG. 185. MAIN SEWER AT CLICHY, PARIS.
The Chagnaud Shield: Longitudinal Section of Shield with Conveyor.

shown in Fig. 185, where the altered cutting edge *i* is also indicated. The length of the shield over all was 17 feet 3 inches.

The frame consisted essentially of two curved girders *B*, *B*, 4 feet 7 inches apart, which were braced together by twelve gussets, and at their ends by two horizontal girders *C*, *C*, which extended beyond the girders *B*, *B*, to the tail of the shield, to which they were connected by their bottom flanges, these latter serving as the base on which the whole framing moved over the cast-iron rollers *K*, *K* (see Fig. 186). On this rear portion of the girders *C*, *C*, rested another moveable independent elliptical girder *D*, supporting an arrangement *F* to take the temporary poling behind the shield. The girders *B*, *B*, were originally prevented from spreading

[1] These figures are reproduced from *Genie Civile*, by courtesy of the Editor.

at their base by horizontal girders, which were, however, removed in order to

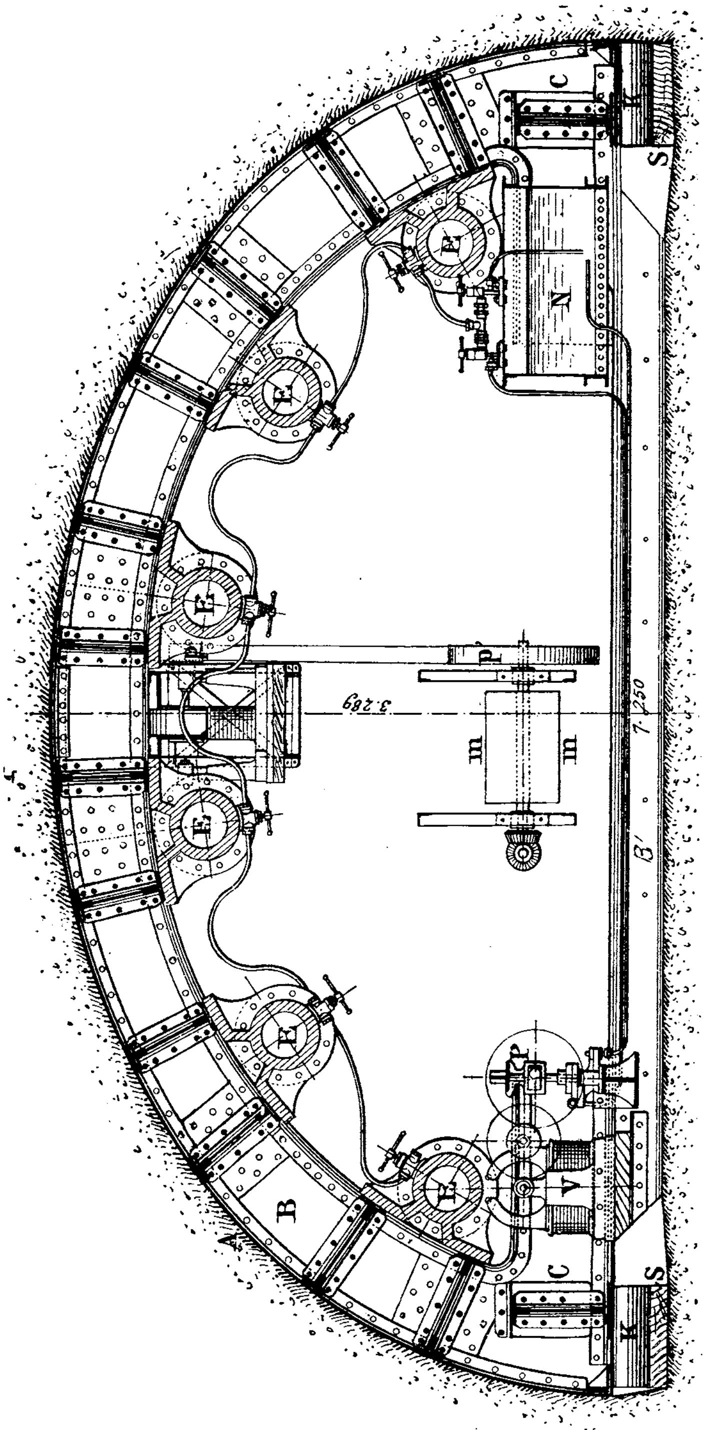


Fig. 186. Main Sewer at Clichy, Paris.
The Chagnaud Shield: Cross Section.

increase the working area, even after the shield commenced its journey. The remaining ends of the original girders are, however, shown in Fig. 186, on the left hand in full lines behind the electric pump *P* and its motor *V*, and on the right in dotted lines behind the tank *W*. These butt ends were connected by two channel irons rivetted back to back, forming the girders *B′ B′*, the upper flanges of the latter being bolted to the lower flanges of the original girders. On these channels was placed the working platform for the miners.

The cast-iron rollers *K, K*, under the frame of the shield were 7 inches in diameter and 1 foot 8 inches long, and rolled on longitudinal timbers *S, S*, having on their upper surfaces plates about $\frac{4}{10}$ of an inch thick, the timbers themselves being made in short lengths, and laid in advance of the shield on the floor of the excavation.

On the concave flanges of the girders *B, B*, were fixed the main rams of the shield, six in number, 9½ inches in diameter, and having a stroke of 3 feet 3 inches (1 metre). These rams were of the ordinary double action type, the piston head being fitted with U-shaped leathers, but the pistons instead of terminating, as in iron-lined tunnels, in a cast-iron head, which bears directly on the last tunnel ring erected, were bolted to the moveable elliptical girder *D*, the ends of which slid on the girders *C, C*, forming the base of the shield. This girder or arch rib *D* was of very little use in distributing the pressure of the rams evenly over the masonry and its only real use was to support the front ends of the roof polings until each length of these was caught up by the leading centreing girder *G*. These rams were driven by hydraulic pumps *P*, worked by a motor *V*, and supplied with water from the tank *N*, the maximum thrust per ram being about 90 tons.

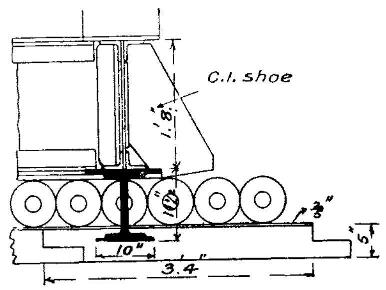


Fig. 187. Main Sewer at Clichy, Paris.
The Chagnaud Shield: Details of the Frame and Rollers.

The ends of the pistons which projected a few inches beyond the moveable girder *D*, bore on the last iron centre *G* erected, which in turn was braced against the preceding one by H-iron gussets *H*, placed opposite each ram. Usually some thirty of these iron centres were erected at one time all braced together in a similar manner, and supporting for some distance behind the shield polings *b*, Fig. 185, by means of wedges *O, O*, and further behind laggings laid directly on the centres, on which the successive lengths of tunnel were built.[1]

A neat form of conveyor worked by electricity was used with the shield. On a bracket at the crown of the shield a small motor *p* was fixed which drove by a band a drum *p′* on the framed girders *a, b, c*. This drum *p′* had on its shaft a mitre wheel which geared with another on the shaft *r*, actuating at its other end a shaft carrying a drum *p″*.

The conveying band *m, m*, was stretched over this drum *p″* and another at the front end of the girder *a, b, c*, this latter being adjustable. The whole frame was pivotted on a block fixed on the rear cross girder *B′* of the shield, the rear end being sufficiently elevated to discharge the material carried into trucks.

The weight of the shield in working order was about 50 tons, and it is reported that it was nearly always possible to move this weight on the provisional tram plates *s, s*, without serious settlement either of the shield or of the thin covering of soil above.

[1] These moveable centres with the bracings behind them resemble those of Rhiza's system (see Drinker's *Tunnelling*, page 677).

The working pressure necessary for driving the shield in ordinary material of little consistency was about 200 tons, in harder material 400 tons.

The mode of working the shield is as follows. When the shield is ready to advance, the pistons of shield rams *E*, *E*, bear on the centre *G* last fixed, the moveable girder *D* moving with the pistons, thus pushing forward the shield into the face which the miners are continuously at work at, and rolling it over the rollers *K*, which are constantly being freed behind, and brought forward again to the front.

As the shield moves forward, and the tail of the roof with it, thus exposing the polings *b*, the wedges *o*, *o*, on the penultimate centre are tightened so as to make the polings close the space left by the withdrawal of the tail. If this is carefully done, no settlement above occurs.

The ordinary length of each advance was equal to the full stroke of the rams, namely, 3 feet 3 inches, in the for the most part sandy soil traversed under the Boulevard National, beneath which the portion of the sewer "extra muros" lies for the greater portion of its length, and the time occupied was usually about fifteen minutes.

At the end of the advance, the pressure in the rams was reversed, and the moveable girder *D* drawn back to its original position close behind the rear curved girder *B* of the shield ; a new centre *G* is fixed under the covers of the shield, new polings *b* are fixed, and the shield is ready to go on.

In very sandy loose soil, a very thin iron plate (one-half of a millimetre) was placed outside the polings and under the shield skin. Its use prevented the sand coming down between the polings, and when these were removed one by one the brick lining was more easily put in if the plate were there. At first some difficulty was experienced by the skin of the advancing shield drawing the thin plates along with it from behind the polings, but this was got over by bending the plates at the ends over the ends of each length of polings, so that these latter held them.

The construction of the permanent masonry lining was usually in progress some yards behind the shield. The polings *b* were removed, two or three at a time with the wedges supporting them, and laid directly in the outside flanges of the centreing girders *G*, this forming the lagging for the arch, which was built on them, and then the next two or three polings transferred, and so on. The work was so arranged that successive lengths of masonry between each pair of centres were in different stages of progress, the rearmost length where work was going on being always more advanced than the next in advance.

The only cases in which difficulty was experienced in building the brick arch was when the material above was very loose sand, but even in this material it was found that the use of the thin plates just mentioned stopped in a large measure the formation of pockets outside the tunnel caused by the falling in of the sand.

It was not the least advantage of this ingenious scheme of work that this removal of the polings, by converting them into laggings, made the leaving of woodwork outside the brickwork very unlikely, while the great length of centreing necessarily required to resist the thrust of the shield ensured that the brickwork of the tunnel would be supported for some time after its erection, and so to some extent prevented the load of the surrounding material being thrown on the brick when actually green.

The daily actual advance of the shield was sometimes 29 feet per day of twenty-four hours, and the daily average over a period of 221 days was 14 feet 9 inches, and in general the masonry arch behind was keyed in two days after the shield had passed.

The remainder, or lower half, of the sewer was constructed by underpinning in the ordinary manner.

It will be seen that an important factor in the success of the shield was the stability of the two platforms or roadways on which the shield advanced. These were of elm, in lengths of 3 feet 3 inches and 1 foot 8 inches wide, covered on the upper surface by an iron plate $\frac{4}{10}$ inch thick bolted to them. They generally rested on white wood planks on the dry sandy material, but in certain spots where water was met with in the sand, short piles were driven to support them.

The work of introducing these roadways in front of the shield for it to run on was one which required care, both in levelling the bed to receive the timbers, and in fixing the lengths of roadway themselves.

The shield suffered but little in the construction of the 4,120 feet of tunnel built under it, and the only damage done to the structure was some buckling of the cutting edge due to driving into some old masonry.

M. Legouëz, who was in charge of the work states [1] that thoroughout the work there was usually a settlement of the ground above of 0·23 inches (6 millimetres), of which amount 0·115 inches (3 millimetres) was caused at the moment of clearing the tail of the shield, and a similar amount during the construction of the masonry lining. This latter settlement, he says, was due in part to the bad condition of the centres after some distance had been driven. They become deformed under the pressure of the rams, and the boltholes in their joints worn, so that they were hardly in a state to maintain a sound temporary poled roof above.

He also notes, as a cause of movement in the ground, that owing to the use of the thin metal plates behind the polings, it often happened that cavities formed during the advance of the shield were, by reason of being behind these plates, not discovered in time to prevent settlement from them, and that, by the use of grouting appliances, all movement of the ground behind the shield could have been stopped.

It would be of interest to know to what extent the planks on which the tracks for the shield were laid, and which remained behind to serve as basis for the centres, were found to have settled by the time the brick arch was finished over them.

It is impossible to believe that some part at least of the settlement of the ground was not due to the sinking of the shield due to the yielding of the tracks beneath its weight, and it is at least probable that the centres when first fixed, however carefully the work was done, settled a little when the weight of the ground came on them, on the advance of the shield.

But however that may be, there is no gainsaying the fact that, by means of M. Chagnaud's combination of shield and centreing, this large tunnel was driven at a depth below the surface to be measured in some places almost by inches, under a busy thoroughfare, with so little disturbance of the ground that the street traffic above was never interrupted.

This was a great feat, and not unnaturally has powerfully influenced the development of shield tunnelling in Paris.

The construction of the first section was completed in 1896, and the second length, "intra muros," or that portion inside the old fortifications of Paris, was commenced in the same year.

[1] *Emploi du Bouclier*, p. 325.

Collecteur de Clichy "intra muros"

This second section was, as previously stated, driven at a much greater depth than the first section, for the major portion of its length, and the conditions governing its construction were, therefore, different.

In this length also, the contractor who undertook the work employed a shield to construct a masonry tunnel. While reverting in one important feature to the English type of shield, by making it cover the whole area of the sewer, in another he went beyond the innovation introduced by M. Chagnaud in discarding the use of temporary polings behind the shield, and building instead the permanent masonry lining within the shelter of the shield itself.

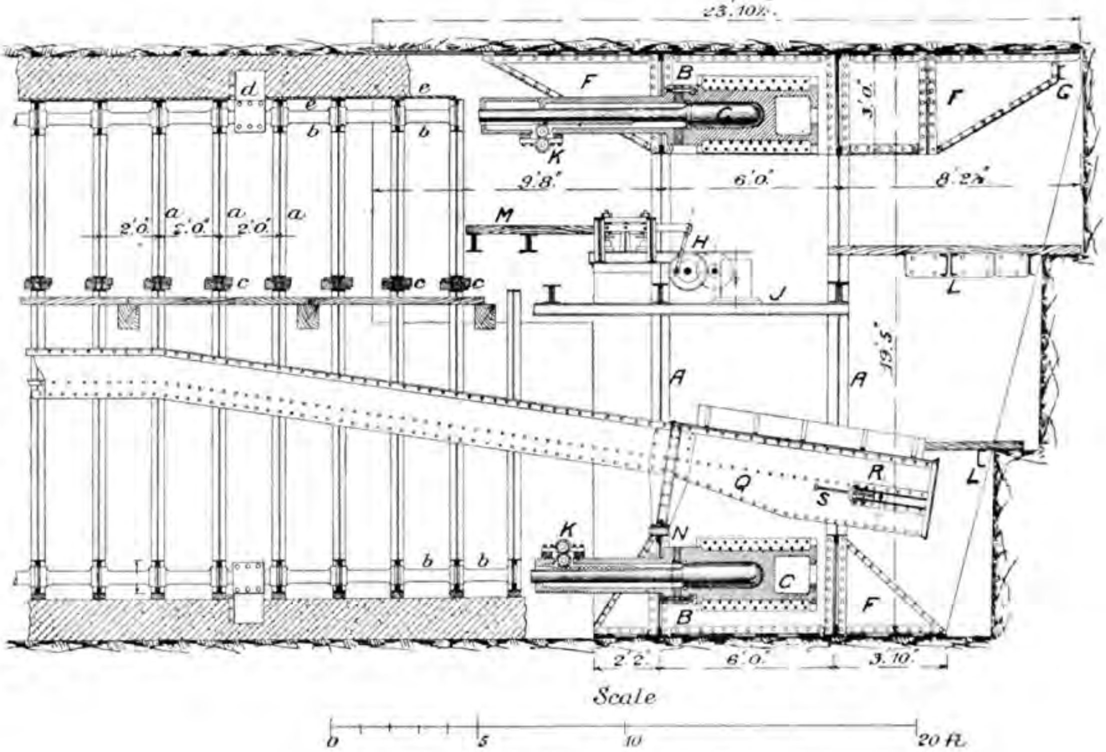


FIG. 188. MAIN SEWER OF CLICHY, PARIS.
The Fougerolle Shield: Longitudinal Section of Shield with Conveyor.

The cross section of the sewer was the same as that of the portion "extra muros" (Fig. 183), and the contractor, M. Fougerolle, undertook the work at a price of about £28 per yard of length, the total distance being about 2,730 yards.

This price does not appear excessive in view of the nature of the ground to be traversed, which for half the distance was wet sand, and for the remainder coarse limestone and marl, with some sand.

The shield and moveable centres used by the contractor, M. Fougerolle, are shown in Figs. 188, 189, and 190, and consisted essentially of an elliptical skin or plating framed on two built-up girders or ribs with a "hooded" cutting edge, and an overhanging tail.

The two main ribs *A*, *A*, were 6 feet apart, and in depth varied from 3 feet 4 inches on the vertical to 4 feet on the horizontal axis of the shield. The webs were $\frac{4}{10}$ inch thick, that of the rearmost one being perforated in twelve places to permit of the shield rams projecting through it. Between these main ribs were fixed plate gussets *B*, *B*, arranged in pairs, so that each pair with the webs of the main girders formed a box in which a shield ram *C* was fixed. The shield was originally designed to admit of twelve rams being mounted in it, but only eight were actually fitted, three at the crown and at the invert, and one at either side.

On either side of the openings, as at *D*, where provision was made for a ram but not used, there were fixed, instead of the plate gussets, wooden frames *E*, *E*, which served equally well as bracings to the main girders.

The skin of the shield consisted of plates of steel, $\frac{9}{16}$ inch in thickness, jointed together inside by covers of the same thickness, the joints being at right

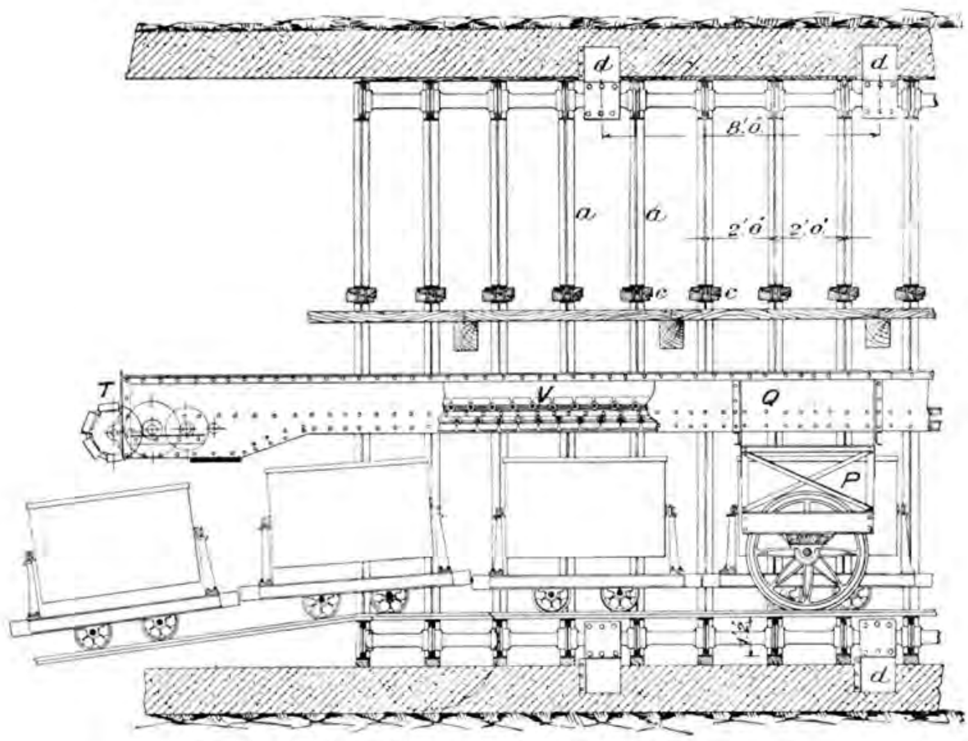


FIG. 189. MAIN SEWER AT CLICHY, PARIS.
The Fougerolle Shield: Section of Tunnel with Centres and Rear end of Conveyor.

angles to the axis of the shield. The tail of the shield in the overhanging portion consisted of two thicknesses of $\frac{9}{16}$ inch steel.

Round the main girders *A*, *A*, the skin formed a complete ellipse, and this extended 3 feet 10 inches in front of the leading girder, and 2 feet 2 inches behind the rearmost one.

The projecting hood in front extended 8 feet 2½ inches at the crown in front of the leading girder, and the overhanging tail which came down nearly to the centre of the shield reached 9 feet 8 inches behind the back one. Both the front and the tail were stiffened with gussets *F*, *F*.

The total length of the shield at the crown was 23 feet 10½ inches (the same as the horizontal diameter) and at the invert 12 feet.

On the front gussets in the crown of the shields was fitted a channel iron *G*, just sufficiently away from the skin to permit of polings being inserted between so as to support the roof of the excavation on front of the cutting edge, when necessary. These polings were pushed forward as the excavation proceeded, to hold up the roof of the excavation, their front ends being driven into the face. When the shield advanced, these polings being free to slide in the channel *G* slid back under the hood, whence they were again pushed out as the excavation for the next length advanced.

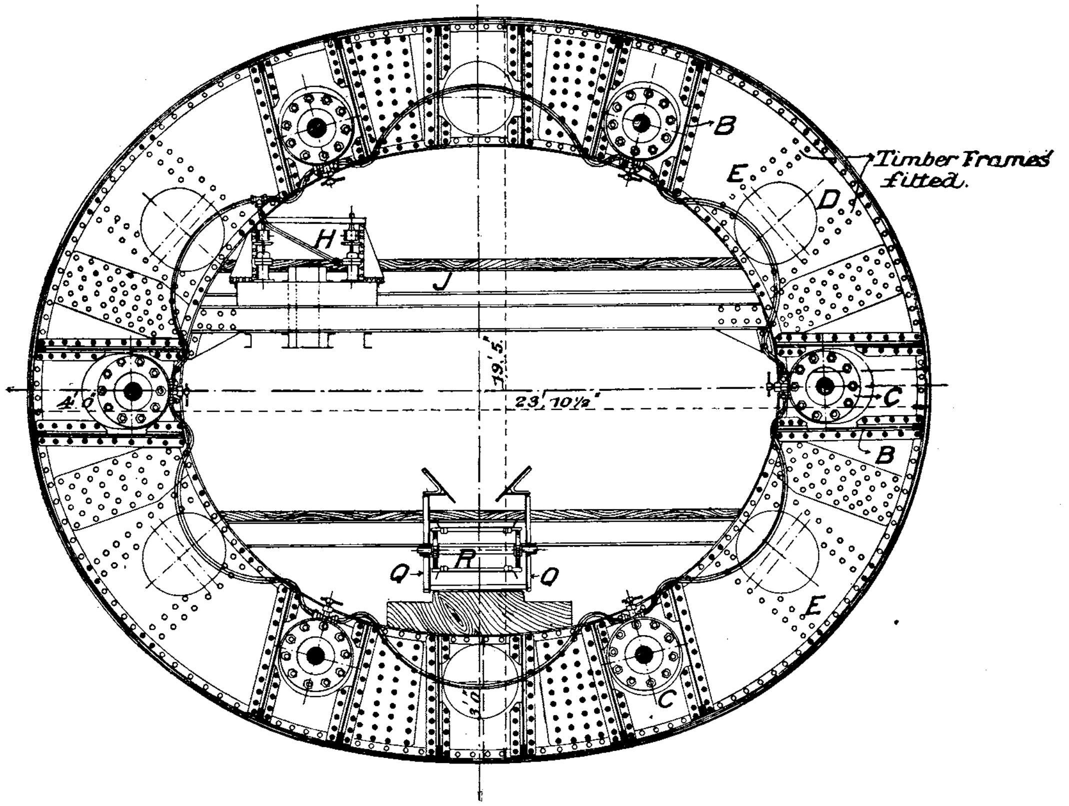


Fig. 190. Main Sewer at Clichy, Paris.
The Fougerolle Shield: Cross Section behind rearmost of the Elliptical Girders *A*, *A*, Fig. 188.

The upper gussets of the tail were, after the shield had started, extended so as to reach within 18 inches of the end of the shield.

Structurally, the most obvious defect in the shield is the absence of vertical stiffening. The shape of the shield suggests that deformation is likely to take place by flattening the crown, this being indeed usual even in circular shields, and M. Legouëz states [1] as a fact that it was found necessary to strut the ribs *A*, *A*, by vertical timbers on either side of the conveyor which occupied the centre of the shield.

The amount of overhang, the crown of the skin being double the length of the

[1] *Emploi du Bouclier*, pp. 347–8. The Author is indebted to M. Legouëz for the drawings from which Figs. 188, 189, and 190 are prepared.

invert, appears very great, though not so excessive as in some later shields employed on the Metropolitan Railway of Paris, and as a result of the absence of any stiffening round the cutting edge, some buckling occurred.

The rams were originally made of cast iron, but cast steel cylinders were subsequently substituted. They were worked by electrically driven pumps *H* fixed on the upper platform *J* of the shield between the main ribs, the usual pressure employed being about 180 tons on the eight rams, or 2¼ tons per ram. The rams, 9½ inches in diameter, had a stroke of about 2 feet, and as the cylinders were single-acting, they were drawn back at the end of the stroke by a pinion *K*, worked by hand and gearing into a rack fixed in the piston, which was of exceptional length, and supported in a cast steel guide.

The working platforms in the shield, in addition to the platform *J* just mentioned, were in front two in number, carried on channel irons *L*, *L*, and on them the miners worked at the face. Behind, in the tail of the shield, was another platform *M*, on which the masons worked when building the arch of the tunnel.

The material excavated was conveyed to the skips behind the shield by means of a mechanical conveyor about 80 feet long, the front end of which was supported on and fixed to the rearmost of the two main ribs of the shield at *N*, the other end being carried on a truck *P*. The machine therefore moved forward with the shield.

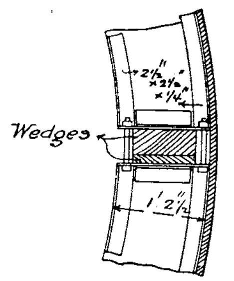


FIG. 191. MAIN SEWER AT CLICHY, PARIS.

The Fougerolle Shield: Detail of Wedges in Centres behind Shield.

It consisted of two girders *Q*, *Q*, of ⅕ inch plates, 2 feet 6 inches apart, stiffened with angle irons on the upper edge, and channel bars on the lower. These latter served also as the lower guide for the travelling carrier, the upper ones being angle irons. At either end of these two girders were fixed between them drums, the front one *R* being on an axle fitted in slots on the girders, and adjustable by means of screws *S*, by which arrangement the carrier was kept taut, and the rear one *T* being geared with a chain of wheels driven by a band from an electric motor carried on the truck *P*. The carrier itself *V* consisted of an endless chain of buckets or dishes 2 feet 2 inches wide, connected together by pins, the ends of which slid in the angle guides fixed to the girders. The rear end of the machine was placed sufficiently high to enable the skips to be brought beneath it as shown in Fig. 189. The motor driving the carrier was of 12 horse-power, and the daily consumption of current 100,000 watts.

The shield was driven forward against the centres *a*, *a*, about 2 feet apart, which were connected together by distance pieces *b*, *b*, of cast iron, these latter being placed opposite the shield rams, so as to receive their thrust and transmit the pressure from the leading centre and distribute it among the thirty or more centres which were usually in position at one time. The cast-iron distance pieces were an improvement on the **H** irons used in a similar capacity in the shield of the "extra muros" section of the sewer, the broad ends of the castings making a better bearing than the sawn ends of the **H** irons against the centres.

The centres themselves were made of plates about 14½ inches deep and 0·23 inches thick, stiffened with two angles at top and bottom, 2½ inches by 2½ inches by 0·23 inches. For purposes of adjustment they were made in two pieces, the ends being bolted together and timber wedges driven between them as shown at *c*, *c*, Figs. 188 and 189, and in detail in Fig. 191.

Each of these pieces was made in two sections for convenience of moving about, and secured together when in position by fish plates. As in the Chagnaud contract, these centres proved somewhat weak, and even though the labour of handling them would have been greater and the obstructions in the tunnel greater had they been made deeper and stouter, the results would probably have been more satisfactory.

As an additional security against movement of the centres under the pressure of the shield rams, anchor plates *d*, *d*, were fixed in the masonry lining of the tunnel, which by means of bolts clutched the distance pieces between the centres. These anchor plates were fixed about 8 feet apart, being built into the brickwork when the latter was being built, but they were not used until the brickwork had had time to set.

The lagging *e*, *e* (Fig. 188) used on the centres was made in strips of inch wood 2 feet wide (to fit the centres and about 4 feet 7 inches long, covered with thin metal plates and stiffened lengthwise by two channel bars 2 inches by 1 inch by ·23 inch. These were convenient for handling, and the channel bars kept the wide boards from warping (Fig. 192).

The working of the shield was on the ordinary lines, the ordinary length of each push being 2 feet, the distance apart of the centres for the masonry. The excavation was taken out in steps, as shown in Fig. 188, and in advancing the shield the only precaution necessitated by the fact that the length of masonry over each new centre was put in under the shelter of the shield itself was the keeping free, as far as possible, the tail of the shield from the masonry, so that the latter was not drawn forward with it.

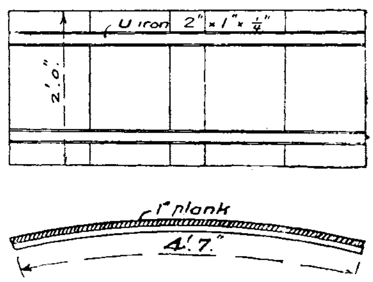


FIG. 192. MAIN SEWER AT CLICHY, PARIS.
Detail of Lagging for Centres.

This was done by driving wedges under the tail and so reducing the friction.

The construction of the masonry lining was usually carried out in steps, the work from invert to crown being spread over about 6 feet. The invert was put in immediately behind the shield on the area left bare as the shield advanced ; the side walls were carried up by another gang between the leading centre and the next one, while a third set of men turned the arch under the overhanging tail of the shield.

This arrangement enabled the lower half of each successive centre to be fixed in advance of the upper portion, and consequently the lower rams of the shield were made with shorter pistons than those in the upper part.

The masonry of the arch consisted of concrete blocks, and cement mortar mixed in the proportion of 350 kg. of cement to 1 cubic metre of sand, or say 1 to 5 by weight nearly.

The average rate of progress was about 10 feet per day of twenty-four hours, and, compared with the rate of progress of the roof shield employed in the " extra muros " section of the tunnel when the upper half only of the work was constructed at the rate of about 14 feet per day, must be regarded as very satisfactory.

In the working of the shield two occurrences are of interest.

As at Blackwall, the plates forming the skin became buckled under the pressure of the ground, but in the case of the Clichy shield it was the tail which gave the greatest trouble, and from the fact that the thickness of the masonry arch was determined by it, it was important to keep this in shape.

The tail collapsed under the pressure of the wet sand over it, and that being precisely the spot where the full thickness of masonry was necessary, the shield was stopped and the defective plates were removed. This was done by opening up from the front of the cutting edge a timbered heading along the top of the shield, from which, when the tail end was reached, a transverse heading was driven, in which the roof plates of the shield were removed and after recurving, replaced. The headings were subsequently filled with concrete.

The other novel feature in the working remains, so far as the Author is aware, unique. As stated above (page 277), a portion of the sewer within the fortifications is of smaller section than the remainder, and on reaching the point where the reduced section ended, the shield itself was reduced in size to deal with the smaller sewer. This was done by excavating around one-half of the shield (see Fig. 193), leaving the other half embedded in the ground, and against the timbered sides of the chamber so made the exposed portion of the shield was strutted, and piece by piece the members and skin of the shield were detached, their superfluous parts removed, and put together again, with the result that, from having a cross section of elliptical form with a major horizontal axis of 23 feet 10½ inches and a minor vertical axis of 19 feet 5 inches, it became an ellipse 20 feet in horizontal and 19 feet in vertical diameter, the decrease in vertical height being due to sagging of the shield.

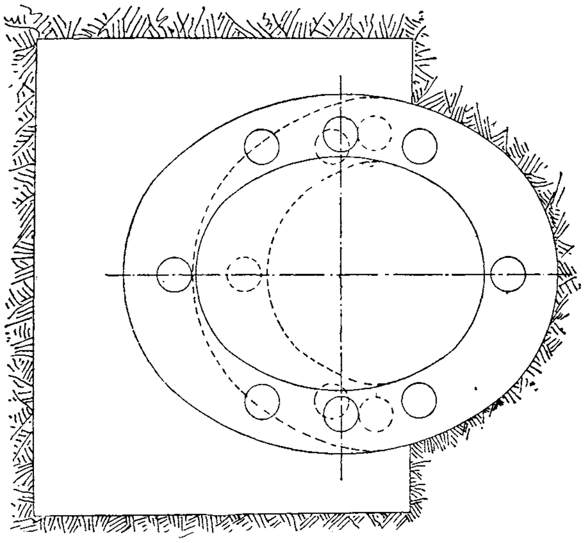


FIG. 193. MAIN SEWER AT CLICHY, PARIS.
Reduction in size of Fougerolle Shield.

The result of this courageous experiment was, on the whole, satisfactory, though considerable trouble was subsequently experienced, due to the fact that, from the conditions in which the change of shape of the shield was made, the new rivetted joints of the shield girders were hardly sufficiently well executed to resist the pressure they had to support. When these joints yielded, the shield spread and it was necessary to repair again the girders. In spite of this, however, the shield finished its course satisfactorily.

The settlement of the ground above, due to the works of the sewer, appears to have been insignificant in amount, and from this point of view the undertaking was a complete success.

The centres, however, again, as in the section "extra muros," proved too weak for the work they had to do, and the anchor plates gave them but little support.

The absence of the moveable girder used in M. Chagnaud's shield was doubtless an advantage, in enabling the shield rams to act more independently when it was required to deflect the shield up or down or sideways, but the number of rams was small for a shield of the dimensions described, and any unequal pressure on the centres due to the thrust of the shield being applied partially by some of the rams only had the effect of distorting them, and so necessitating subsequent refitting and increased cost in re-erection.

An increase in the number of rams, and the fitting them with T-shaped shoes, while it would have necessitated an increased number of struts between the centres, would have avoided much of the expense actually incurred in maintaining in good order the centres, and have minimised the trouble occasioned by the breaking down of single rams from time to time.

The Siphon de l'Oise (1897)

The success which had attended the employment of the shield in conjunction with masonry in the work just described led to the use of similar machines in other sewer works in and around Paris. For the most part the details of the operations varied but little from the methods employed in the second section of the Collecteur de Clichy, but a new departure was made in the Siphon de l'Oise in the manner of constructing the sewer lining in concrete within a steel plate casing.

This work, which forms a part of the system of sewage disposal of Paris, consists of a syphon tunnel 6 feet 8 inches in internal diameter which, starting from a shaft on the left bank of the River Oise, near its junction with the Seine, at Conflans St. Honorine, passes under the river, and connects with an outfall sewer towards Triel, the material tunnelled through being loose earth, gravel and sand.

Of a total length of 4,200 feet the part forming the syphon, 919 feet in length, was constructed in concrete by means of a shield, and with compressed air, the period during which the shield was actually working being from November, 1897, to December, 1898.

The shield itself was of the Greathead type, closed in front with a diaphragm containing doors somewhat of the pattern of the East River Tunnel Shield, and a front hood with an overhang of about 3 feet. Its length was, in proportion to its diameter, much greater than usual, the figures being 16 feet 2 inches over all to 8 feet 7 inches.

The tail of the shield extended beyond the rearmost frame about 6 feet 4 inches, due to the necessity of securely holding the tunnel lining during the process of compressing the concrete of which it was formed. For the same reason the shield rams were ten in number or double the usual number for an iron-lined tunnel of such small dimensions.

The internal diameter of the shield was 4 inches greater than the external diameter of the steel casing of the tunnel to allow of this latter being grouted round with mortar as the shield was withdrawn.

This space between the two plates was maintained by means of distance pieces of steel fixed inside the tail of the shield, not as in the case of the St. Clair and Blackwall Tunnel Shields at the extremity of the tail, but about 3 feet 6 inches from it, so that immediately the shield was moved forward, a clear space was left for filling in the mortar.

The excavation in front was carried out on the same lines as in the City and South London Railway work in water-bearing gravel. The face was close poled, and the sides also, and in very bad ground the polings were made very narrow, and only removed one by one. The joints were pugged, but no grouting appears to have been used with the face.

In loose earth the crown was held up by curved plates fitted under the hood of the shield (which hood was much smaller than is usual in French shields), and the front edges of these plates were driven into pockets made in the face by chisels.

The hydraulic pressure necessary to drive the shield rarely exceeded 20 tons per ram or 200 tons in all, but the rate of progress was not very satisfactory, even allowing for the difficulty of arranging the work in a tunnel of such small diameter in bad ground, and with a form of lining which was composed of three distinct parts all having to be worked separately. The mean progress was only 2 feet 7 inches per day, and often only 1 foot 8 inches.

The limit of air pressure was about 24 pounds per square inch, the greatest depth below water level being about 43 feet.

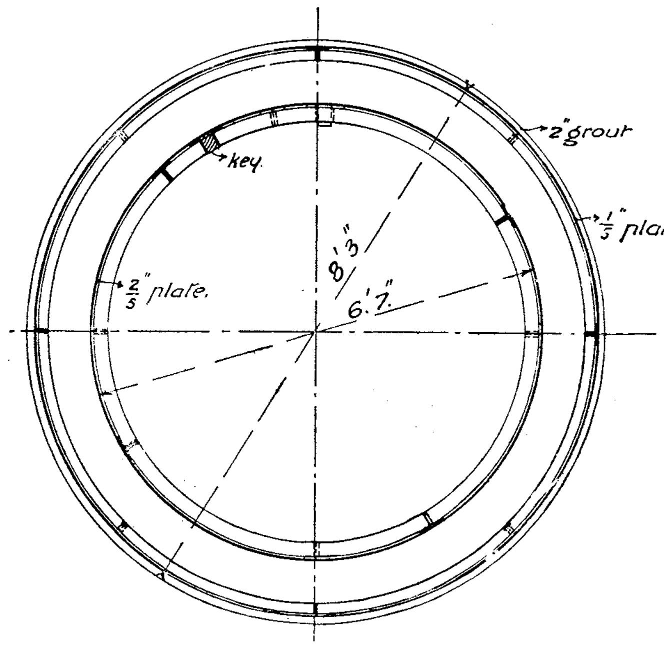


FIG. 194. SYPHON UNDER THE RIVER OISE, FRANCE.
Cross Section of Tunnel Skin, and Centreing.

The airlock combined in one structure the features of an ordinary horizontal lock, combined with a vertical chimney above it with double doors through which concrete could be introduced, and having also a side shoot lock (similar to those fixed on the Blackwall shield but never used), through which the material excavated could be discharged.

It is in the permanent lining of the tunnel, however, that the main interest of this work lies. Abandoning the idea both of the temporary timber lining of the Chagnaud system, and the immediate construction under and in contact with the skin of the shield of the permanent masonry lining as in the Fougerolle method, the engineers erected within the shelter of this shield two steel plate skins, the one a permanent outside casing to the concrete ring, the other a temporary centreing within it, and the space between these they filled with concrete in lengths of 1 foot 8 inches, compressing it by means of the shield rams, which bore against it and effectually compacted it, in pushing the shield forward.

The outside skin (see Fig. 194) was composed of rings of steel plates $\frac{1}{5}$ inch thick and 20 inches wide, each ring consisting of four plates joined by bolts to each other and the adjoining rings by angle irons 2·36 inches by 2·36 inches by ·23 inch riveted to the plates. The rings were made to break joint.

Outside of this skin there was left, as the shield moved forward, an annular space 2 inches wide, which was filled by a mason "feeding" in mortar, which, by the pressure of the air in the tunnel, was carried in between the steel ring and the tail of the shield, and effectually filled the space left by the latter.

The inner, or centreing skin, consisted of thicker plates, these being $\frac{2}{5}$ of a inch thick, made into rings 20 inches wide, and 6 feet 8 inches internal diameter.

Each ring was composed of four segments, and one key, the latter being about 8 inches wide, but the segments and the keys were made so that on an average ring a space of about 3 inches was left which was closed by wedges covered with $\frac{1}{8}$ inch plates. In general, ten of those rings were in use at one time, or in other words, 16 feet 6 inches of the concrete lining last erected was kept supported by them, and with the rate of progression generally maintained, this meant that the green concrete was held up for at least a week after being rammed into its place.

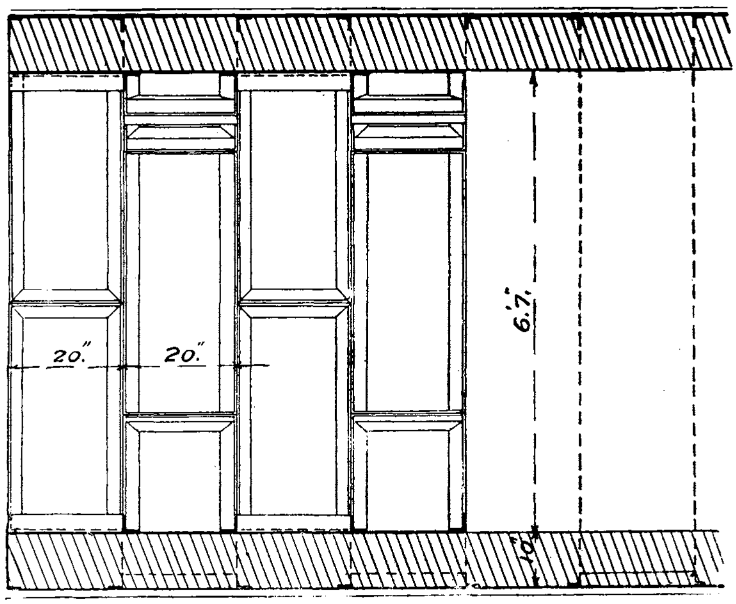


FIG. 195. SYPHON UNDER THE RIVER OISE, FRANCE.
Longitudinal Section of Tunnel.

The method of constructing the permanent lining is indicated in Fig. 196, in which the upper portion of the tail of the shield and the corresponding part of the tunnel lining is shown. *A* is the tail plate of the shield, *B* being one of the distance pieces fixed within it to ensure a space being kept between the shield and the outer skin of the tunnel to allow of grout being filled in outside the latter. At the end of the last forward move of the shield to its position as shown in the drawing, and the consequent erection of the tunnel lining within it, the outer steel ring and the centreing are complete to *C*,*C*, and the concrete between them to *D*, the grouting outside the outer ring being filled in to *E*.

The tail of the shield has, therefore, an overhang of about 1 foot over the finished portion of the tunnel, and the rams being drawn back into their cylinders, the two outside rings *F* and *G* are fixed in position, *F* being grouted outside as far as *H*, before the second one is erected.

The centreing ring *J* is then fixed and bolted to the preceding one, and the space between it and F filled with concrete, the face of the concrete next the shield being temporarily held up during the filling with shutters strutted from the frame of the shield.

When the space behind the ring J was filled, the shutters to the concrete were removed and the rams of the shield applied to the mass as in the figure. The concrete was by this means compressed as far as H' and, being made solid, formed a buttress against which the shield advanced some 20 inches.

The rams were then withdrawn, and the centreing K erected, when the same process was repeated.

The grout surrounding the tunnel lining consisted of 1 part of Portland cement to 3½ parts of sand, and the concrete tunnel itself of 1 part of Portland cement, 3½ parts of sand, and 4½ parts of gravel. The rendering which was finally laid over the inside of the tunnel was $\frac{2}{5}$ inch thick, and consisted ot 2 parts of Portland cement to 3½ of sand.

It was found that it was almost impossible to make the steel lining watertight, by reason of the difficulty of making the angle iron joints, fastened together by bolts, a good fit; but though this defect involved considerable extra expense in

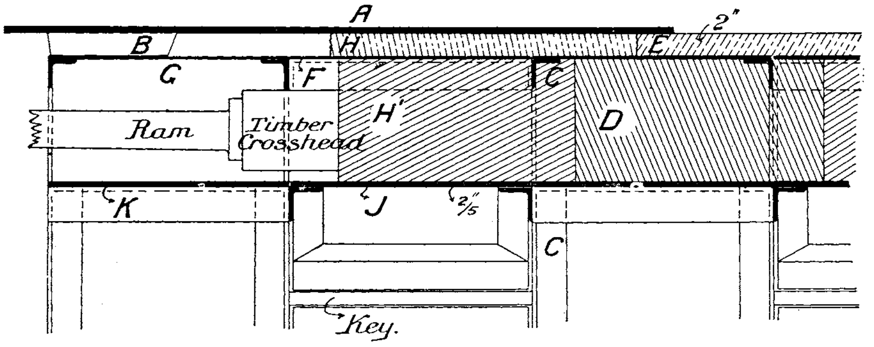


FIG. 196. SYPHON UNDER THE RIVER OISE, FRANCE.
Method of filling in Concrete Lining.

maintaining the air pressure, it is probable that, by the air drawing the cement of the concrete to these openings, a large quantity was held in the concrete, which, in work of this shape, would otherwise have been wasted in the invert. It would probably have been advantageous to have grouted up each successive length or ring of concrete by means of a Greathead grouting pan.

In the curved lengths of the tunnel, the necessary adjustment of the rings was made by introducing lead packings of the necessary thickness between the steel rings of the lining.

It is clear that the economy effected by the use of a combined concrete and steel plate lining instead of one of cast iron, must almost entirely depend on the price of cast iron in the locality where the work is done.

In this case the amount of excavation per yard forward was 6½ cubic yards as against 4½ in the case of a tunnel of similar internal diameter lined with cast iron, while the operations of erecting the steel and concrete lining were much more tedious and expensive than the same operations in a cast-iron tunnel.

In any case there can be no doubt that where the relative cost of the two systems is approximately the same, the ease with which the cast-iron tunnel can be erected by unskilled labour, and the immediate arrival of the lining at its full strength as soon as erected, make the iron tunnel preferable to a composite masonry and metal one, even if the latter be constructed under the most favourable conditions as regards excellence of workmanship and supervision. But it is very doubtfu if at any time a concrete lined tunnel, built in successive rings as one constructed under a shield must be, is ever, as regards strength, anything like as strong as an ordinary concrete structure of similar dimensions, but constructed on conditions which obtain in ordinary engineering work in concrete. It is very questionable whether the successive rings of concrete really bond together, and it is always possible, in the case of trouble with the shield, or delay by any other cause in compressing the concrete in position, that when this is done, crystallization of the cement has already occurred, and consequently the actual strength of the mass is far below its presumed quality. A free use of grout sprayed over the face of the finished work so that the escaping air from the pressure chamber would force it into the interstices of the concrete would, no doubt, do much towards consolidating it, but this at best is a palliative, and concrete fortified in this way is not the same as concrete properly set once and for all.

The Paris Extension of the Orleans Railway (1898)

Until the year 1898, the Paris Terminus of the Orleans Railway Company was in the Place Walhubert, close to the Pont d'Austerlitz, but the inconvenience of a terminus so far from the central part of the city induced the company in that year to extend their line along the left bank of the Seine to the Quai d'Orsay, where, near to the southern end of the Pont de Solferino, a new terminus was built. The length of this extension is about 2½ miles, of which distance the whole, with the exception of the portion between the Pont d'Austerlitz and the Pont Sully, is in tunnel, and, as the level of the quays along the whole length is only a few metres above the ordinary level of the river, the invert of the tunnel is constructed in water-logged material (see Fig. 222).

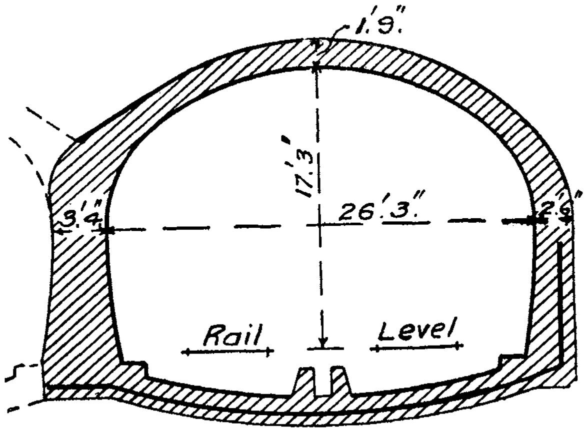


FIG. 197. ORLEANS RAILWAY, EXTENSION, PARIS. Cross Section of Tunnel between the Place St. Michel and the Quai d'Orsay.

The section of the tunnel is, for the greater portion of the length of the ordinary double line masonry tunnel type, 29 feet 6 inches wide, and with a headway above the rails of 15 feet 7 inches.

The roof is elliptical in shape, 2 feet thick at the crown, and rests on two side walls with a thickness of about 2 feet 7 inches, the invert being 1 foot 9 inches thick.

The masonry was of concrete blocks, or of limestone,[1] set in cement mortar. The concrete blocks were in the proportion of 4·5 cwt. of Portland cement to 21 cubic feet of stone, and 14 cubic feet of sand.

[1] Limestone was used with the shield employed between the Quai d'Orsay and the Place St. Michel.

The portion of the tunnel, however, between the Place St. Michel and the terminus was constructed with the view of constructing at a later date a second tunnel alongside the first, and to do this the side wall on that side (and the haunch of the arch above it) was constructed of extra strength, thus making the cross section of the tunnels un-symmetrical (see Fig. 197).

This portion of the tunnel was only 26 feet 3 inches wide, with a headway at the centre over the rails of 17 feet 3 inches, and like the other part was built of moulded concrete blocks set in cement mortar.

In both sections, the extrados of the arch was covered with cement rendering nearly 3 inches thick, and the intrados, side walls and dish of the invert with

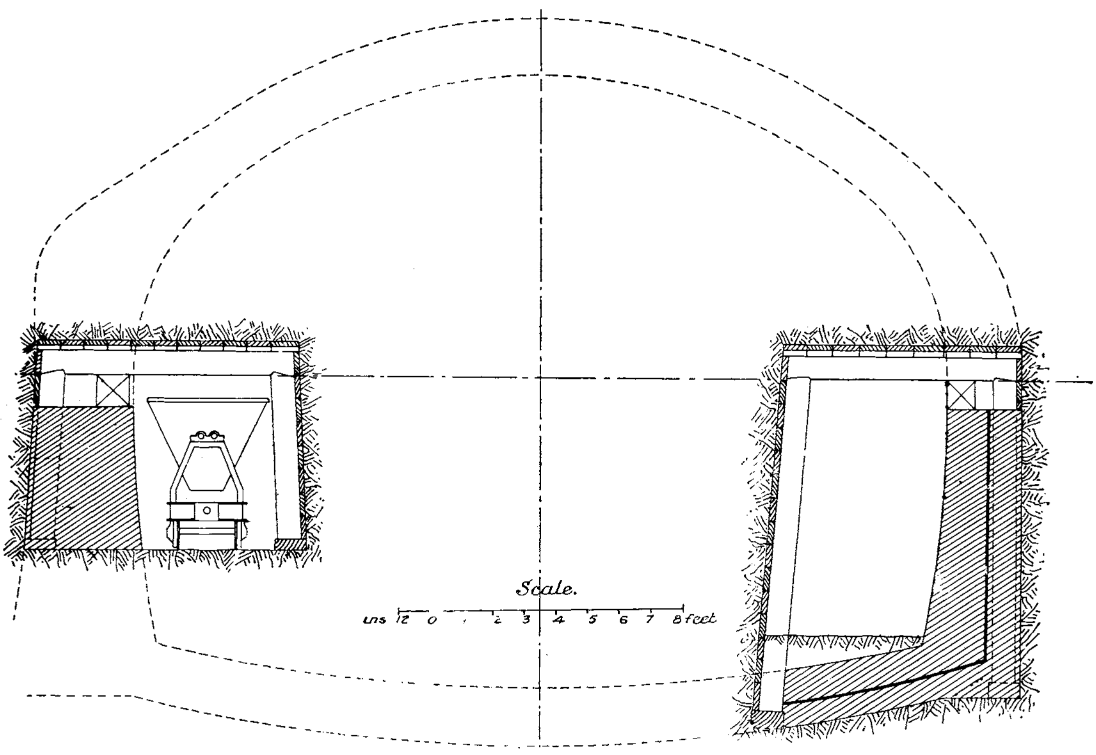


FIG. 198. ORLEANS RAILWAY EXTENSION, PARIS.
Method of driving Side Headings in advance of the Chagnaud Shield.

a thickness of 1½ inches, while a damp course of the same material was made in the middle of the invert, and carried up in the side walls, nearly to the springing line (see Figs. 197 and 198.)

The methods employed for the construction of these tunnels varied somewhat, but two lengths, namely, from the Ponte de Sully to the Petit Pont and from the Place St. Michel to the terminus under the Quai d'Orsay, were built with the aid of roof shields. These were both the designs of M. Chagnaud, and in general followed the lines of the one he had so successfully used in the Collecteur de Clichy.

One very important variation, however, was made from the earlier practice; the side walls were first built in headings driven and timbered in the ordinary manner, and on these sidewalls, the shield subsequently was rolled forward, the masonry of the walls forming solid bases on which the roller paths could be laid without risk of settlement.

The various stages in this method of working can be understood from Figs. 198 to 201. The first stage consisted in opening out two side galleries or headings on either side of the tunnel, timbered in the ordinary way with head and side trees, and close poled in the top and outer side. These headings were made sufficiently high to permit of the side walls being built up to a certain height, leaving space for the laying of the platforms on which the shield subsequently moved.

The second stage comprised the construction of the side walls within these headings, and the transfer of the weight of the roof from the outside side trees to the new walls.

The operations of these two stages were kept well ahead of the shield which formed the third stage of the work, so that the side walls had time to become set before the weight of the shield was put on them.

The shield in its advance removed all the upper part of the excavation, making, as it went on, the masonry tunnel complete, as regarded the arch and side walls, and leaving behind to be excavated only the dumpling between the two headings originally driven, and the space for the invert.

The fourth and last stage included the removal of the central dumpling, and the construction of the invert, which was built in short lengths.

In some cases the side headings driven were made large enough to allow of the construction of 3 or 4 feet of invert, in addition to the side wall, in others the side walls alone were built (both forms of construction are shown in Fig. 198).

The material tunnelled through consisted almost entirely of made ground, and of old masonry walls and foundations. These latter gave, naturally, great trouble, and in some cases necessitated the sinking of trenches from the street level.

Generally speaking, however, the tunnel work, which in some cases was only 1 foot 3 inches below the quay level, was carried on without interruption of the road traffic above; when, however, the cover was as little as 2 feet, the movement of the shield usually produced in advance of the cutting edge an undulation in the road which, in one case, reached the height of 3 feet, and in such places the tunnel was built by cut and cover work, the shield being simply pushed forward into the solid beyond.

The shield employed between the Pont de Sully and the Petit Pont was designed by M. Chagnaud on the same lines as the shield of the Collecteur de Clichy (extra muros), but with a modification of the arrangement of the centres and the polings and lagging above them, designed to obviate the necessity for using lagging by means of a system of girders and moveable timbers which formed a kind of prolongation of the shield, and though capable of movement relatively to it were not rigidly attached.

The scheme proved a failure and, the new centres being removed, the section was finished by employing the methods of the earlier shield.[1]

The second shield employed was, however, more successful, the general arrangements for erecting the masonry tunnel being on the lines of the system employed

[1] For description and plate of this machine see *Genie Civile* of February 11, 1899. See also Philippe's *Le Bouclier*, pp. 64–83.

on the Collecteur de Clichy intra muros, the masonry being laid under the protection of the shield itself.

This shield is shown in Figs. 199, 200 and 201, and is singular in being made dissymmetrical to suit the shape of the tunnel on the length from the Quai d'Orsay to the Place St. Michel. It is a roof shield or " carapace," and consists essentially of a plate skin fixed in a frame formed by two semi-elliptical girders E, E, about 5 feet 1½ inches apart, centre to centre, and rigidly framed together by numerous plate bracings F, F, which again are secured to an internal skin.

They rest on the cellular girders G, G, the bottom flanges of which form the tables beneath which are laid the rollers H, H. They are prevented from spreading

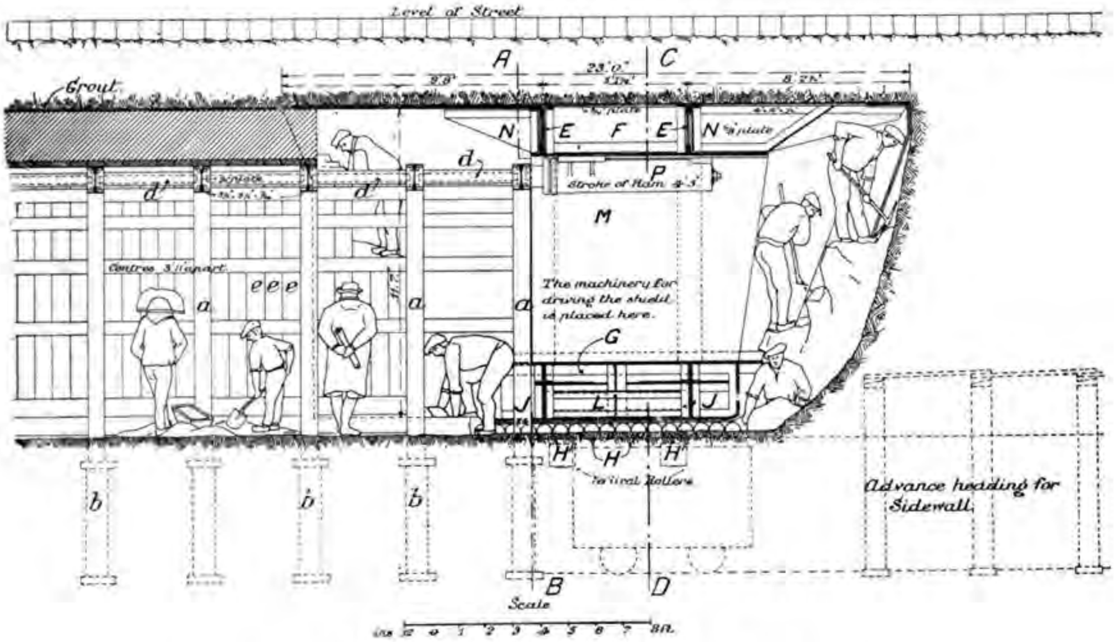


FIG. 199. ORLEANS RAILWAY EXTENSION, PARIS.
The Chagnaud Shield: Longitudinal Section, showing method of working.

by the horizontal girders J, J, which support the working platform of the shield, and carry at their centres king posts K, K, supporting the crowns of the main girders. They also are braced together by smaller girders L, L.

The skin itself was ¾ inch thick, the front of the cutting edge and all of the tail being of double thickness. Its length over all was 23 feet, the cutting edge overhanging 8 feet 2 inches beyond the front one, and the tail extending 9 feet 8 inches behind the rear one of the girders E, E. The horizontal width of the shield was 32 feet, and its height from the underside of the girders G, G, to the extrados of the skin 11 feet 8 inches.

The girders E, E, were 1 foot 10 inches in depth of web, with angle irons 4 inches by 4 inches by ½ inch. Rivetted to the lower angles was a plate M, which formed, so to speak, the lower flange of a box girder, of which the other flange was the skin, and the two girders the vertical webs. This plate M projected some distance in advance of the front girder E, thus giving additional support to the gussets of the cutting edge (see Fig. 199).

The skin of the shield, which both before and behind was of less extent at the base than at the crown, and the two girders E, E, were carried on the box girders G, G, which extend beyond the main girders about 2 foot 9 inches below the cutting edge, and 1 foot 9 inches under the tail, of the shield. These girders were 2 feet deep, and considering that the entire weight of the shield rested on them, and that

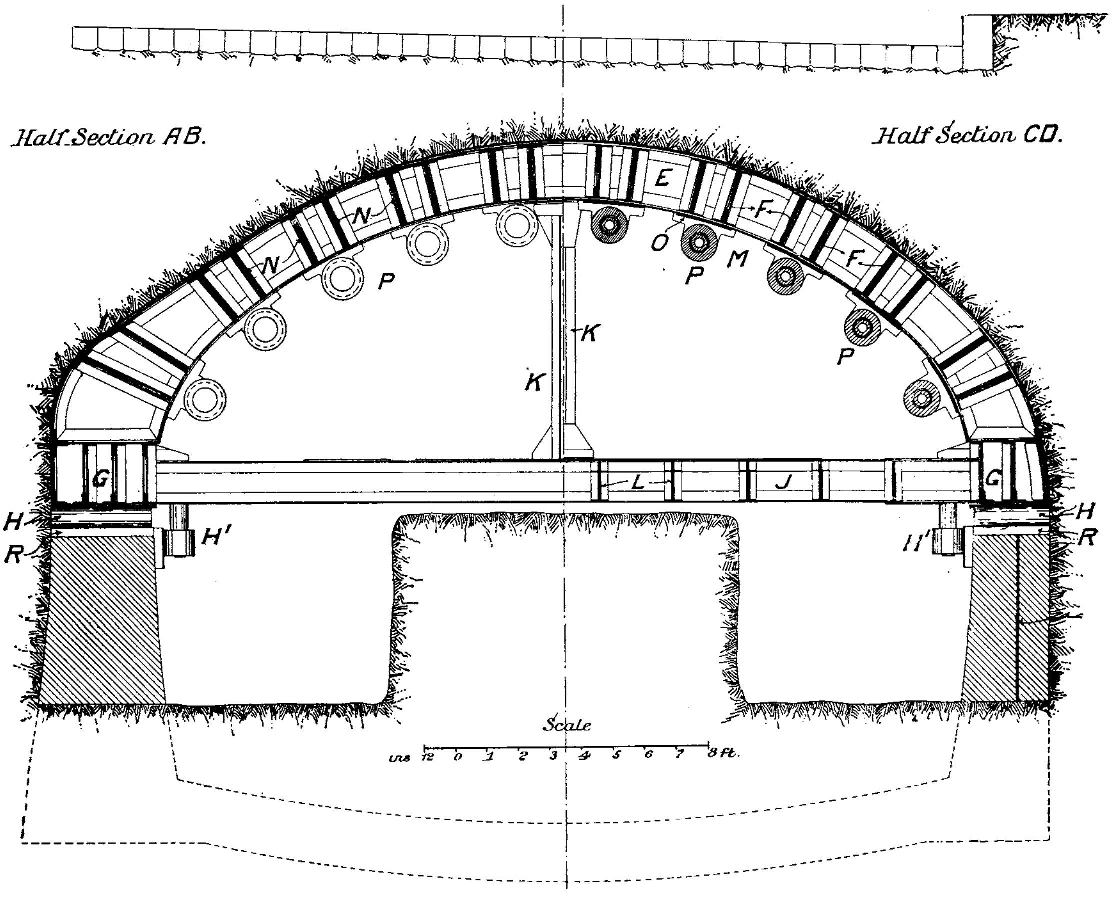


FIG. 200. ORLEANS RAILWAY EXTENSION, PARIS.
The Chagnaud Shield: Cross Sections A, B and C, D, Fig. 199.

they had to meet any unequal loading caused by settlement of the masonry bed in which the machine moved, they do not appear too strong, although it must be said they are much more satisfactory than the similarly placed single web girders in the Chagnaud shield of the Clichy " extra muros " sewer, in which there was no masonry bearing for the shield at all.

The overhanging roof of the shield was stiffened, both fore and aft, by brackets N, N, arranged in line with the gussets F, F, between the main girders ; these were, as will be seen from the section A, B, and C, D, Fig. 200, arranged in couples, under each of which the inside plate or skin *M* was thickened by an extra plate *O* forming a base to which was bolted one of the rams *P*.

At the crown of the shield, the distance between these brackets was nowhere more than 2 feet, and it is due to the strength thus given to the shield, that it arrived at the end of its work in good order, without any buckling, a condition of things not usual in machines with plate-cutting edges.

The total weight of the shield including the rams and their fittings was about 100 tons.

The rams, ten in number, were, as at Clichy, but, contrary to the usual custom, placed below the main girders instead of within them, and as already described were

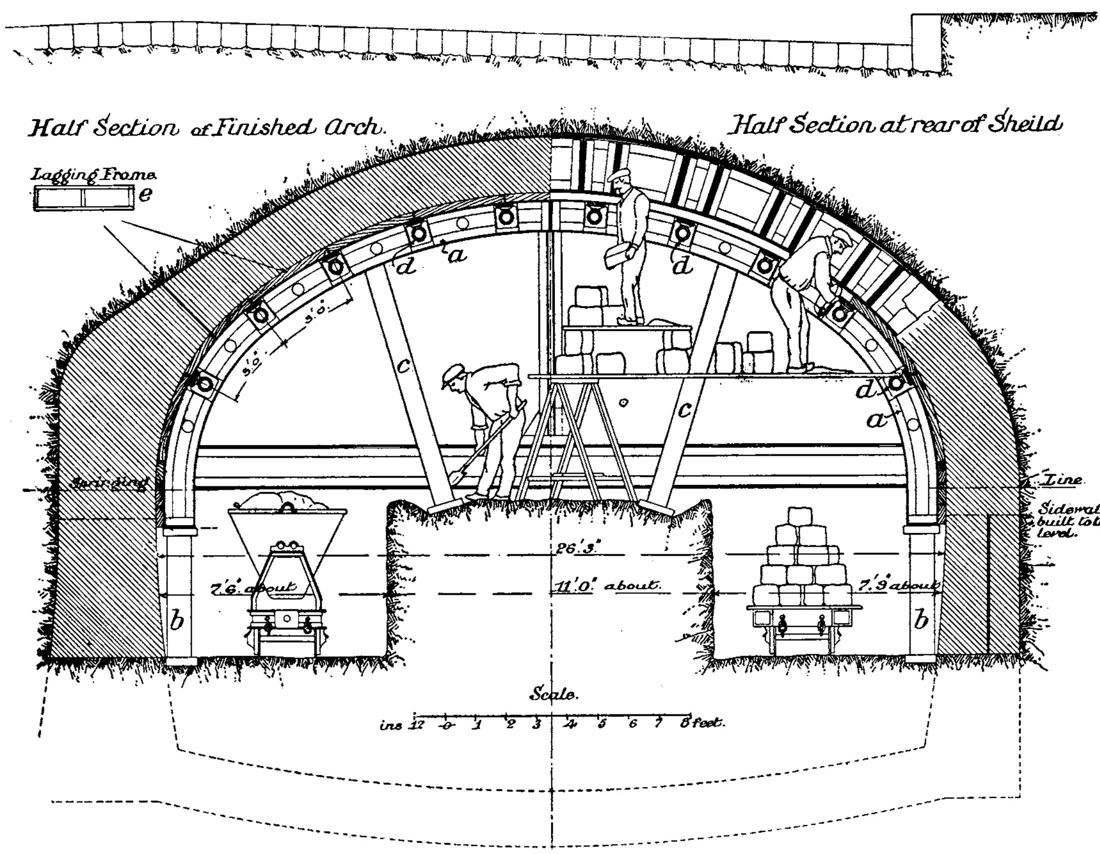


FIG. 201. ORLEANS RAILWAY EXTENSION, PARIS.
The Chagnaud Shield: Cross Sections.

bolted to the gussets *F*, *F*. This arrangement puts a very heavy strain on the bolts, and on the frame of the shield, but has the advantage that, the position of the rams being fixed, by the fact that they must bear on the centres carrying the masonry of the tunnel, the reduction of the depth of the girders *E*, *E*, sufficiently to clear the rams greatly increases the working space in the shield.

The stroke of the rams was 4 feet 3 inches, and the diameter of the pistons 9¼ inches, the hydraulic pressure employed being about, on the average, 1,000 pounds to the square inch. This pressure was supplied by an electrically driven pump fixed on the stage in the shield.

The rams were constructed with a central draw-back cylinder similar to those used on the Great Northern and City Railway and in the Holborn Tunnels, and shown in detail in Fig. 76.

The rollers *H*, *H*, on which the shield advanced, were 7 inches in diameter, and rested on elm sole pieces *R*, *R*, having their upper surface protected by a $\frac{5}{8}$ inch plate. These sole pieces were laid on the previously constructed masonry side walls which afforded a rigid base for the operations of the shield.

In addition to these horizontal rollers two vertical ones *H′*, *H′*, were fixed on either side of the shield, and so placed as to bear against sole pieces fixed against the face of the side walls. These assisted materially in guiding the shield, by providing, so to say, a wheel base 4 feet 1 inch long rolling on each side wall. A longer distance between the rollers might have been arranged with advantage, as no curve traversed by the shield was less than 1,000 feet radius, and an increased length between them would have increased the guiding power of the rollers, without increasing the difficulty of driving the shield.

The working of the shield was on similar lines to that of the shields described earlier in this chapter. As the shield advanced by pushing against the centres supporting the tunnel behind, the masonry arch was built up in steps, the tail of the shield being long enough to admit of the erection of three centres 3 feet 11 inches apart.

Seven masons were employed, three working on either side between the three centres, while the fourth keyed in the arch over the last of the three. The most troublesome part of the work was the packing securely with mortar the spaces left by the tail plates of the shield, and the necessity of doing this with care somewhat retarded the rate of progress, or at any rate made it more convenient to advance the shield, not in lengths of 4 feet to suit the distance between the centres, but in lengths of 15 to 16 inches at a time.

The mortar grouting was the more important, as in general the masonry was not built tight to the skin of the shield, but with about 1 inch clear all round.

In constructing the roof of the tunnel under shield, water was not met with, the level of the river water being well below the springing line of the arch, and indeed it is not easy to see how the work of constructing the permanent masonry lining could have been carried out had the material surrounding the shield been waterlogged.

The excavation in front of the shield and the filling of the skips was performed by a gang of ten men, and was much facilitated by the existence of an old disused sewer which lay along the line of the tunnel and along which the skips of spoil were sent forward and discharged into barges at a convenient point, thus avoiding all interference with the service of skips delivering stone and mortar, etc., for the construction of the tunnel.

The average rate of progress was a little less than 10 feet per day.

The centres were forty in number, and weighed with their cast-iron struts, etc., about 16 cwt. each.

Each centre *a*, *a*, Fig. 201, consisted of a web, 1 foot 3 inches deep and $\frac{1}{4}$ inch thick, stiffened with two angle irons $3\frac{1}{2}$ inches by $3\frac{1}{2}$ inches by $\frac{3}{8}$ inch rivetted on at top and bottom. For convenience of handling, each centre was made in two halves, bolted together at the crown. When in position, it was wedged up at the ends on props, *b*, *b*, and supported also by rakers *c*, *c*, the effect of which was to maintain, better than had so far been the case, the proper shape of the centres. Between each pair of centres were ten cast-iron distance pieces, *d*, *d*, *d*, which were axial with the rams of the shield, the thrust of which they distributed along the whole number of centres. It was found, however carefully these distance pieces were fitted, that a movement took place among the centres, when the pressure of the shield was applied, to the extent of about ¾ inch.[1]

Instead of the usual lagging on the centres, small frames *e*, *e*, *e*, made of strips of wood, were used (see Fig. 201). These frames were about 3 feet 4 inches long and 9 inches wide, and instead of being like ordinary lagging laid parallel to the centre line of the tunnel, were laid with their longer sides parallel to the centres, their ends being supported on the cast metal flanges of the distance pieces *d*, *d*, *d*.

"The employment of these frames gave good results, enabling the masons to keep always close to their work, and consequently giving them greater freedom of movement."

M. René Philippe, from whom the previous lines are quoted, makes, in commenting on the general progress of the work, the following observations[2] :—

Generally the roadway (above) was made as the shield went on, for the caulking by grout, although carefully executed, could not fill the hollow lift by the removal of stone blocks and other obstacles.

When the rate of excavation was slow the masons overtook the miners, and this in spite of the fact that their numbers were reduced from eight to six, and that they were employed in moving the centres ; but later, the masonry kept back the miners, to the extent of making them lose two "pushes" of the shield, or 2 feet 8 inches, in an eleven-hour shift.

In loose ground the nose of the cutting edge was extended by means of wood polings fitted inside the hood, and between it and an angle iron fixed inside it, and about 1 foot behind the cutting edge.

In consequence of the tail of the shield failing on several occasions, it was found necessary to raise up the shield in order to maintain the masonry arch at its proper level above the rails. The sole pieces (*R*, *R*, in Fig. 200) were in consequence thickened, with the double inconvenience that, in the first place, the thicker pine sole pieces were compressed under the weight of the shield, thus causing it to undulate in its advance, and, secondly, the vertical rollers being left with a less bearing surface, failed to act as guides to the machine.

The value of the lateral bearings was here clearly shown, the bearing plate fitted on the face of the side wall showing the effect of the vertical roller bearing on it, while no sign of failure appeared in the wall itself.

Under the pressure of the shield rams, the cast iron distance pieces were compressed, and the centres moved backwards, sliding under the arch of the tunnel : the extent of this movement of the centres being shown by numerous observations to amount to from 14 to 18 millimetres each "push" ; and when the rams were drawn back, it was noticed that the centres, in springing back to their original position, were likely to draw the more recently constructed masonry with them ; and in consequence the system was adopted of wedging the lagging frames, *e*, *e*, *e*, against the back girder, *E*, of the shield (at the end of the stroke), by means of eight chogs placed alongside the cast-iron distance pieces ; with the result that no movement was observed among the lagging frames, nor fissures in the masonry lining.

This shield seems to have been a great advance on the previous machines of M. Chagnaud. In its general construction it appears to have been well-proportioned for its work, and in the method employed of constructing in advance the side walls of the tunnel as bases on which the shield could advance, there is no

[1] Philippe's *Le Bouclier*, p. 92. [2] Philippe's *Le Bouclier*, p. 92.

doubt that its designer has found the best method of driving a shield for the construction of shallow tunnels in loose or compressible material when water is absent.

In details, the use of vertical rollers bearing on the faces of the side walls already constructed, appears to be justified by the results, and the substitution of small framed laggings for the usual horizontal strips on the centres proved a useful innovation.

Chapter IX

THE SHIELD IN MASONRY TUNNELS (continued)

THE TREMONT STREET TUNNEL, BOSTON, U.S.A.—WORK COMMENCED WITHOUT A SHIELD—A ROOF SHIELD DECIDED ON—METHOD OF WORK—DETAILS OF CONSTRUCTING THE SIDE WALLS—DETAILS OF THE SHIELD—THE SLIDING SHOES—CAST IRON BARS BUILT IN THE BRICK ARCH TO RECEIVE THE THRUST OF THE SHIELD RAMS—RATE OF PROGRESS—THE BOSTON (U.S.A.) HARBOUR TUNNEL—CONDITIONS OF COMPRESSED AIR WORK—DETAILS OF THE SHIELD—METHOD OF WORKING—RATE OF PROGRESS—THE METROPOLITAN RAILWAY OF PARIS—COMPARATIVELY LIMITED EMPLOYMENT OF SHIELDS—METHODS OF SHIELD WORK ADOPTED—SECTIONS IN WHICH SHIELDS WERE EMPLOYED—THE CHAMPIGNEUL SHIELDS—DETAILS OF THE SHIELD—CENTRAL ADVANCE HEADING USED—METHOD OF WORKING—CENTRES FOR MASONRY—RATE OF PROGRESS—INTERRUPTION OF STREET TRAFFIC ABOVE—GENERAL REMARKS ON THE CHAMPIGNEUL SHIELD—THE LAMARRE SHIELDS—DETAILS OF THE SHIELD—TIMBER CENTRES—UNSATISFACTORY RESULTS OF WORKING—THE DIEUDONNAT SHIELDS AND THE WEBER SHIELDS—GENERAL REMARKS ON THE METROPOLITAN RAILWAY SHIELDS

The Boston Underground Railway (1897)

DURING the construction of this railway, which was commenced in 1894, and is now approaching completion, roof shields were employed on two sections of the line for building a double line tunnel of concrete and brickwork, and achieved a marked success. In the first section carried out in this manner under Tremont Street in 1897, at a depth of from 10 to 14 feet from the roadway to the extrados of the arch, the street traffic was but little interfered with, and the rate of progress of the work was satisfactory.

In the second length, where shields were employed, a similar tunnel, but entirely of concrete, was driven under Boston Harbour, the minimum cover being about 18 feet and the maximum height of water 90 feet above the invert of the tunnel. Compressed air was employed in this part of the work, which was commenced in 1900 and is now finished.

The Tremont Street Tunnel

The Tremont Street Tunnel (1897) should, if strict chronological order were adhered to, be described between the Clichy Sewer of 1895 and the Orleans Railway of 1898. It shows, however, with the Harbour Tunnel, constructed under the same engineer, Mr. H. A. Carson, such an advance on the Paris undertakings, and the two tunnels have so many features in common, that they are brought together in the same chapter, although the one was built some years later than the other (see Figs. 202, 203).

The railway under this street consists, at its south end at the junction with Park Street, of two separate single line tunnels which unite in a bellmouth in Tremont Street, and this in turn becomes a double line tunnel with a width at springing of 23 feet, and height from invert to crown of arch of 17 feet 9 inches. This section

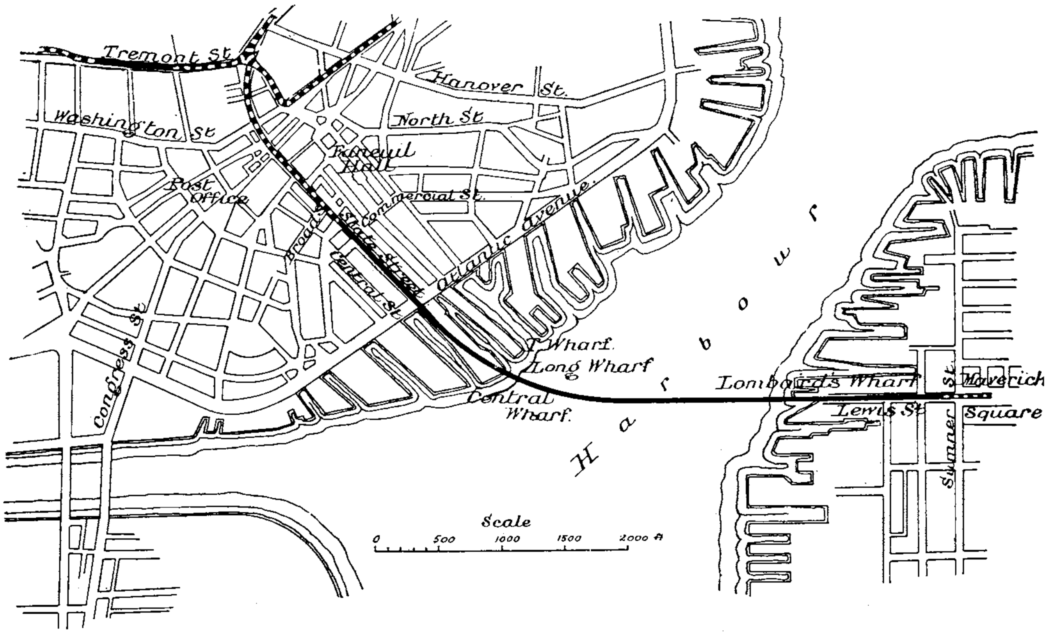


FIG. 202. UNDERGROUND RAILWAY, BOSTON, U.S.A.
Plan showing position of the Sections constructed under Shield in Tremont Street and under the Harbour. The full Black lines indicate the lengths of Shield work.

of tunnel extends the full length of Tremont Street to its junction at its north end with Scollay Square.

It was originally specified that the tunnel should be built for a short distance at either end of the street by the "slice" method, and the remainder by "an

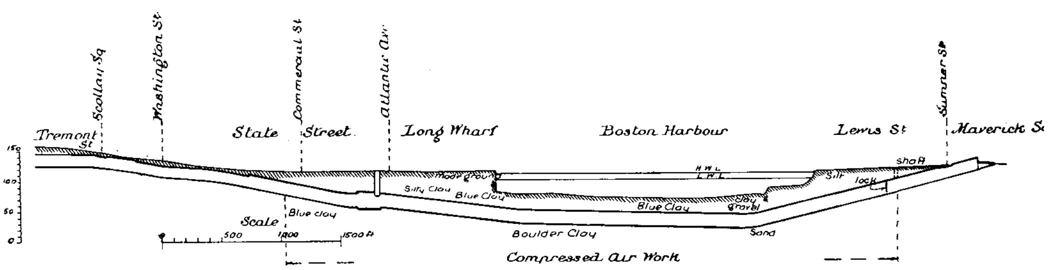


FIG. 203. UNDERGROUND RAILWAY, BOSTON, U.S.A.
Longitudinal Sections showing Tremont Street and Harbour Tunnels.

acceptable mode of tunnelling," the provisions of the contract as first awarded being such as practically gave the public the enjoyment of the entire roadway and footpaths during the day, and even at night gave the necessary area for the circulation of wheeled and foot traffic.

The contractor for the Tremont Street tunnel, which was known as "Section 6" of the railway, commenced operations by excavating two "slices" at the north end of his contract about 24 feet apart, and then, in order to demonstrate the feasibility of the method he proposed to follow for the remainder, commenced to connect them by tunnelling (as distinguished from the "cut and cover" of the "slice" work).

His method was to drive in the first place small headings on the lines of the side walls, but only one-half their height, to build in these the lower portion of the concrete walls, and then to drive a second heading over each of the first to obtain the full height of the side walls. He then drove a centre heading on the line of the axis of the tunnel, about 10 feet wide and 6 feet deep, roofed with squared crown bars about 12 feet long which were placed to clear the proposed arch.

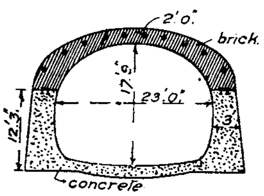


FIG. 204. UNDERGROUND RAILWAY, BOSTON, U.S.A. Section of Tremont Street Tunnel.

This heading was subsequently widened out by driving laggings in either side, the whole of the roof so made being supported on timbers resting on foot-blocks. At the same time another similar heading with crown bars was driven by the engineers of the railway in the adjoining length. The results of the two experimental headings were alike: the sandy clay, sand and gravel, containing some boulders, forming the natural material below the street, and doubtless disturbed by the street and building excavations of a hundred and fifty years, showed signs of settlement immediately the central headings were made; and the movement naturally increased as the excavation was widened out. In consequence the contractor was notified that the crown bar system of tunnelling was unsatisfactory, and shortly after the Commissioners directing the work of the railway took over the construction of the section, and finished it without the intervention of a contractor.

Mr. Carson, the Commissioners' Chief Engineer, decided to employ a shield for the construction of the length of tunnel between the "bell mouth" at the south end of Tremont Street, and the junction of this street with School Street. North of School Street he continued to employ the "slice" method, but the methods used in this work do not come within the scope of this book.

Where the roof shield was used, the method of working, already described as in use in the extension of the Orleans Railway in Paris, was in its main features adopted with one new and most important feature, though in point of time it must be remembered that Mr. Carson's work preceded the Paris undertaking. In the first place (see Fig. 205) the side walls were first built in concrete in small drifts timbered with head and side trees, and the roof and nearly the whole of the sides close poled. For a length of 132 feet at the south end of the total length of 550 feet built under shield, these side walls were built in double tunnel, as described above, but for the remainder single headings of sufficient size to admit of the whole side wall being built in one operation were driven.

In both cases, after the headings were driven, and before starting the masonry of the side walls proper, the spaces between the timber settings were filled with concrete, flush with the inside face of the frames, all polings being removed as the concrete was put in. In this way a close joint between the concrete and the surrounding earth was insured, and the possibility of any pockets or cavities behind the wall avoided.

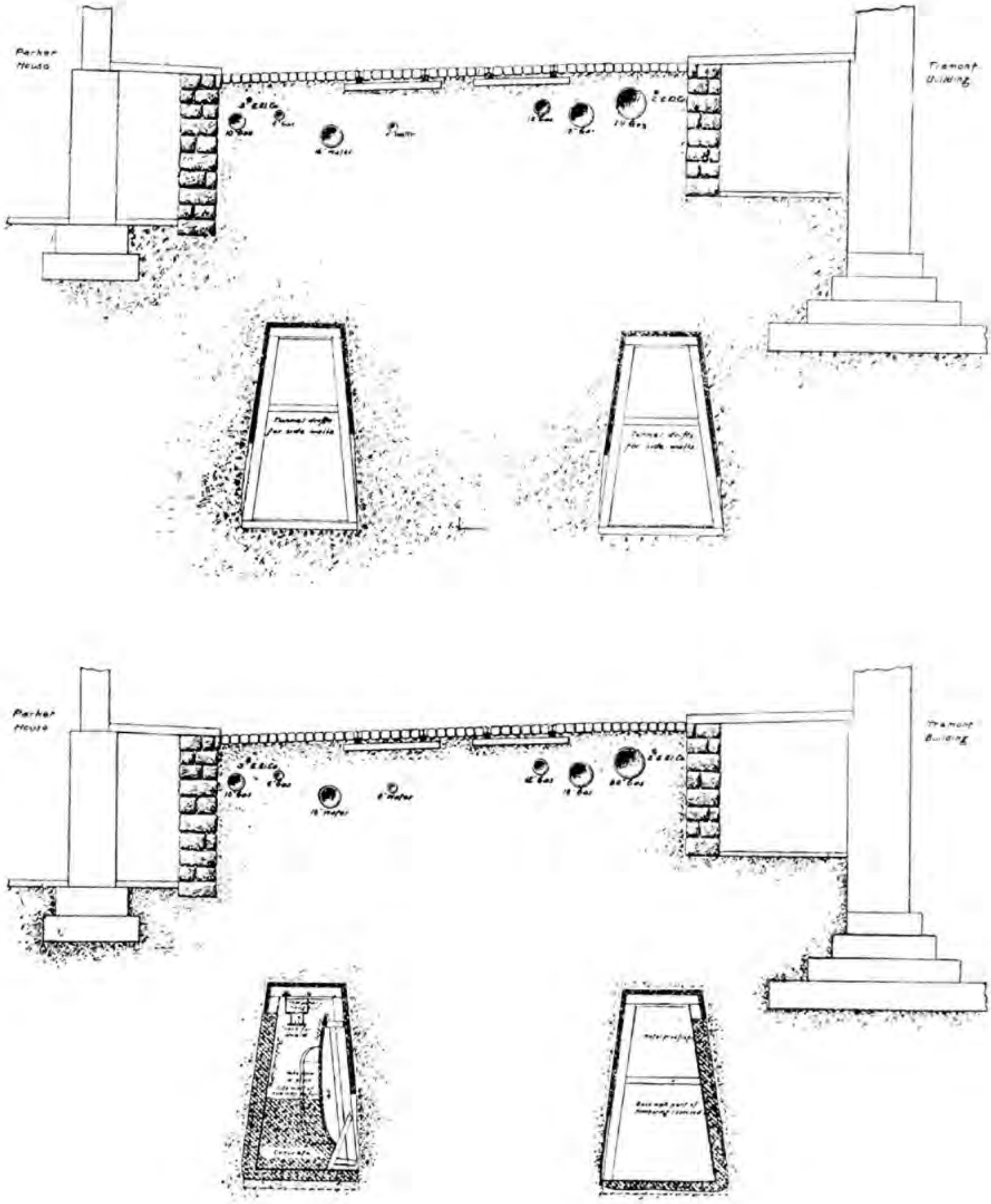


FIG. 205. UNDERGROUND RAILWAY, BOSTON, U.S.A.
Method of Tunnelling under Tremont Street.

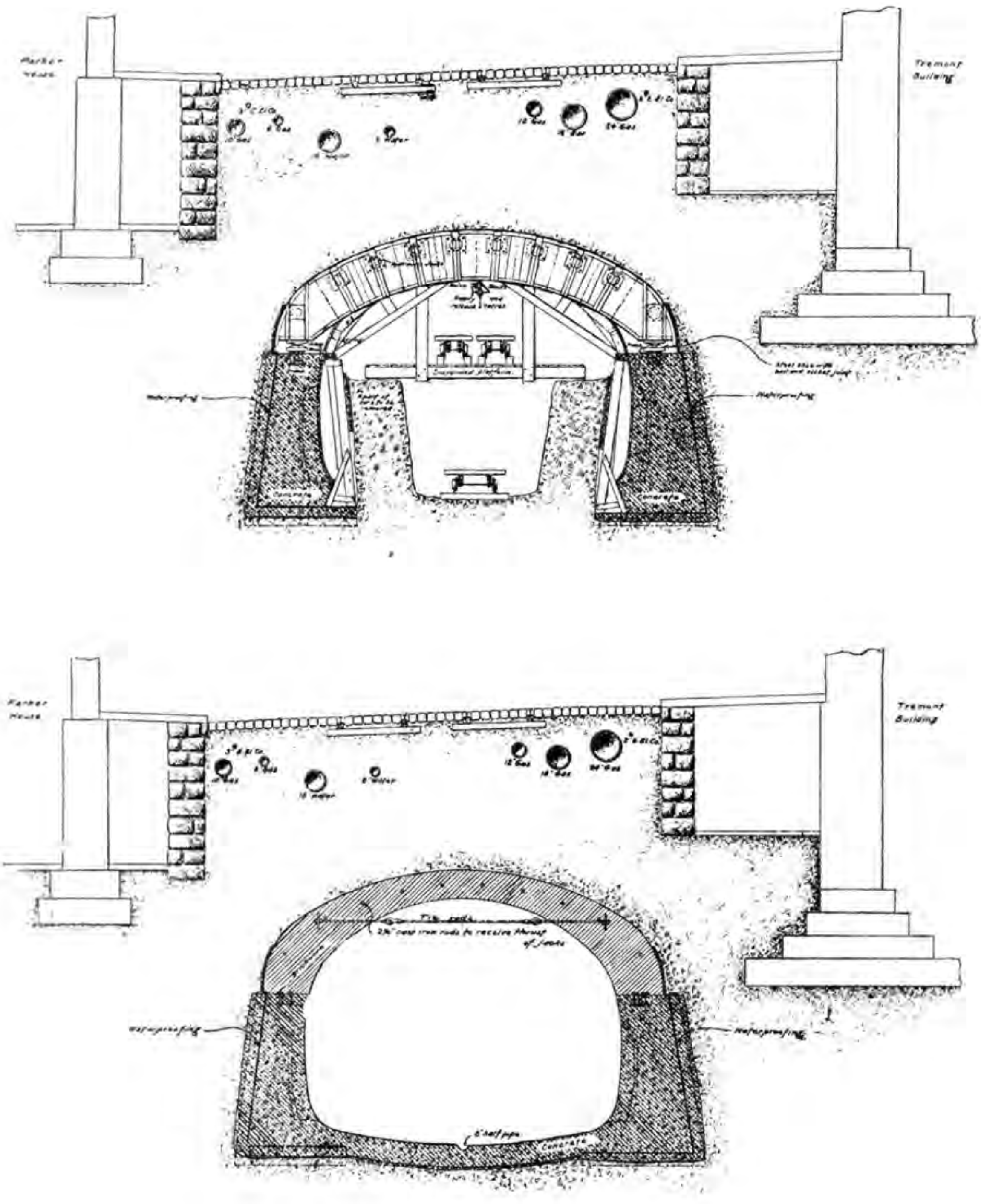
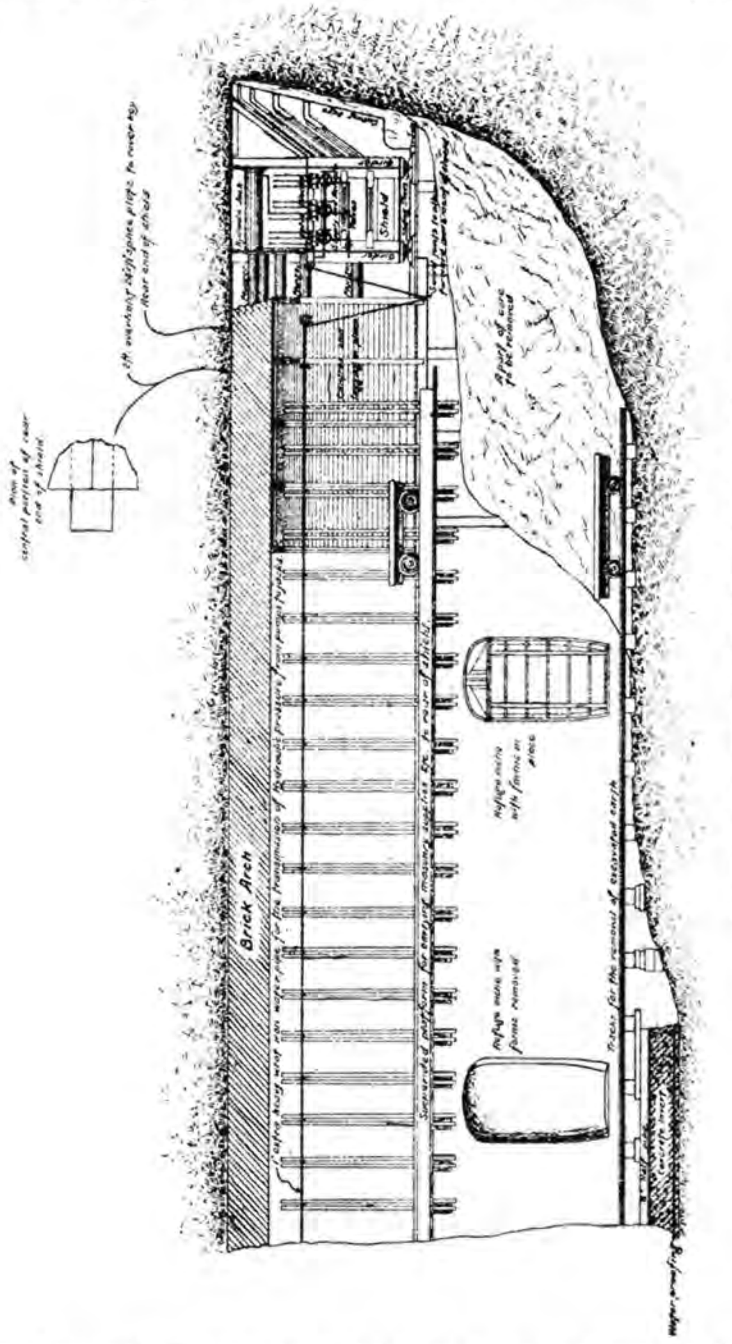


FIG. 206. UNDERGROUND RAILWAY, BOSTON, U.S.A.
Method of Tunnelling under Tremont Street.

The inside surface of this concrete was then plastered with Portland cement, which in turn was treated with asphalt, to make a vertical water-tight joint. Against this face again was built the true side wall of the tunnel (see Fig. 205), which



Longitudinal vertical section through Shield and Subway.

FIG. 206A. UNDERGROUND RAILWAY, BOSTON, U.S.A.
Method of Tunnelling under Tremont Street.

was carried up to the springing line of the arch, and on its top was fixed the roadway in which the shield subsequently travelled. This consisted of two rolled joists (Figs. 206 and 208) 10 inches high with 5-inch flanges, framed together and having rivetted to their bottom flanges a plate 15 inches wide and 1 inch thick.

These were embedded nearly their full depth in each wall, and made perfectly rigid bearing surfaces for the shoes of the shield.

The shield weighed about 22 tons and cost about £1,200. In general arrangement it differed but little from the roof shields previously considered, the main structural difference being in the more satisfactory proportion of its base to the length and height of the machine (see Figs. 207, 208, 209).[1]

The length of the skin of the shield was 12 feet long and 1 inch thick, the main ribs *E* and *F* supporting it being 4 feet apart. The front hood had a projection of 4 feet, the skin being bevelled off so that it only extended 2 feet below the base of rib *E*. Behind, the tail overhung 4 feet, an extra plate *C*, however, 2 feet wide, extending 2 feet beyond the tail proper, to assist in protecting the keying in of the tunnel arch.

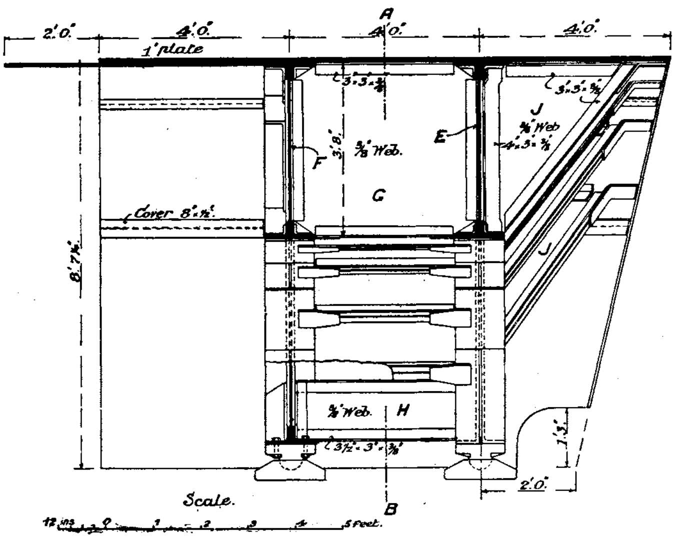


FIG. 207. UNDERGROUND RAILWAY, BOSTON, U.S.A.
The Tremont Street Shield : Longitudinal Section.

The length of the base was over one-third of the total length of the shield roof.

The width of the shield over all was 29 feet 4 inches, and its height over all was 8 feet $7\frac{1}{4}$ inches.

The length of the shield, therefore, was much less in proportion to its width, and the width of the base greater in proportion to its length, and to its height greater than in any of the Paris shields. The first modification of the French pattern ensured greater ease of direction, the second greater stability. The ribs *E* and *F* were made each 3 feet 8 inches deep, the web being $\frac{1}{2}$ inch thick for the greater part of its length and $\frac{5}{8}$ inch thick at the ends over the bearings. The flanges consisted of plates $12\frac{1}{2}$ inches wide by $\frac{5}{8}$ inch thick at the centre, and $12\frac{1}{2}$ inches wide by $\frac{1}{2}$ inch thick at the ends to correspond. These ribs were bound together by nine gussets, *G, G, G*, $\frac{3}{8}$ inch thick, secured to the ribs and to the skin plates by angle irons 3 inches by 3 inches by $\frac{3}{8}$ inch. Two small girders *H, H*, were also fitted between the ribs immediately over the track on which the shield moved.

But in this shield no horizontal tie girders united the extremities of each rib, nor was there any working platform, forming an integral part of the shield. Below the lower flanges of the ribs there was no framework of any kind to impede the work of excavating the face. The shape of the shield was maintained solely by the rigidity of the ribs *E* and *F*, as there was no framing to prevent them spreading under the superincumbent weight.

The front hood of the shield was supported by brackets, *J, J*, of similar construction to, and in line with, the gussets *G, G* between the ribs. The tail of the

[1] The Author is indebted to Mr. Carson for the drawings from which these figures are prepared.

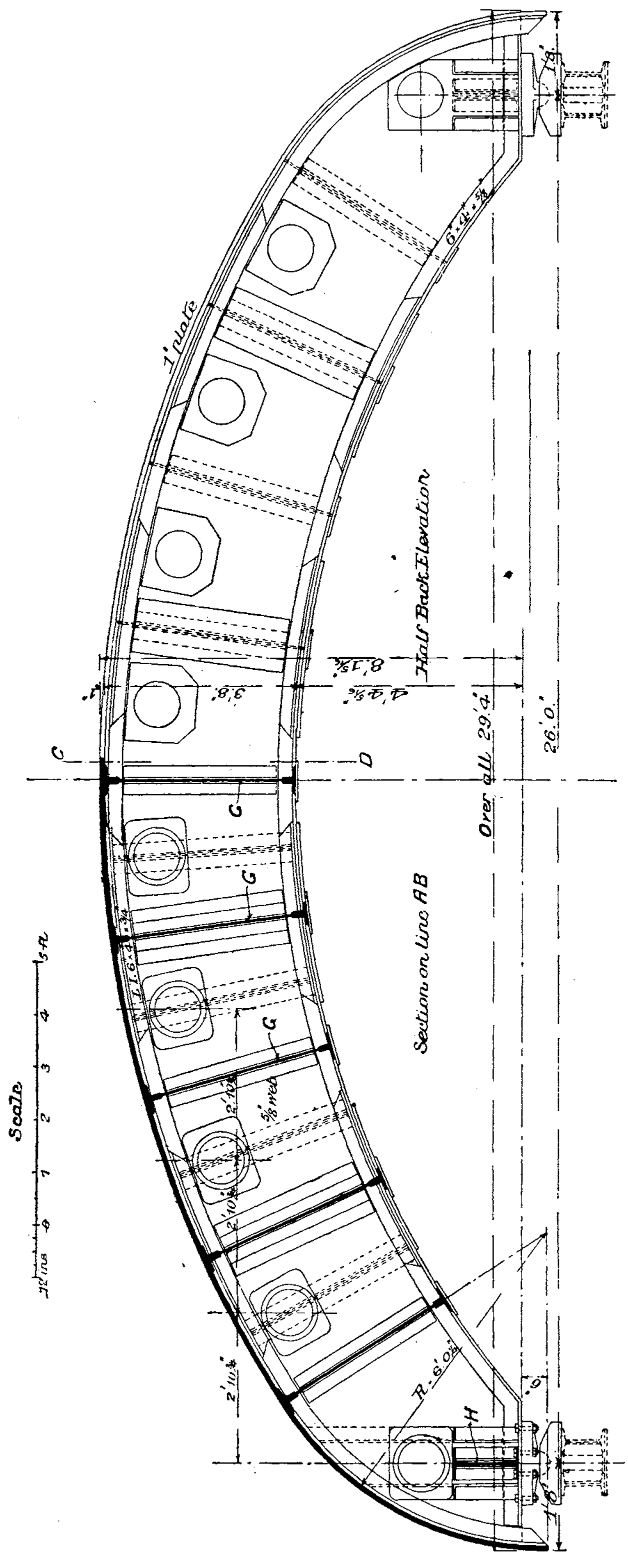


FIG. 208. UNDERGROUND RAILWAY, BOSTON U.S.A.
The Tremont Street Shield: half section on line *AB*, Fig. 207, and half back elevation.

shield was unsupported by brackets; indeed, its length, 4 feet, was barely long enough to admit of the brick arch being built under it.

The ribs rested on cast steel shoes of a special pattern (for details see Fig. 209). Each shoe consisted of two parts, an upper casting bolted to the rib, and having a hemispherical base, and a lower one, or sliding plate, into a cavity of which the upper one fitted. The lower plate moved over the track girders as already described, and the knuckle joint made by the two parts of the shoe facilitated the movement of the shield about either end of the ribs when a change of direction was necessary.

The rams for driving the shield were ten in number, eight of them placed between the gussets *G*, *G*, and one over each of the girders *H*, *H*. They were 6 inches in diameter, and could work up to a maximum pressure of 3,000 pounds per square inch, which amount was, however, seldom required, 1,200 pounds per square inch, which was equivalent to a total thrust of over 500 tons, being usually sufficient. On the front rib *E* the rams bore on castings bolted to the web, and holes for them were cut to correspond in rib F, the web of which was strengthened by extra plates round the holes.

The most important improvement made by Mr. Carson consists, however, in the introduction of cast-iron bars, $2\frac{1}{4}$ inches in diameter, into the masonry of the tunnel arch, disposed so as to receive each one the thrust of one of the shield rams. This idea, Mr. Carson states, was suggested to him in the first place by Mr. W. L. Aims, the resident engineer of the East River Gas Tunnel in New York.

These bars were built in as each length of the tunnel was constructed, the ends being loosely secured in line with the preceding ones by iron sleeves about 3 inches long.

This ingenious arrangement at once avoided the difficulties met with in pushing against the centres supporting the masonry, and on the other hand in using the newly constructed arch as an abutment.

In the former method, employed with the Chagnaud and Champigneul shields, the pressure of the shield always, sooner or later, produced distortion in the centres and generally rupture in the green masonry of the arch; in the latter, the use of the masonry itself as a fulcrum proved entirely destructive of the strength of the material.

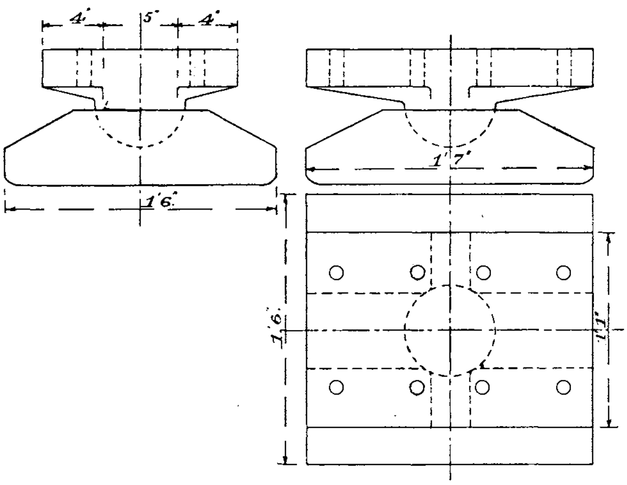


FIG. 209: UNDERGROUND RAILWAY, BOSTON, U.S.A.
The Tremont Street Shield: Cast Steel Shoes.

Mr. Carson's arrangement by avoiding both these disadvantages is a distinct step in advance in masonry work under shield, nor does it appear likely that the presence of the cast-iron bars in the brick arch will, by destroying in some measure its homogeneity, weaken it as a structure.

The rate of progress was 9 feet per day of twenty-four hours under normal conditions.

Behind the shield, the masonry arch was carried on light wooden centres; the removal of the material excavated was provided for by a trench (see Fig. 206) sunk below the floor level of the shield excavation, and the materials for the masons were brought forward on a track supported on timbers slung from the centres.

The space left by the skin of the shield was filled in by cement grout pumped through pipes left in the brick arch.

About 450 feet of the total travel of the shield was in ground composed of closely compacted clay and sand, unfavourable to rapid progress, and sometimes boulders as large as 4 feet across were met with. The remaining 100 feet traversed by the shield was in loose sand and gravel, and in this portion the cutting edge of the shield was kept hard up against the working face, instead of, as in the clayey portion, removing a space in front of the cutting edge, into which the shield could be pushed with small expenditure of power. The rate of progress of the two systems did not, however, vary materially.

The period occupied in driving 550 feet of tunnel was ninety-two days, so that the average rate of progress was about 5·1 feet per day. When the shield was actually working, however, the rate of progress was, as stated above, nearly 9 feet per day.

The Tunnel under Boston Harbour, or East Boston Tunnel

This tunnel connects the underground railway of Boston, of which the Tremont Street tunnel just described forms part, with the town on the other side of the harbour known as East Boston. The width of the harbour where the tunnel crosses it is about 2,000 feet, but, owing to the crossing being an oblique one, the length of tunnel under the waterway is about 2,400 feet, and if the docks on either side of the harbour be taken into account, the total length constructed under navigable water is about 3,500 feet (see Fig. 203).

The tunnel is 23 feet 4 inches wide at springing, and 20 feet 6 inches from invert to crown, or somewhat larger than the Tremont Street Tunnel, which in section it resembled. It is built entirely in mass concrete, and is, up to the present, much the most important work carried out in that material by means of a shield. It was not, however, the first tunnel so constructed. In 1897, in connexion with some drainage works near Paris, a small circular tunnel, 6 feet 8 inches in diameter, was driven under the River Oise[1] near its junction with the Seine, which is of concrete, its method of construction being much the same as that now to be described, save that the shield used followed English models, and was circular.

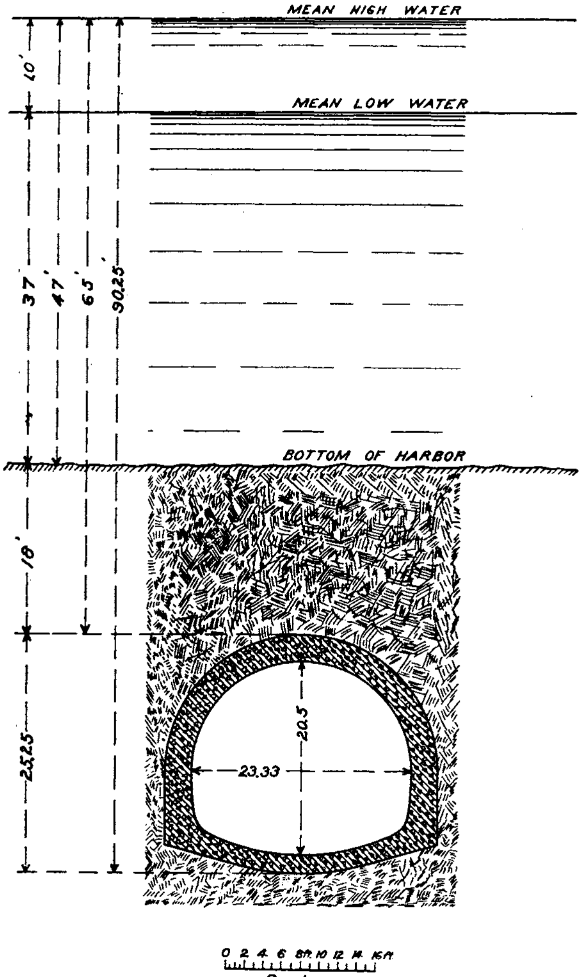


FIG. 210. UNDERGROUND RAILWAY, BOSTON, U.S.A. Section of Tunnel under the Harbour.

The maximum depth (see Fig. 210) of the excavation below high water mark was about 90 feet, and the cover over the crown beneath the harbour bed about 18 feet at the least. The material met with was, however, for the most part strong blue clay and boulder clay, and sometimes a sandy and silty clay permeable by water. Large boulders were occasionally met with and some strata of coarse sand.

[1] See page 290.

Probably for the greater part of its length the tunnel could have been driven without compressed air, or at any rate with only a few pounds pressure, but the risk involved in working without the security given by the provision of compressed air, under a wide and deep waterway, and the assistance which a pressure of even 20 pounds per square inch gives in holding up the area of the excavation, when working at such a depth, made the installation of an air-compressing plant almost obligatory.

The usual pressure under the river was from 18 to 20 pounds per square inch, and only occasionally was as high as 25 pounds. The amount of free air delivered per man per hour was only on the average about 1,200 cubic feet, a quantity considerably below that usually considered necessary, but the engineer of the work

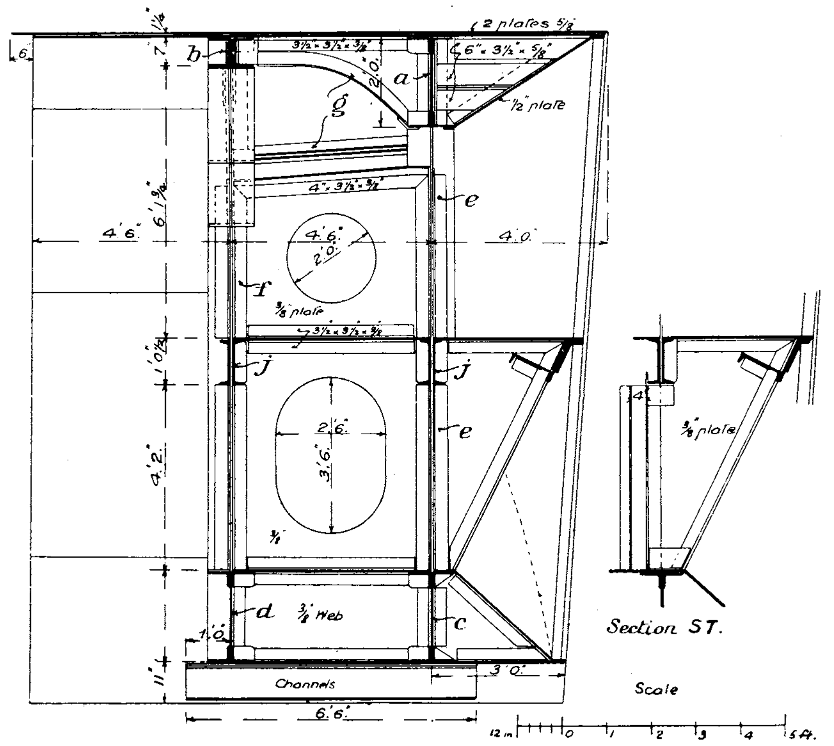


FIG. 211. UNDERGROUND RAILWAY, BOSTON, U.S.A.
The Harbour Shield: Longitudinal Section, and detail at $S\ T$, Fig. 212.

states that few cases of compressed air sickness were brought to his notice. The air was delivered behind and also in the top of the shield, and in each advance heading for the side walls. The temperature varied from 80° to 90° Fahrenheit, and it was noted that the heat of the tunnel was increased by chemical action in the concrete, which, two days after setting, had an interior heat 40° above that of the air in the tunnel.

The amount of carbonic acid in the air of the tunnel averaged during a considerable portion of the time nearly 3 parts in 1000, a much higher percentage than is advisable, even with the comparatively low pressure employed. But on occasion the percentage rose to 6·9 parts in 1,000 or nearly ·7 per cent., an entirely dangerous condition for work.

The hours worked were also in excess of those usually accepted as safe. The

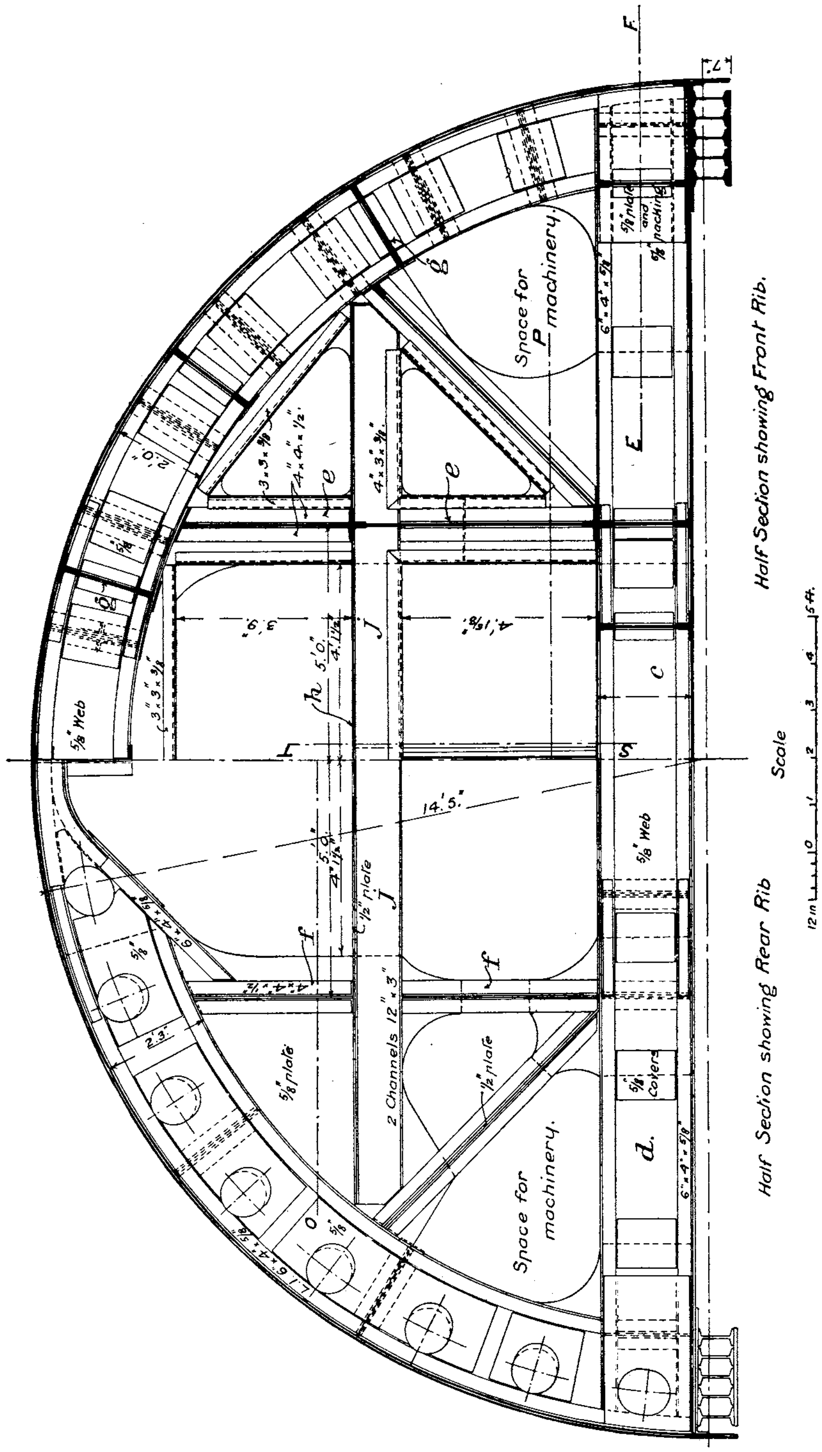


Fig. 212. Underground Railway, Boston, U.S.A.
The Harbour Shield: Cross Sections.

day was divided into two eleven-hour shifts from 7 a.m. to 6 p.m., and from 7 p.m. to 6 a.m., with a break of one hour at noon and midnight respectively.

No safety screens [1] were provided in the tunnel, but an emergency lock (see Fig. 218) was fixed in the upper part of the bulkhead, above the working air locks.

Two air compressors were provided for the supply of air to the tunnel of the Ingersoll-Sergeant type, with a combined capacity of 1,560 cubic feet of free air per minute at 18 pounds pressure. The compressor for machinery worked at 125 pounds pressure per square inch.

The conditions of the specification referring to compressed air work were as under :—

Special care and such appliances as are requisite shall be used to insure the proper ventilation of tunnel and similar work. The amount of carbonic acid gas present at any time at the working faces shall not be allowed to exceed one part to 1,000 parts of air. The contractor shall amply provide means and appliances for the safety of the work and for the safety and health of the men employed in it, which shall include : electric lighting, telephonic communication between all parts of the work : suitable resting places for the men, and a drying place for clothes, a compressed-air chamber fitted with bunks if the air pressure exceeds 20 pounds per square inch above the normal : an emergency air lock (in addition to the ordinary working air locks) in each airtight bulkhead for the tunnel, with access thereto from the ordinary working levels : arrangements such that it shall not be necessary for men to climb any stairs immediately after getting out (of the air-chamber) ; keeping every portion of the work in a thoroughly sanitary condition ; and dry earth closets and other necessary conveniences for the men.

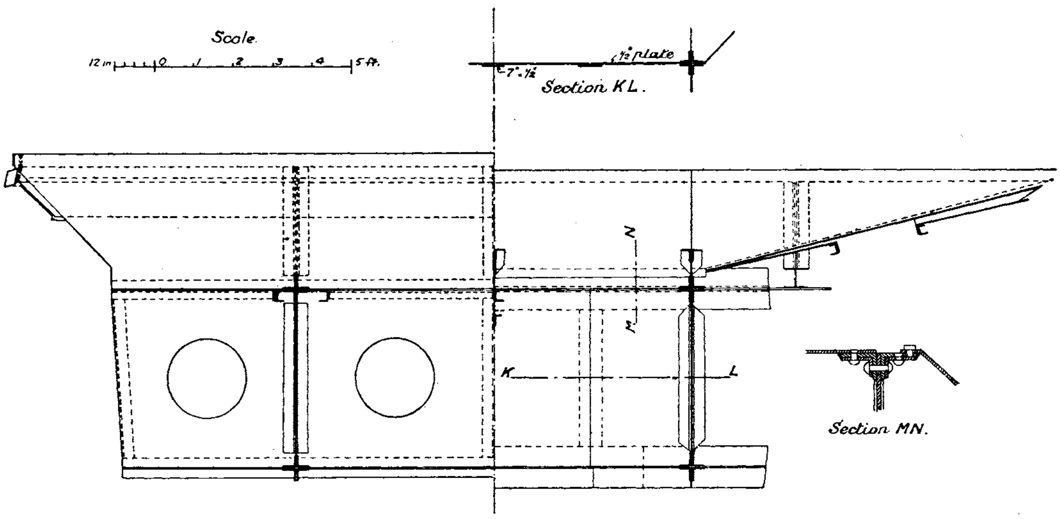


FIG. 213. UNDERGROUND RAILWAY, BOSTON, U.S.A.
The Harbour Shield : Sectional Plan on line $O P$, Fig. 212.

The shield employed is shown in Figs. 211, 212, 213, 214 and 215.[2] Two shields were constructed, that shown being the second one used, the only differences between the two being in some variations in the proportions of the joists and rollers on which the shield travelled, and in an alteration made at the crown of the rear girder, whereby the access to the new concrete arch for keying it up was improved.

The general arrangement of the framework resembles the French models much more closely than did the Tremont Street Shield. The two main

[1] See pages 206, 243 and 261.

[2] The Author is indebted to Mr. Carson for the drawing from which these plates are prepared.

ribs, *a*, *b*, 2 feet deep, with their horizontal ties, *c*, *d*, and their vertical frames, *e*, *e*, *f*, *f*, are so rigidly bound together, not only by the usual gussets, *g*, *g*, but by other plates connecting the vertical and horizontal frames, that they practically form one framing.

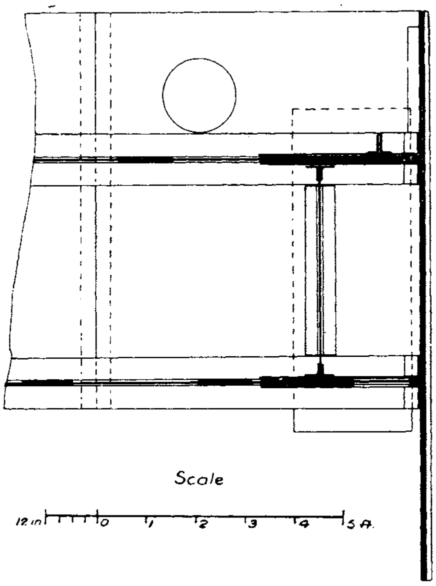


Fig. 214. Underground Railway, Boston, U.S.A.
The Harbour Shield: Section on line *E F*, Fig. 212.

The plates connecting the tie girders, *c* and *d*, form the lower platform of the shield, and the upper platform, *h*, is carried on double channel bars, *j*, *j*, which brace the two ribs.

Great strength is obtained by thus making the body of the shield one solid frame; on the other hand the working area is seriously limited by the number of bracings, and, as will be seen from Fig. 212, the largest apertures in the centre of the shields are 8 feet 2 inches wide, and 4 feet 1½ inches and 3 feet 9 inches high respectively. These formed the working area of the shield, the portions of the framing under the haunches being filled with the hydraulic machinery.

The ribs and frames rested at either end on longitudinal girders, formed of five rolled joists 9 inches deep (6 inches deep in the first shield), having a top flange ½ inch thick and a bottom flange 1 inch thick. The length of these girders was 6 feet 6 inches, which amounted to 50 per cent. of the length of the skin at the crown, a proportion much more reasonable than in most of the roof shields noticed previously.

In the first of the two shields the rear rib, *b*, was made 2 feet deep throughout; in the second it was cut away at the crown (see Fig. 212) to facilitate the keying up of the concrete arch.

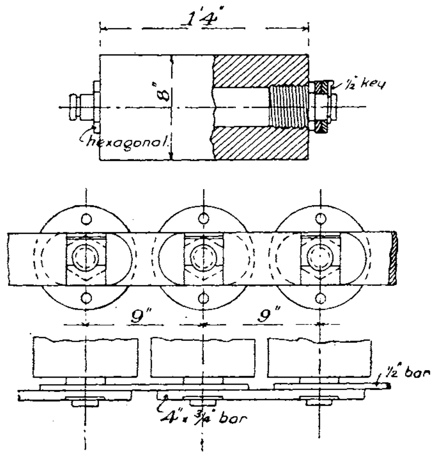
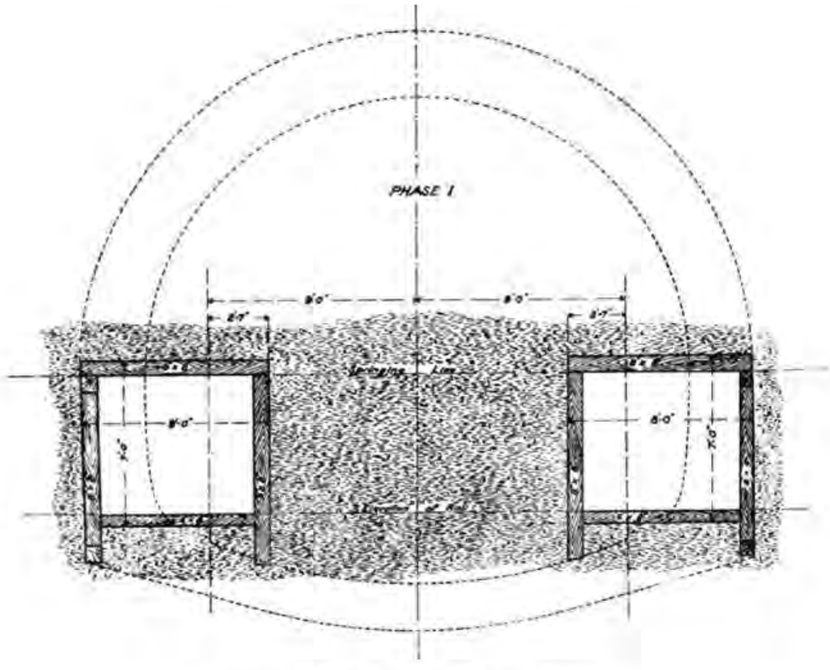


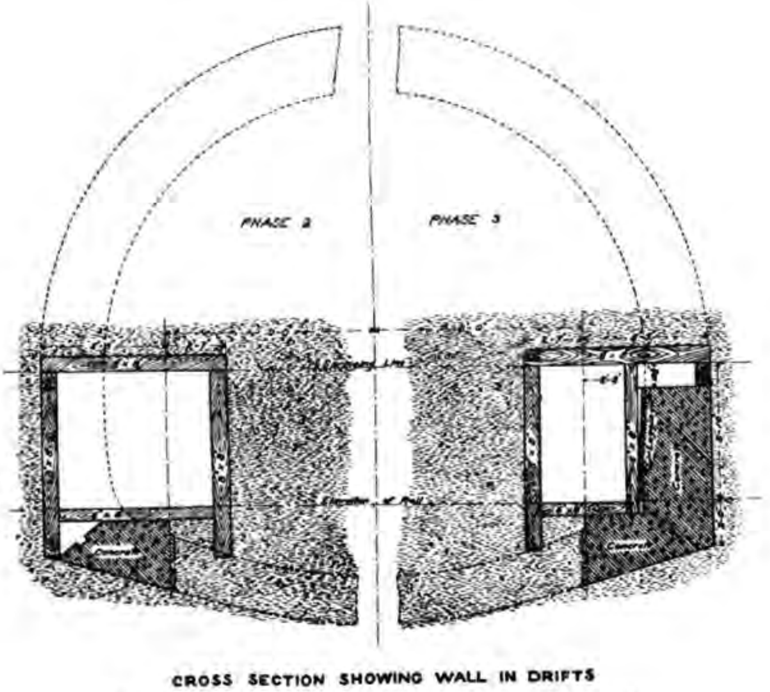
Fig. 215. Underground Railway, Boston, U.S.A.
The Harbour Shield: Details of Rollers.

Sixteen hydraulic jacks, worked by pumps with a capacity of 4,000 pounds per square inch fixed in the shield, were fitted in the shield between the ribs, and bore, not on the centres supporting the concrete arch, but on sixteen lines of cast-iron bars, each 3¼ inches in diameter and 30 inches long, imbedded in the concrete arch, each bar being loosely connected to the preceding one by a sleeve of cast iron (see Fig. 219). Generally the shield moved with a total pressure of 20 to 30 tons.

The shield travelled on rollers (see Figs. 215 and 218) framed together much as are similar rollers in the expansion bearings of a girder bridge, and these again moved on plates flanged to assist in guiding the shield fixed on the top of the concrete



CROSS SECTION SHOWING SIDE DRIFTS



CROSS SECTION SHOWING WALL IN DRIFTS

Fig. 216. Underground Railway, Boston, U.S.A.
The Harbour Tunnel: Method of working.

sidewalls built in advance of the shield. As the shield moved forward, the rearmost roller was removed, and fixed in the front again, eighteen rollers being used on each path.

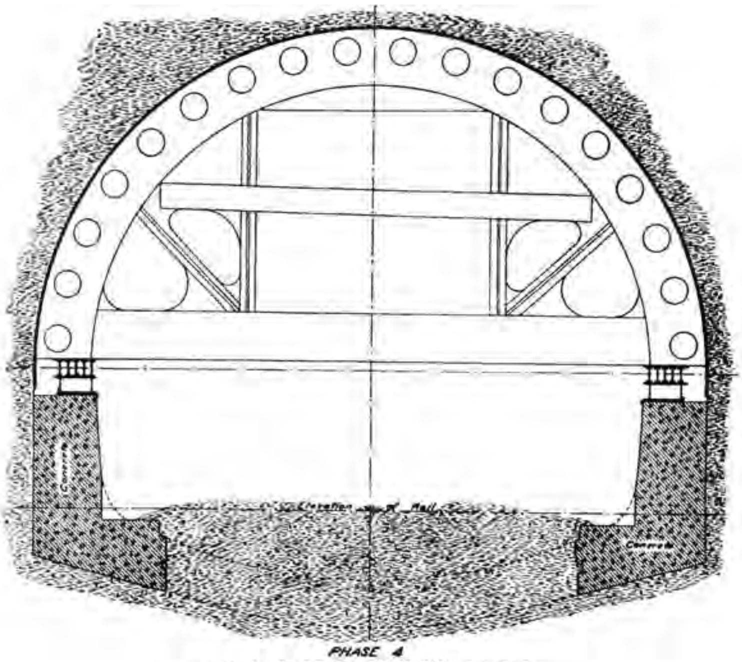
The weight of the shield, exclusive of the hydraulic jacks and pumping gear, was about 52 tons.

The method of working followed closely that adopted in the Tremont Street Tunnel. A shaft was sunk at the East Boston end of the section to be constructed under shield to the required depth of 42 feet, and in it were at once constructed the permanent invert and side walls, which latter were carried up to within 1 foot 4 inches of the springing line of the arch, that being the level of the tracks or plates on which the shield was to run. From the shaft two headings, each 8 feet square, (see Fig. 216) were driven, one for each side wall of the tunnel, in advance of the shield. The timbering of the headings consisted of 8 inch by 8 inch spruce fir headtrees, with similar sidetrees on the inside side of the headings, but having on the outer side the headtrees supported by a longitudinal timber 6 inches by 8 inches, supported on props 8 inches by 8 inches, and 2 feet 6 inches apart, centre to centre, which again rested on a foot block, or rather longitudinal timber, 8 inches square.

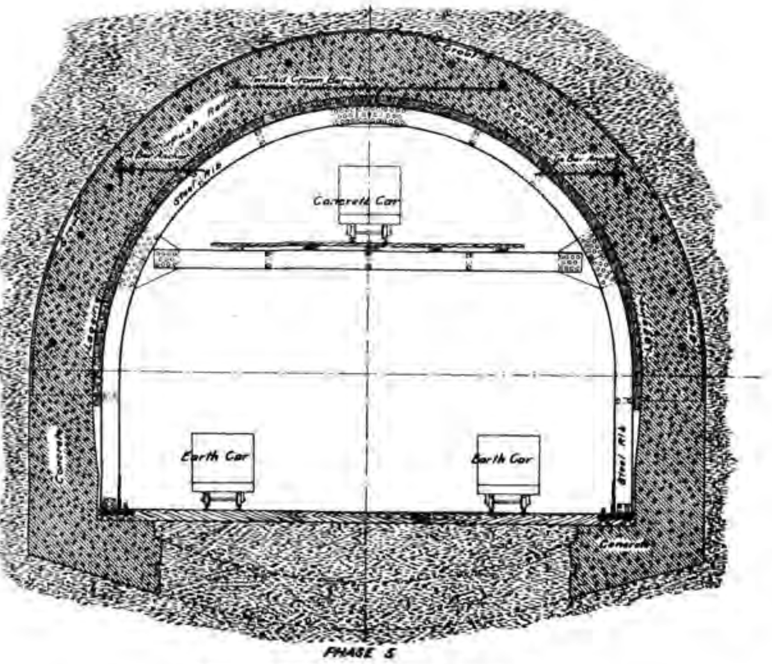
This framing was further strengthened by struts between the inner and outer sidetrees, placed just high enough to clear the concrete invert. The outside face was close-poled between the sidetrees with 2-inch boards. It was found that on exposure to the air the clay swelled in a few hours, often sufficiently to crush the timbering.

The material excavated was removed by hand barrows. When the headings had been driven about 40 or 50 feet, the bottoms (see Fig. 216) were excavated, and the foundations of the walls and a small portion at each end of the invert was put in lengths of from 16 to 20 feet. When the concrete had set the weight of the roof was transferred from the outside sidetrees, by fixing under it, 3 feet from its outer end, a longitudinal timber 6 inches by 8 inches, which was supported on posts 3 feet apart, and wedged in the concrete of the invert. When this was made secure, the outside trees and poling boards were removed, and the concrete wall put in up to within 16 inches of the springing line, the inside face being filled against shuttering fixed to the posts previously put in.

The shield having been erected on the side walls built in the shaft, it was forced into the face of earth, the bulkhead having been removed, and as it advanced in lengths of 2 feet 6 inches at a time, the concrete arch was constructed behind it under the tail of the shield (see Fig. 218), the cast-iron bars for receiving the thrust of the shield rams being built into it. These bars remained, of course, in the arch, and, in addition, a crown bar of twisted steel was left in each length, and temporary tie bars were also placed on each side by which the green concrete was anchored to the centres. The new masonry was supported in centres made of steel 10-inch channel bars and spaced 2 feet 6 inches apart. Logging 4 inches thick was placed on the ribs to hold up the concrete. Timber ribs, similar to the grouting ribs used in English shields in cast-iron lined tunnels, were used to hold the fresh concrete in its place, the thrust of the ribs being taken, however, entirely by the cast-iron rods. The keying up of the arch presented some difficulty. In the first shield built, the back rib, being 2 feet deep at the crown, made the key of the arch almost inaccessible, but the difficulty was got over by using the two uppermost apertures in the web of the rib, which was constructed to admit of

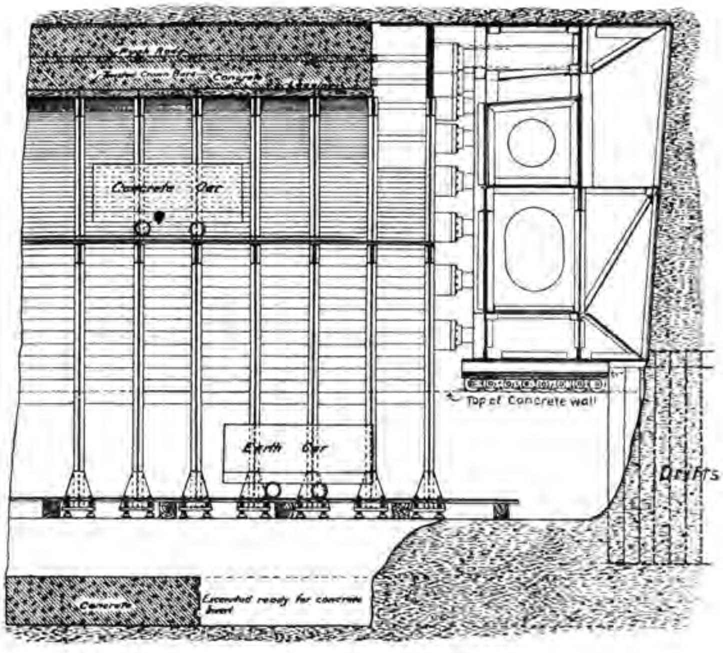


CROSS SECTION SHOWING SHIELD

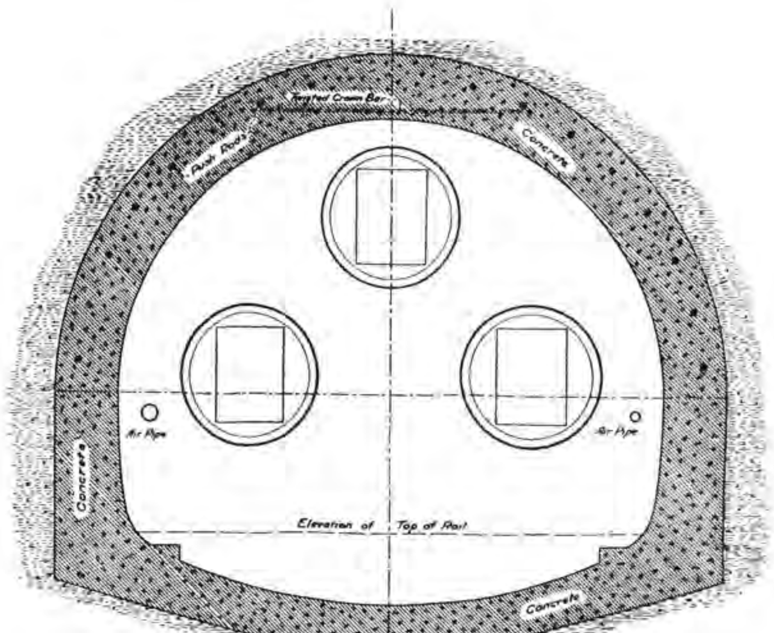


CROSS SECTION SHOWING CENTRE

FIG. 217. UNDERGROUND RAILWAY, BOSTON, U.S.A.
The Harbour Tunnel: Method of Working.



LONGITUDINAL SECTION AT SHIELD



CROSS SECTION SHOWING AIR LOCKS

FIG. 218. UNDERGROUND RAILWAY, BOSTON, U.S.A.
The Harbour Tunnel: Method of Working.

eighteen rams being used, only sixteen, however, being actually fitted. Curved sheet-iron troughs were fitted between these openings and the top of the arch, and concrete fed into these troughs from the front of the rib was pushed by properly-shaped rammers into the crown of the arch to key it up. This difficulty was avoided in the second shield by making the crown of the rear rib, *b* (Fig. 212), very shallow, and so permitting access to the key.

The space left vacant over each new length of the arch ring by the advancement of the tail of the shield was filled with grout composed of two or three parts of sand to one of cement, which was forced by air pressure through a vertical pipe built into the arch for the purpose. In England neat lias lime is always used for grouting up cavities of this character, mainly because it is less likely to set and choke the pipe during the process of filling than is cement, if used neat, and because the proper mixing of cement with a due proportion of sand, which would retard the setting, would occupy too much time and also space.

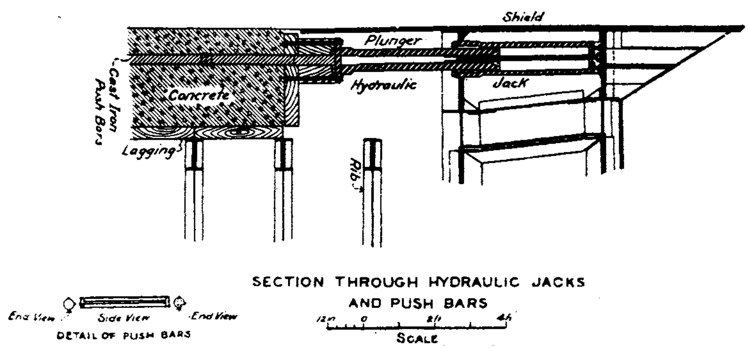


FIG. 219. UNDERGROUND RAILWAY, BOSTON, U.S.A.
The Harbour Shield: Details of Rams and Push Bars.

A sufficient number of centres to allow of each one remaining in position for thirty days were provided.

The character of the concrete, as provided in the specification, was that to each 123 pounds of dry Portland cement there should be 2½ cubic feet of sand and 4 cubic feet of gravel. Roughly this meant about 6 to 1 cement concrete. Crushed stone in place of gravel, and fine crushed stone in place of sand, were also used.

There does not appear to have been any marked shrinkage[1] in the concrete roof, and what little there was was of little importance, due to the fact that the tunnel was for the greater part of its length surrounded by solid clay. But the successful use of cement concrete in the favourable conditions here met with does not establish any ground for preferring it to cast iron as a tunnel lining in material where any risk of a large inrush of water may be possible, nor does it affect the fact that, at present prices, the employment of a cast-iron lining would, in England, by reason of the reduction in the amount of excavation made by its use, work out at about the same price per yard run of tunnel, and would at the same time allow the daily rate of progress to be increased. In the case of a tunnel in water-bearing material, the rapidity with which a cast-iron lining can be erected (and

[1] Observations were taken on experimental beams of concrete 8·9 feet long and 8 inches square. It was found that the shrinkage in twelve weeks amounted to 0·028 per cent. If the concrete were immersed in water, the shrinkage was about 0·009 per cent.

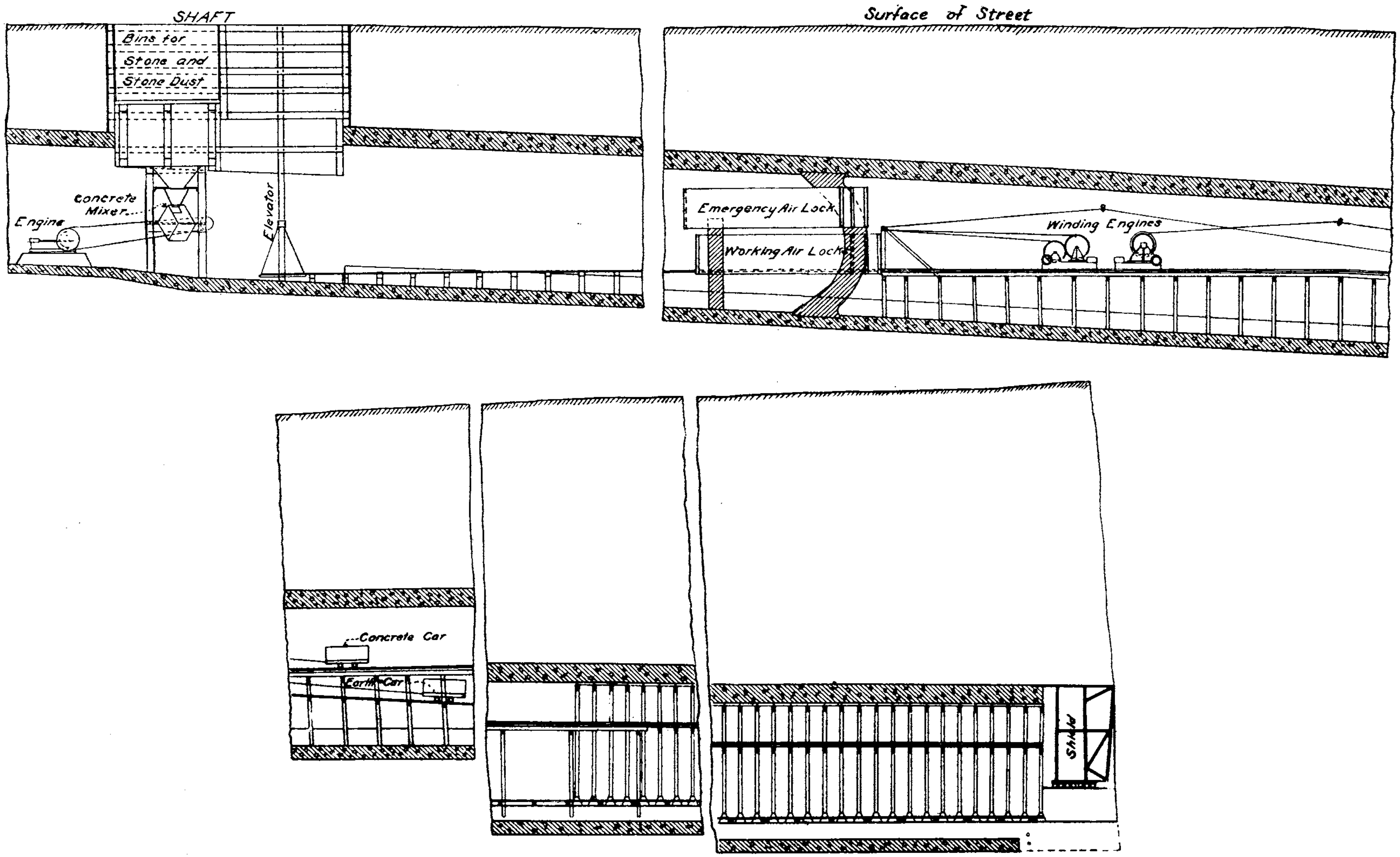


FIG. 220. UNDERGROUND RAILWAY, BOSTON, U.S.A.
The Harbour Tunnel: Longitudinal Sections showing Working Arrangements.

attain its full strength at once), and the ease with which it can, by caulking, be made practically watertight, make it always the preferable material. In the Boston Tunnel Mr. Carson estimates that at the end of thirty days the arch was of only one-half its permanent strength.

The excavation of the dumpling between the side walls was done at the same time as the arch was being built (see Fig. 218). In general the side walls were built about 100 feet in advance of the shield, and the alignment of the tunnel was kept by two parallel lines being run along the headings for these walls. The invert of the tunnel was constructed later, usually in lengths of about 10 feet.

When the shield had advanced some 200 feet, almost entirely in clay with silt and coarse sand at the crown, but little water being met with, a halt was made to allow of air-locks and bulkhead being put in (see Figs. 218, 220 and 221).

Three locks were provided, the two lower ones for working purposes, the upper one as an emergency lock. These locks were 27 feet long and 6 feet in diameter, and were built in a brick bulkhead which differed from those previously described in this book, in being simply a dome - shaped mass 3 feet thick having a versed sine of 6 feet, and strengthened with iron hoops. This dome was keyed into the concrete tunnel lining.

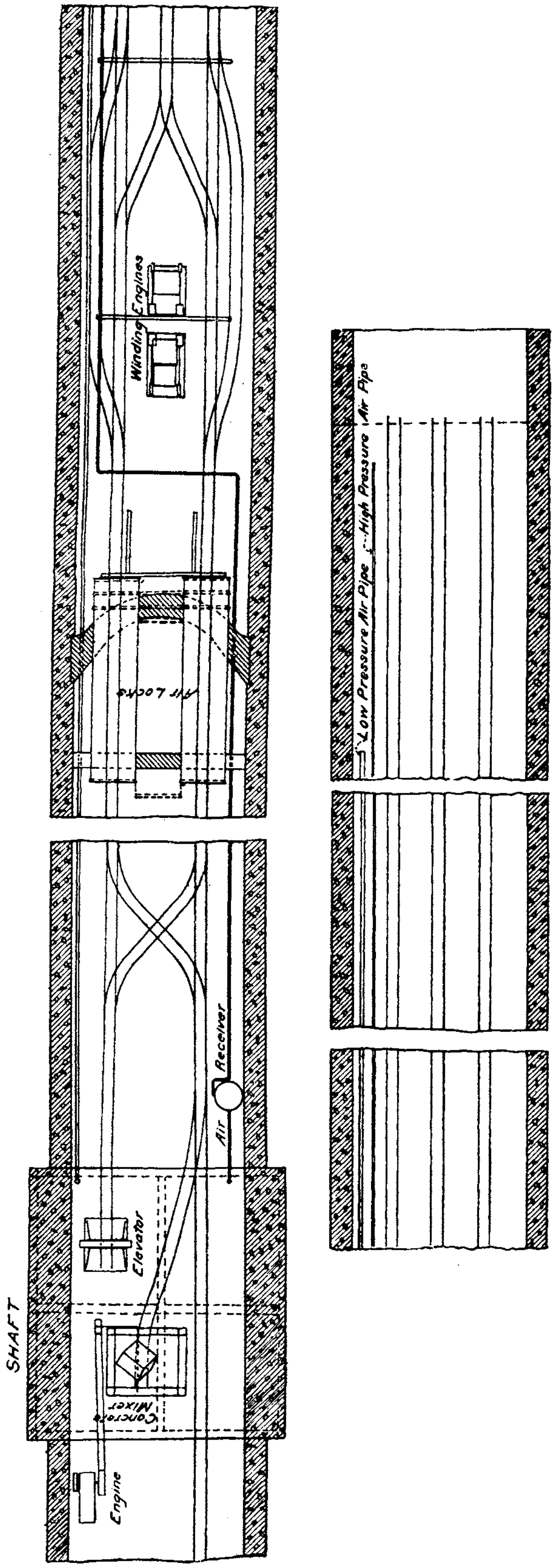


Fig. 221. Underground Railway, Boston, U.S.A.
The Harbour Tunnel: Part Plans showing Working Arrangements.

The working arrangements of the tunnel are shown in Figs. 220, 221, the only feature requiring comment being the provision of an upper track for the conveyance of concrete for the arch. This track was carried on joists fixed on the centres, to which they formed struts, and, when the centres, as they became unnecessary were moved forward, on timber frames.

The quantity of material to be handled amounted to about 22 cubic yards of excavation, and 8 cubic yards of concrete per yard forward. These quantities include the whole of the tunnel from invert to crown.

When work was in regular progress under compressed air, the average weekly advance was about 32 feet, the maximum distance travelled in one week being 45 feet.

The work was on the whole singularly free from accidents, either to the machinery or to the men employed. On two occasions, however, the frames of rolled joists which formed the bases of the shield on each roller path gave way, owing to some irregularities in the levels of the side walls. To make these up to the necessary height to receive the plates on which the rollers travelled, timber joists were laid on them, and these joists crushed under the load and in consequence put such a strain on the rolled joists over the rollers that they crippled and had to be renewed.

The accidents were unimportant, and merely emphasize the fact that the weak point in all roof shields is that all the weight over the whole area of the shield is thrown on a very limited bearing surface, the soundness of the foundations of which depend on conditions outside of the shield itself.

The period occupied in driving the tunnel under the river (which work formed the first section of the East Boston Tunnel) was from January 26, 1901, when the working shaft near Sumner Street, East Boston, was completed, to June 30, 1903, the distance driven under shield being 4,280 feet. This gives an average rate per day of 4·8 feet or about 33 feet per week, a very satisfactory average, considering that the time required for the installation of the air-locks and fittings, and all interruptions such as those necessitated by repairs to the shield, track shiftings and the like are included in the period given above.

The Metropolitan Railway of Paris

Schemes for the construction of an underground railway in Paris, on similar lines to that constructed in London, have during the last forty years been numerous, and have been the subject of many parliamentary inquiries and discussions. It was not, however, until 1898, when the near approach of the great international exhibition of 1900 made improved transit facilities in the city a matter of urgency, that a general scheme of urban lines under powers conferred by the State was approved by the Conseil Municipal of Paris, and a commencement made with the most important part of it, namely the line connecting the Porte de Vincennes in the east with the Porte de Maillot in the Avenue du Bois de Boulogne in the west of Paris. This line (see map, Fig. 222) was opened to traffic in July, 1900, and in the same year the second or northern portion from the Arc de l'Etoile to the Place de la Nation via Batignolles, Montmartre and Menilmontant was commenced, the complete circuit being finished in 1903.

The construction of an urban line of such magnitude (the lines to-day open to public traffic are 16½ miles in length) presents innumerable interesting engineering features,[1] every known method of tunnelling being employed to suit the varied conditions under which the underground works had to be carried out, but only those sections of the line where shields were used are treated of here, and it is somewhat notable that, in spite of the success which had attended the use of shields in the construction of masonry tunnels in Paris in the years immediately preceding the commencement of the work, on the whole so little effective use was made of this method of tunnelling in an undertaking which for most of its length involved the driving of a double-line tunnel under busy thoroughfares where cut-and-cover work was, except in special cases, entirely prohibited.

In the second or northern part of the railway no shields were employed, and in the part first constructed from Vincennes to the Quartier de l'Etoile, out of eleven sections into which the line was divided they were not used at all in four, were tried and abandoned in three, and in four sections only appear to have achieved a certain measure of success.

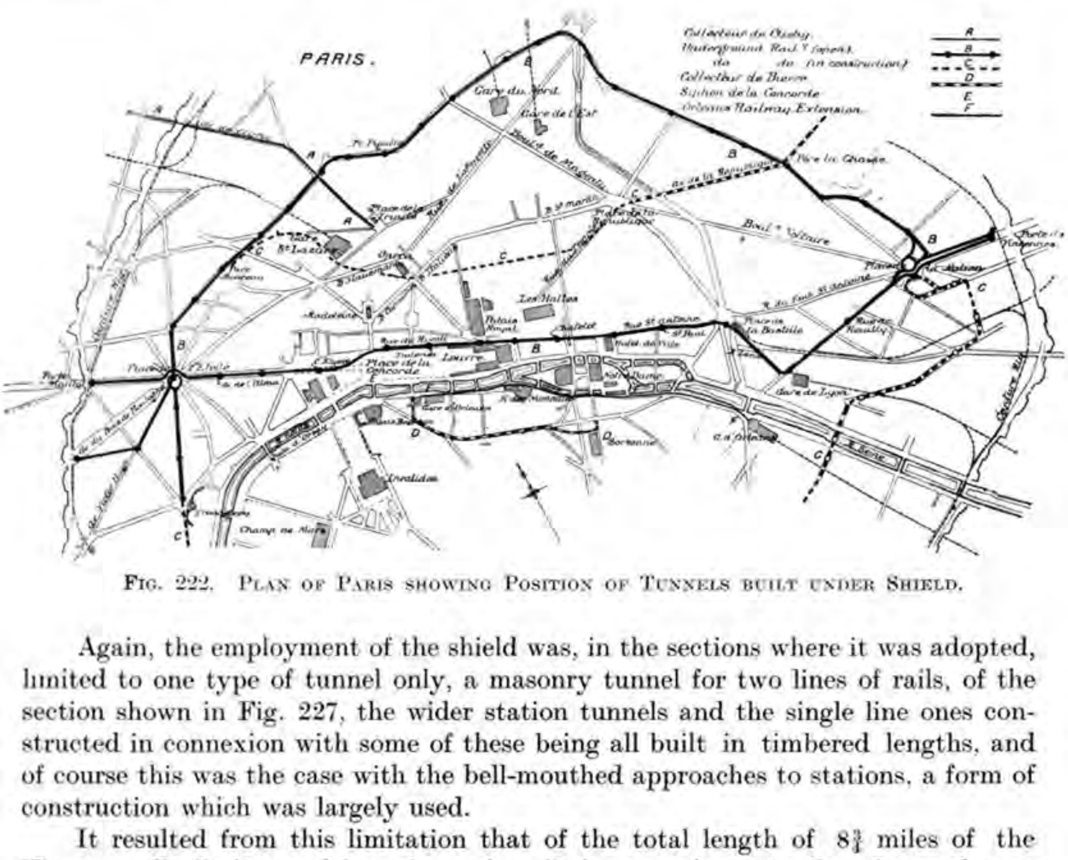


FIG. 222. PLAN OF PARIS SHOWING POSITION OF TUNNELS BUILT UNDER SHIELD.

Again, the employment of the shield was, in the sections where it was adopted, limited to one type of tunnel only, a masonry tunnel for two lines of rails, of the section shown in Fig. 227, the wider station tunnels and the single line ones constructed in connexion with some of these being all built in timbered lengths, and of course this was the case with the bell-mouthed approaches to stations, a form of construction which was largely used.

It resulted from this limitation that of the total length of 8¾ miles of the Vincennes-Etoile line and branches only a little more than 1½ miles of tunnel were constructed under shield,[2] and apparently the results were not too satisfactory, as although the employment of a shield for the construction of the double line tunnels

[1] The only account of the work up to the present which gives a description of the whole of the undertaking is M. Jules Hervieu's *Chemin de Fer Metropolitan du Municipal de Paris*, Paris, 1903, which is the official history of the railway.

[2] See Philippe's *Le Bouclier*, in which considerable space is given to a description of the somewhat unsatisfactory work on this line.

was originally made a condition of the contracts for the various sections of the first or Vincennes-Etoile line, their use in the second or northern line was permissive only, and as a fact shields were not, as stated above, used in that part of the railway at all.

A feature of all the shield work was the return, save in one section, the fourth (in which however the shield method of working was hardly tried, so complete was the failure of the machine used), to the system of the Collecteur de Clichy, in which the first operation was the driving of the shield for the construction of the arch, the building of the side walls being left until the first stage was completed.

This system of working, whatever other inverts it possesses, has the grave demerit in the case of tunnelling through a material of varying character, but nearly always of uneven stiffness, such as made ground broken by old foundations resting on gravel and sand, of requiring that the shield advances on platforms slight in character, built in short lengths, and yielding, as the weight of the shield comes upon them, more or less as the material beneath has more or less consistency.

It is probably to this method of working, and also to the fact that many of the shields employed were constructed with a length of base remarkable even among roof shields for its disproportion to the length over all of the roof, that much of the ill success which attended the use of shields on this railway was due.

As an example of the curiously disproportionate planning of the shields it may be mentioned that one of them had a base only two-ninths of its total length, and two-fifths of its height, while the tail was twice the length of the base. Naturally, when such an engine advanced on an unstable bed, its structural instability and tendency to rock was assisted by the nature of its support, and in consequence the guiding of it became an impossibility.

Of the various shields employed two types only met with some degree of success ; of the first, known as the Champigneul shield, two were employed on the first, one on the eighth, and one was installed but not used on the eleventh section ; of the second type, the Lamarre shield, two were used, one on the sixth and one on the seventh section.

The smallness of the part played by shields in the construction of the Vincennes-Etoile section of the railway is clearly shown in the following table.

TOTAL LENGTH OF LINE, INCLUDING BRANCHES, TO PORTE MAILLOT, AND TO THE TROCADERO $= 8\frac{3}{4}$ MILES ABOUT.

	Section.	Length of Section. Feet.	Length built under Shield. Feet.
1.	Porte de Vincennes to the Rue de Reuilly	5,885	3,854
2.	Rue de Reuilly to the Rue Lacuée	4,380	132
3.	Rue Lacuée to St. Paul	3,734	1,614
4.	St. Paul to the Châtelet	3,803	459
5.	Châtelet to the Tuileries	4,351	—
6.	Tuileries to the Champs Elysées	4,089	295
7.	Champs Elysées to the Avenue de l'Alma	3,825	689
8.	Avenue de l'Alma to the Porte Maillot	4,593	1,309
9.	Avenue de Wagram to the Place Victor Hugo	3,555	—
10.	Place Victor Hugo to the Porte Dauphine	2,444	—
11.	Place de l'Etoile to the Place du Trocadero	5,121	—
	Total length in feet	45,780	8,352

Thus a little over 18 per cent. of the whole length of the line was constructed under shield, and even if the length of the stations which constitute an appreciable part of the whole mileage of an urban railway be deducted from the total length, the proportion of the remainder in which shields were employed was only, assuming the total length of the stations at 8,200 feet, about 22 per cent.[1]

The eleven shields constructed for the railway were distributed as under :—

Section	1.	2	shields, type	Champigneul
,,	2.	1	,, ,,	Baudet Donon & Cie.
,,	3.	2	,, ,,	,, ,, ,, (Dieudonnat)
,,	4.	2	,, ,,	Moranne. (Weber)
,,	6.	1	,, ,,	Baudet Donon & Cie. (Lamarre)
,,	7.	1	,, ,,	,, ,, ,, ,,
,,	8.	1	,, ,,	Champigneul
,,	11.	1	,, ,,	,,

It will be seen that the shields of the Champigneul type, in spite of the complete abandonment of the one erected for work in the eleventh section, nevertheless were employed in building 5,163 feet, or more than five-eighths of the total length of 8,352 feet constructed under shield.

Of the remainder the Lamarre shield was employed in the construction of 689 feet of tunnel, and the Dieudonnat shield in a length of 1,746 feet. This last, however, proved so unsatisfactory that it is not easy to understand how it was employed even over the distance recorded.

Shields of the 1st and 8th Sections of the Paris Metropolitan Railway

The Champigneul shield[2] and the centreing connected therewith is illustrated in Figs. 223, 224, 225, and 226, which, though the details of the work varied somewhat in the different sections, show the general arrangement of all the installations sufficiently well, as the four machines built, three of which were used, came from the same factory, and were practically alike, resembling in general features the Chagnaud Shield of the Collecteur de Clichy.

The shield shown in the figures is the one employed on the Vincennes length of the first section of the railway.

The central framing of the shield consisted of two elliptical girders, *A*, *A*, 6 feet 5 inches apart centre to centre, and measuring 28 feet 3 inches along the major axis, the height from the springing line being 8 feet 9½ inches. At the crown they were 2 feet, and at the springing line 2 feet 7½ inches deep, the webs being $\frac{4}{5}$ inch thick, and the angle irons which formed the flanges 3¼ by 3¼ by ½ inches.

They were braced on the horizontal axis in the usual manner by two girders, *B*, *B*, which in turn were united by nine transoms, *C*, serving as supports to the working platform *D*.

Sixteen plate gussets, *E*, *E*, between them completed the frame, the spacing of these being arranged so that each pair of gussets formed the base of one of the shield rams.

The skin of the shield was $\frac{7}{10}$ inch thick, the tail piece being doubled, or nearly 1½ inches thick. The total length at the crown was 23 feet 2 inches, the forward hood measuring 8 feet 2 inches, and the tail 8 feet 7 inches. At the bottom of the shield the hood extended 4 feet 5 inches in front of the leading girder *B*, and the

[1] There were twenty-five stations, with a platform length of from 75 to 100 metres.

[2] The Author is indebted to M. Legouëz for the drawings of this, and of the Lamarre shield.

tail of the shield, which at the springing level was nearly the same length as at the crown, was then cut back, and at the base only extended 5 feet 6 inches behind the rearmost main girder.

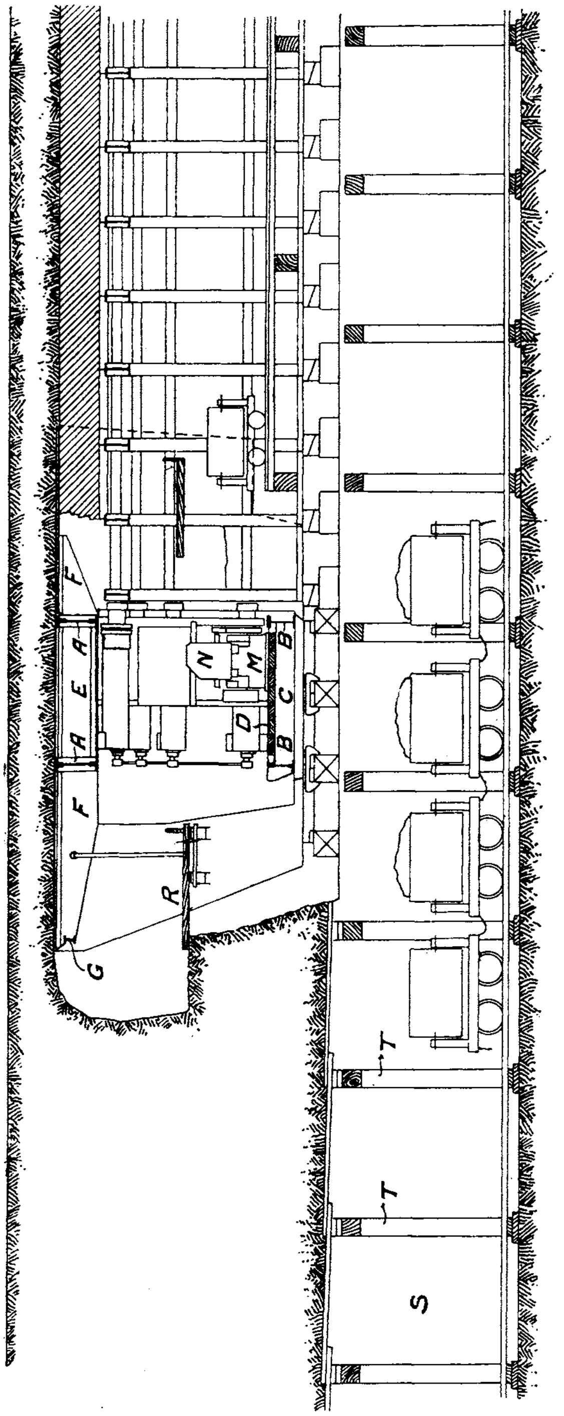


FIG. 223. METROPOLITAN RAILWAY, PARIS.
The Champigneul Shield: Longitudinal Section showing Method of Working.

The base of this shield, therefore, is ·28 of its total length, or well under one-third.

The overhang of the front hood and of the tail were supported by sixteen brackets, *F*, *F*, similar in construction, and aligned with the bracing girders, *E*, *E*, between the main ribs, *A*, *A*, and the hood was stiffened by two channels, *G*, 6 inches by $2\frac{1}{2}$ inches by $2\frac{1}{2}$ inches, rivetted on either side of a plate 6 inches by $\frac{3}{8}$ inch.

In case of necessity the hood could be further extended for the protection of the miners by sliding poling bars between the hood and angle irons fixed for the purpose inside it. When any such protection was actually required, however, the miners usually preferred to pole from the top of the cutting edge in the usual way.

The shield rested, not on rollers moving on a roller path beneath them, but bore, by means of cast-iron shoes, *H*, *H*, on cast-iron rails, *J*, *J*, which were laid on transverse timbers, *K*, *K*. (Fig. 225.)

The rams employed on the shield, eight in number, were similar in character to those of the Orleans railway shield, and had a stroke of 3 feet 4 inches, with a piston diameter of $9\frac{1}{4}$ inches, and the hydraulic pressure was about $1\frac{1}{2}$ tons per square inch.

M. Philippe states [1] that the shield was sometimes driven with a total pressure

[1] *Le Bouclier*, p. 141.

on the eight rams of 144 tons, and that the total pressure never exceeded 500 tons ; this gives a maximum pressure on the skin of the shield—assuming that the pressure

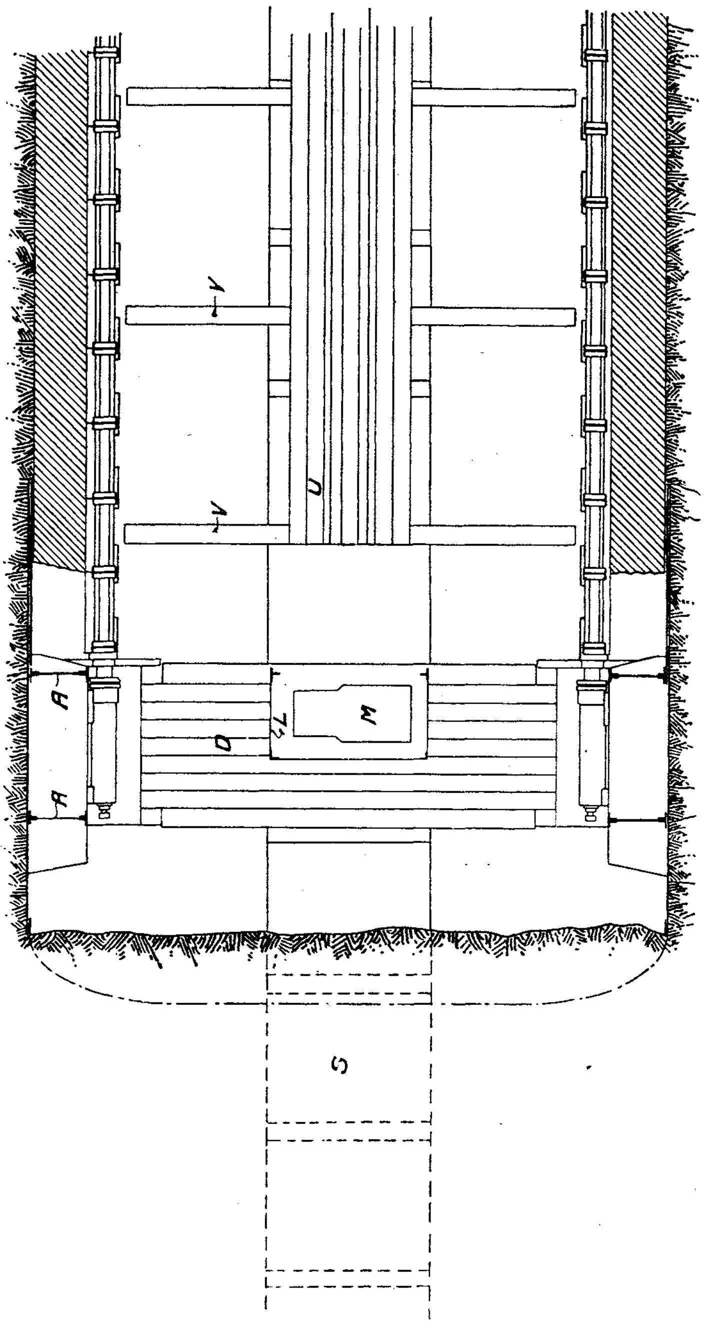


Fig. 224. Metropolitan Railway, Paris.
The Champigneul Shield : Sectional Plan showing Method of Construction.

is uniform on the sides and top, which is hardly likely—of about 1,500 pounds per square foot.

The position of the machinery for driving the shield is shown in outline in

Fig. 225. This was contained in a housing *L*, built in the centre of the shield, the pump *M*, a three-throw one, being fixed on the main platform of the shield, and the electric motor *N* for driving it, and the valves *P* for working the rams, being disposed on a second stage above.

The push of the shield occupied about twenty minutes in favourable circumstances.

The shield used on the Vincennes length of the first section had slung from its front hood a working platform *R*, to enable the miners to get at the upper part of the face, and from the tail of the shield was also hung a removable platform for the masons working on the upper part of the arch. These arrangements were altered somewhat in the shield used on the eighth section, when the miners at the face did not work at two levels under the hood of the shield, but got the excavation by cutting gullets in the face, leaving between them walls of material which were cut away

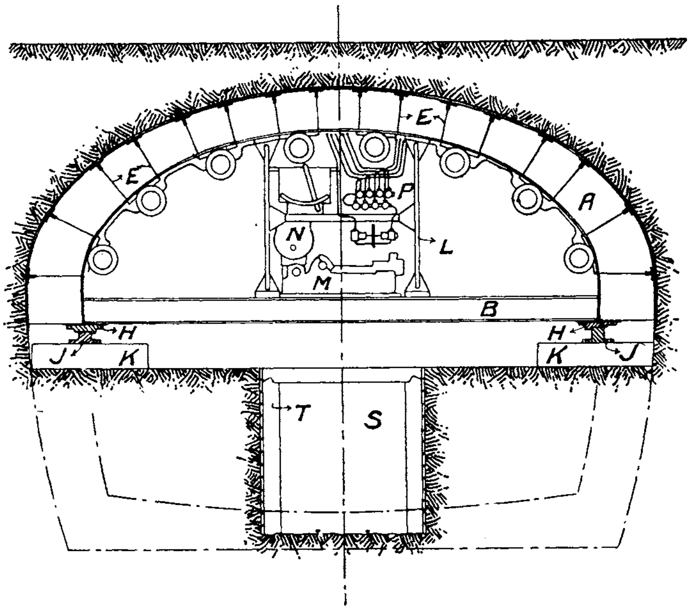


Fig. 225. Metropolitan Railway, Paris.
The Champigneul Shield: Cross Section.

by the cutting edge of the shield in its advance. The platform for the masons also, instead of being suspended from the roof as shown in the figure of the Vincennes shield, was fixed on a light frame attached to the shield itself, and rolling on the siding rails behind it, an arrangement saving some labour as the platform thus advanced with the shield.

The method of working adopted with the Vincennes shield, and with that employed on the eighth section of the railway, differed in one respect from the arrangements previously employed with similar machines in earlier works. While the shield of the Collecteur de Clichy (extra-muros) [1] advanced without any previous heading having been driven, its base resting on the tracks laid on the undisturbed material beneath—and on the other hand, the shield of the Orleans Railway extension [2] moved on brick footwalls previously built in headings driven in advance for

[1] See Fig. 185. [2] See Fig. 200.

the purpose, the central dumpling being the last part of the excavation to be removed—there was in the case of the shield now under consideration a central heading driven in advance of and below the shield, which was otherwise operated, as was the Clichy shield, moving on tracks laid direct on the soil beneath.

This heading became, as the advance of the shield removed the ground above it, a trench or cutting accommodating a line of rails for a service of skips, into which the spoil from the front of the shield could be shovelled directly, thus facilitating the work, not merely by the easy removal of the spoil, but by the greater freedom of movement the arrangement afforded on the working platform of the shield, and by the upper line of rails being always available for the bringing up of material for the masons, etc.

The use of this heading is open to the objection that in its construction the soil on each side of it on which the shield moves may be disturbed, and so produce settlements when the weight of the shield comes on it.

The cost of the excavation of the heading is of course greater than if the same material were removed behind the shield, but from the fact that although with the Reuilly shield on the second part of the first section of the line, a trench of similar dimensions to the heading shown in the drawings was made behind the shield to accommodate a line of rails, the heading was adopted with the two other sections which were commenced later, it would seem that the extra cost of the heading was repaid by the economy effected by its means in working the shield.

With the Vincennes shield this heading, *S*, *S*, Figs. 223, 224 and 225, was generally kept about 250 to 300 feet in advance of the shield, its section being in section nearly a square, with sides 6 feet 6 inches long.

The material passed through was not water-bearing, but consisting as it did of made ground and soft sand for the most part, with some marl, it was necessary to timber the heading; the frames, *T*, *T*, being set about 7 feet apart, and the top and sides close-poled. As the shield advanced the roof poling was removed, but the headtrees were left to strut the trench so formed.

The driving of the shield differed in no respect from the same process in similar shields already described, save that by the provision of the central trench all the spoil from the face was loaded directly into skips below, instead of being cast on the platform of the shield.

The line of rails for supplying materials to the masons, etc., instead of being laid on the floor of the upper half of the tunnel, was laid on a planked platform, (Figs. 224 and 226), supported on transverse beams, *V*, *V*, resting on blocks at their ends. These beams were long enough to reach across the full width of the tunnel, so that when required the removal of most of the soil yet remaining after the shield had passed could be effected without interfering with the working of the line of rails above.

The masonry arch of the tunnel was built under the protection of the tail of the shield, as with the Orleans railway shield, without the use of any temporary timber roof polings, a space of about 2 or 3 inches being left between the arch and the skin, which space was afterwards filled very imperfectly with mortar, the centres employed being the usual iron plate and angle iron ones, spaced 3 feet 4 inches apart, and thirty in number.

They were made in two pieces, the joint at the crown being formed by angle irons rivetted to the webs, and forming a flat end to each half rib, which were fastened together by bolts. By the use of packings in this joint considerable adjustment of the centres was possible.

The centres were spaced by cast-iron distance pieces, which served to distribute the thrust of the shield rams, and in some cases they were supported by props resting on footblocks on the ground beneath.

They appear very light for the work, each half weighing only about 650 pounds; they, however, appear to have served satisfactorily, and kept their shape fairly well.

The laggings were 3½ inches thick, and as usual made in lengths to suit the spacing of the centres.

The daily rate of progress of the shields where the advance heading was used was nearly 13 feet on the Vincennes section and about 12 feet on the eleventh section,

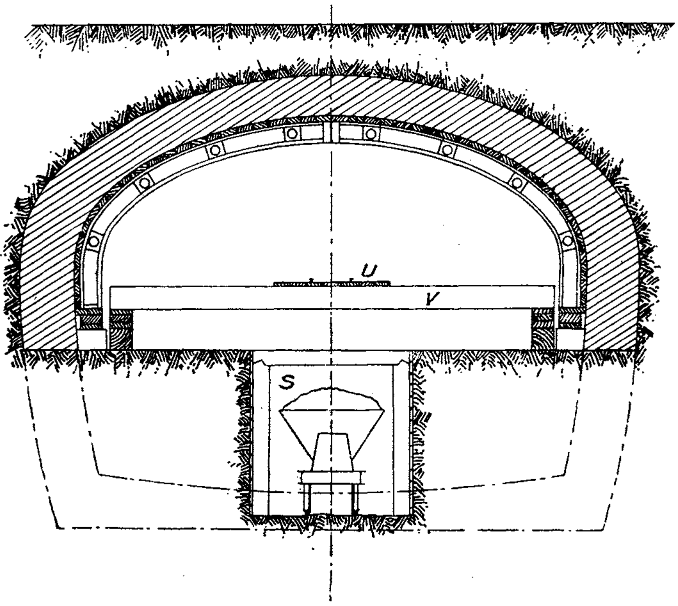


FIG. 226. METROPOLITAN RAILWAY, PARIS.
The Champigneul Shield: Cross Section of Tunnel with Centres.

while the Reuilly shield without a heading made about 11 feet 6 inches, the days when the shield was actually advancing only being counted.

If, however, the whole time from the start of the shield to its final stoppage be taken, the figures are as follows: Vincennes shield, 11 feet; shield of the eighth section, 8 feet 9 inches; and the Reuilly shield, 10 feet.

The fact that the figures so obtained are only about 16 per cent. less than those obtained by counting only the working days speaks well for the general soundness of the shields' construction. In shield work of this character a waste of time for repairs equal to 25 per cent. of the whole period occupied would not be excessive.[1]

But the rate of advance, however satisfactory, of these shields hardly compensates for their failure to perform the special work they were expected to do,

[1] The shield of the Collecteur de Clichy is said by M. Philippe, *Le Bouclier*, page 15, to have travelled "normally" 14 feet 9 inches per day. Its average from start to finish was only 8 feet 9 inches, a waste of 40 per cent. in time thus being shown.

and which was the reason for stipulating for their use when the contracts for the railway were drawn up. They completely justified the expectations of their designers in so far as their use enabled the work to be done on the lengths on which they were employed far more rapidly, perhaps ten times more rapidly, than it could have been done with ordinary timbered lengths, with the same limited number of openings for the ingress and egress of material. But as means for tunnelling under the streets without disturbance of the city traffic, they must be considered as failures. Indeed, when the second portion of the Metropolitan Railway was commenced, the use of shields for tunnel work was made optional, which, as the work was carried out under the supervision of the same engineers as the first section, would appear conclusive as to the lack of confidence felt in this method of working.

The Champigneul shields were the most satisfactory of those employed, but even they, if M. Philippe's notes are exact, left much to be desired. The space left between the masonry arch and the skin of the shield was, as far as possible, filled with mortar, "but often as the shield advanced, the ground above fell in and packing became impossible: the disturbance of the soil being transmitted to the pavement broke it up."[1] (Injections of cement mortar were tried with only moderate success.) "This movement of the ground damaged the roadway very much; with an average cover of about 6 feet over the shield, serious hollows were produced, however small the amount of settlement of the ground, and its consequent drawing with the shield: settlements of over 30 inches were not uncommon, with the result that the traffic of the street above was limited to the sides clear of the area where the shield was. This was written of the shields of the first section; of the shield of the eighth section the same author[2] says that with it the disturbance of the street above was greater and occurred oftener, a condition in part due, however, to the yielding character of the ground on which the shield rails were laid.

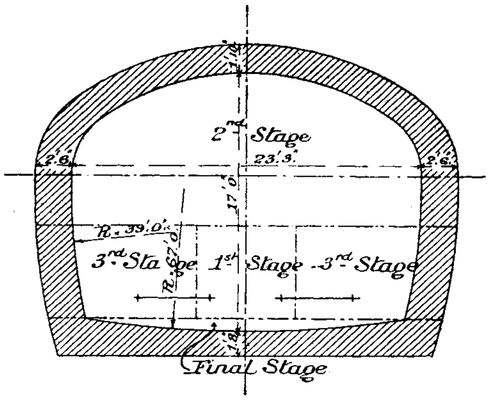


FIG. 227. METROPOLITAN RAILWAY, PARIS.
The Champigneul Shield: Diagram showing the Successive Stages of the Work.

It is not easy to indicate a remedy for the movement of the ground above the shield. Given the conditions, which obtained alike in the Orleans Extension Railway and in the one now under consideration, the roadway must necessarily be broken up. Even were it possible to avoid leaving any open space round the finished masonry, which, however, probably had but little to do with the more serious dislocations of the roadway, the movement of a machine measuring 28 feet across and 23 feet in length, and propelled by rams having a total thrust of hundreds of tons, must necessarily break up the mere shell of cover (only 2 or 3 feet thick) above it. It is probable that the shield in such circumstances draws with it a certain thickness of the superincumbent load, and as the amount of the material so disturbed will vary almost with every yard of advance, undulations of the road above will naturally be produced, and at the same time cavities be formed above

[1] Philippe, *Le Bouclier*, p. 154.
[2] Ibid. p. 165.

the shield, and this will probably always be the case when the cover to the shield falls below a certain thickness, which will vary with the nature of the soil.

When the portion of the arch under the shield was complete, the remainder of the excavation was taken out in sections, as shown in Fig. 227. The third and fourth stages were removed in lengths, of about 6 feet long generally, but not always, several of these lengths being constructed at the same time with a 12-foot distance, or two lengths, between them, and the side walls built under the arch already erected. The bottom was taken out and the invert built also in short lengths, this forming the fourth and last stage of the tunnel construction. For the practical reason of not interfering more with the shield work than was necessary, this last operation was frequently delayed until the other work was nearly completed.

Shields of the 6th and 7th Sections of the Paris Metropolitan Railway

In the sixth and seventh sections of the railway shields of the type Lamarre were employed, and though these can hardly be considered to have achieved the moderate success obtained by the Champigneul shields, some part of their failure may fairly be laid to the deficiencies of the centering against which, as in all tunnels carried out by this method, they bore, and the rigidity of which forms an important element in the success of the system.

The shield (see Figs. 228, 229) in its general outline resembled those already described, but its length over all at the top was only 19 feet 9 inches as against 23 feet 2 inches, the width and height over the springing line being of course the same. The distance apart of the main frames supporting the roof was 6 feet 9 inches, and to that extent the base was more proportionate to the length of the shield.

On the other hand, however, the balance of the shield was not so satisfactory by reason of its bearing surfaces in the transverse direction being, not as in the other roof shields previously described, at the sides of the frame, but under the lower member of the framework, which, by its construction, could not support the extreme edges of the shield at each side.

Figs. 228 and 229 show in outline the longitudinal and cross sections of the Lamarre shield. As already stated, the general outline of the shield is similar to other roof shields ; in one respect, however, a considerable variation is made. The roof shields considered hitherto all had frames consisting essentially of two elliptical girders, with horizontal tie-girders beneath them to prevent any spreading of the shield. In the Lamarre shields, the frame of the shield consists of two frames or diaphragms, *A*, *B*, in which holes are cut to give access to the face, and this arrangement undoubtedly gives greater rigidity than the other and more usual one, and must prevent any tendency in the machine to settle at the crown.

On the other hand the working area of the shield, instead of being clear of all encumbrances (except the machinery) between the overhead ribs and the working platform, is cramped by the introduction of the vertical members of the frames to an extent which can be easily seen by comparing Figs. 225 and 229.

These frames *A*, *B* do not extend the full width of the shield, the outside skin being extended beyond them and supported by gussets, *C*, *C*, fixed upon a plate *D*, which forms the base of the shield between the frames, and is turned up to meet the skin. The advantage of this is not obvious, and the disadvantage is unfortunately very definite. Had the lower member of the frames *A*, *B* been extended to the base of the shield at *V*, *V*, the shield could have been supported for its full width. As constructed the outside supports of the shield are necessarily 5 feet within the extreme limits of the skin, an arrangement which must diminish the stability, and in consequence increase the difficulty of handling the shield.

The framing of the shield is stiffened by bracings, *F*, *F*, and gussets, *G*, *G*, and as a structure the machine is satisfactory. But the accessory arrangements leave much to be desired. The shield is supported on sliding plates, *H*, *H*, which rest on transverse sleepers, *J*, *J*, and in addition to the fact that, by the construction of the frames *B*, *B* the shield has thus considerable lateral overhang, the arrangement does not admit of the same accuracy of alignment as is possible when the whole shield travels on only two rails or bearing surfaces.

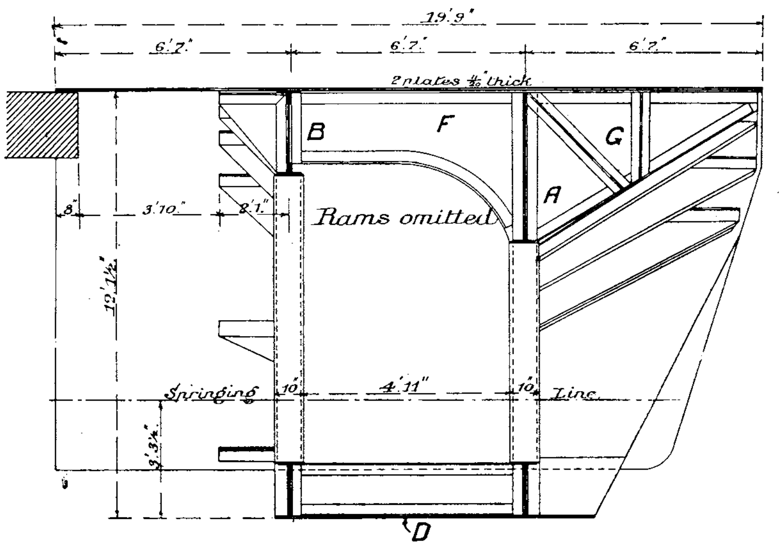


Fig. 228. Metropolitan Railway, Paris.
The Lamarre Shield: Longitudinal Section.

A further defect is to be found in the arrangement whereby the nine rams *K*, *K*, are arranged, so that four of them are fixed between the horizontal members of the frames *A*, *B*, a position where they can be of little use, and which compels the encumbering of the working area behind the shield with corresponding horizontal frames to the centres, and wedge pieces between them, since following the usual French practice the shield rams bear on the centres supporting the arch behind.

It will be seen from Fig. 229 that while six of the rams are fitted between the webs of the frames *A* and *B*, and, as in English practice, are framed between them, the three upper ones bear only on the front frame *A*, and pass beneath the back frame *B*, to which they are hung by stirrups, *L*, *L*.

The rams are $7\frac{1}{2}$ inches in diameter, with a stroke of 3 feet 4 inches. They are single-acting, being drawn back after the stroke by a small parallel ram, and could be worked up to a pressure of 110 tons each.

The electric pumps and other machinery are placed indifferently in the centre or side compartments.

The skeleton centres supporting the masonry were twenty in number, and were of timber. Each was supported at the centre by a king post 9 inches by 3 inches, bearing on a horizontal cross timber, on the ends of which the centres rested, wedges being driven under them to permit of their adjustment. Between the centres, and in the line of the rams, were nine distance pieces, also of wood, 8 inches square. The use of timber centering and framing proved very unsatisfactory ; every push of

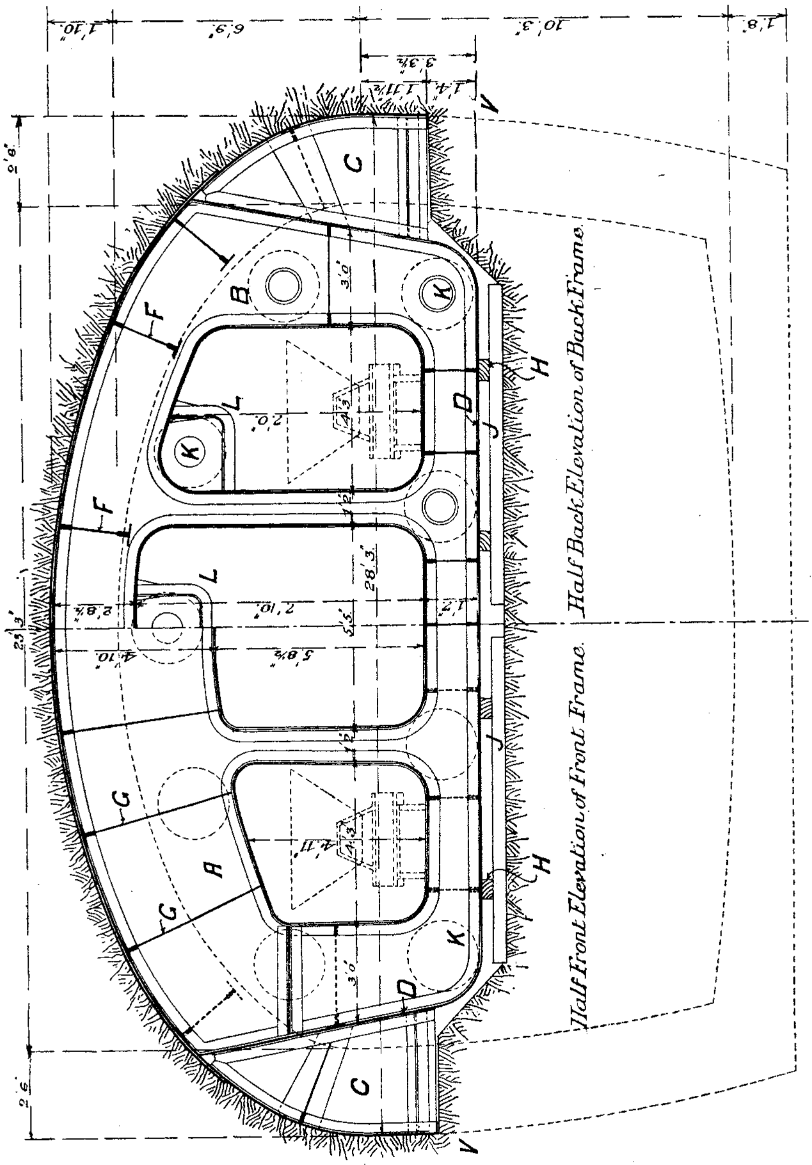


FIG. 229. METROPOLITAN RAILWAY, PARIS.
The Lamarre Shield : Cross Section.

the shield was to a greater or less extent reduced in value owing to the yielding of the timber work on which it bore, and the ill effects of such yielding on the guidance of the shield were accentuated by the method of supporting the shield in sliding plates bearing on cross sleepers in and about the central part of the shield base instead of on two defined tracks at the sides.

The design of the shield, which necessitated a solid base beneath the central portion, precluded the use of an advance heading like that which proved so useful in Sections 1 and 8, and the excavation for the lower half of the tunnel was done after the arch was finished. For some distance in Section 6 water was met with, and a small timbered heading about 5 feet high by 4 feet wide was driven ahead to a pump in the Place de la Concorde. When the soil was fairly drained the side walls were put in by underpinning, and the invert in successive widths.

The daily advance was with both shields from 5 feet 6 inches to 6 feet 6 inches per day.

Little that is favourable can be said of the Lamarre shield ; it was difficult to guide, it was slow, it did not provide a satisfactory working area either for the miners or masons, the centres were unsatisfactory, and the movement of the surface of the ground above was considerable ; but this last feature may, however be said to be common to most of the shields employed in shallow tunnels.

Shields of the 2nd and 3rd Sections of the Paris Metropolitan Railway

These shields were of the type known as Dieudonnat, from the contractor who employed them. They resembled, in construction, the Lamarre shield [1] without the vertical members in the frames, and it must be said of them that they possessed the faults of that machine in an exaggerated degree. The base was only 22 per cent. of the length of the roof, no less than 44 per cent. of which composed the tail behind. As the height of the shield was two and a half times the length of the base, the driving of the shield on a uniform gradient would probably have been in any case almost an impossibility, but the use of timber centres and framing behind, which in the case of the Lamarre shield gave so much trouble, was an additional handicap, and every movement of the shield caused dislocations in the ground above and in the masonry behind.

Of the three Dieudonnat shields built, one was abandoned after travelling 132 feet, another accomplished 538 feet, and the third 1,076 feet.

Shields of the 4th Section of the Paris Metropolitan Railway

These shields,[2] known by the name Weber, from the contractor who employed them, resembled the Dieudonnat shields in their construction. They were designed with the object of constructing the tunnel in mass concrete, and for the purpose were constructed with two sets of rams, the one for pushing against iron centres erected behind, and the other for compressing at the same time the concrete last filled in.

The process proved a complete failure, and was abandoned after a short trial, both shields finishing their course in what may almost be described as open trench, for the superincumbent material was removed for a width of about 14 feet in the centre of the shields, leaving these to perform the work of holding up the material on the haunches only. Behind the shields the centres were erected, and roof poling put in in the haunches to allow of concreting in the ordinary manner later.

The aggregate distance travelled by the two shields was only 459 feet, and for the greater portion of this length they were practically useless in that it was necessary to open out a trench above, and so to create an interference with the traffic above which it is the especial function of such machines to render unnecessary.

[1] For a sketch of the Dieudonnat shield, see Philippe's *Le Bouclier*, pp. 166 and 167.
[2] For a sketch of the Weber shield see Philippe's *Le Bouclier*, pp. 186, 187.

TUNNEL SHIELDS

General Remarks, Paris Metropolitan Railway

The part played by the shields throughout the work cannot be considered satisfactory. It is true that the rate of progress obtained with even the least efficient of these machines was considerably greater than could have been made by the "cut-and-cover" process with the same amount of interruption of the street traffic above; but these shields failed in supporting the roadway above them, not merely in comparison with the circular shields used in London (which for the most part have worked at a greater depth below the surface), but as compared with the Chagnaud roof shield used in making the Collecteur de Clichy "extra muros" in similar conditions in Paris, while if compared with the Tremont Street shield, used in identical conditions in Boston, U.S.A., their performances appear still more unsatisfactory.

A comparison of the Clichy shield with the Champigneul shield shows that whereas the length of the base under which the rollers on which it moved were placed on the former amounted to 60 per cent. of the total length of the hood, the length of bearing of the latter was less than one-third (29 per cent.) of the total length at the crown, and this difference in the proportions of the machines goes far towards explaining the results obtained by the two machines. The shield with the narrower base must, in the nature of things, be more difficult to push forward under a superincumbent mass of earth, heavy enough to effect it, and not thick enough to have much effect as an arch supporting the roadway, than one which is built with a base so proportioned to the whole area of the roof that any extra pressure at the back or front of the latter will be resisted by the weight on the area immediately over the base. This necessary condition for the stability of a shield appears obvious, but all the shields employed on the Paris Metropolitan were built with an insufficient length of base.

Compared with the Tremont Street shield, the Paris Metropolitan shields have bases but little shorter in relation to their total length, but it must be remembered that they in every case travelled in a temporary track laid on the floor of the excavation and therefore liable to variation of level with every change in the material met with, and with every error made in the laying of the track. The Tremont Street shield, on the other hand, was driven on previously built side walls in which were built steel joists laid to the required gradient. The shields' tracks were therefore practically immovable, and consequently one contributory cause of the Paris shields' failure was absent.

But in comparing the two systems it must be remembered that the average cover over the Paris shields was perhaps about one-half that over the Tremont shield, and it may fairly be questioned whether, given the conditions of the Paris shields, the Tremont shield would have done any better than them.[1]

[1] For a description of a shield recently used in a later extension of the Paris Metropolitan Railway see next chapter.

Chapter X

RECENT TUNNELLING WORK CARRIED OUT WITH A SHIELD OR WITH COMPRESSED AIR

IN addition to the undertakings referred to in chapters IV, V, and VII, the Greathead shield has since been almost continuously at work since 1895 in London, in one or other of the numerous "tube" railways which the last ten years have seen projected.

The full list of these undertakings is given below, the mileage in each case being that given in the Act or Acts of Parliament authorizing the construction of the railway :—

	Miles.
City and South London	8·25
Waterloo and City	1·5
Central London	6·25
Baker Street and Waterloo	5·4
Charing Cross, Euston and Hampstead	8·1
City and Brixton	4·0
Edgware and Hampstead	6·0
Great Northern, Piccadilly, and Brompton	7·1
Metropolitan District Deep Level	4·9
North-west London	3·7
Great Northern and City	3·5
Watford and Edgware	6·2
West Metropolitan	2·3

In such of these railways as are already commenced (1905) the system of construction does not vary save in details from that described in chapter IV, the uniformity being due to the fact that the nature of the material to be dealt with is practically the same in every case, namely London Clay.

Other works in which a shield is employed, which are now in course of construction, are the Rotherhithe Tunnel, London; the Dee Tunnel, near Aberdeen; the Paris Metropolitan extension; the Hilsea Tunnel, Portsmouth; and the recently completed Brackenagh Tunnel, near Dublin.

The Rotherhithe Tunnel [1]

This tunnel, work on which has only recently been commenced, will be the largest and most important work of its kind in England, and abroad the tunnel under the harbour at Boston, U.S.A., alone [2] equals it in magnitude.

That tunnel, which, however, was not built in one piece, the shield employed being of the roof or carapace type, was constructed in concrete under shield and compressed air for a distance in all of 5,140 feet, and has a sectional area (outside) of 600 square feet, while the Rotherhithe tunnel will be constructed of cast iron with a circular shield and compressed air for a length of 3,689 feet, and will have a sectional area (outside) of 707 square feet.

Its external diameter will be 30 feet, a size [3] hitherto only reached by some short lengths of railway tunnels constructed in London Clay.

Fig. 230 shows the position of the tunnel and its approaches, and a longitudinal section, from which it will be seen that it is in close proximity to Brunel's Thames tunnel,[4] now a railway tunnel, and, like it, is intended to link up the populous districts on either side of the Thames, wheeled traffic between which at present must cross the river either by the Tower Bridge, 1½ miles west of the northern entrance to the proposed tunnel near Stepney Junction, or by the Blackwall tunnel, the same distance as the crow flies to the east of the same point.

These crossings are, however, owing to the curving of the river and the lie of the streets, distant 1 mile 7 furlongs and 5 miles respectively from the main entrance to the Surrey Commercial Docks, situated close to the southern end of the tunnel.

The tunnel has, therefore, been undertaken by the London County Council as a work of metropolitan importance, and will, it is expected, be completed in from five to six years' time.

The estimated cost of the work, including land and compensation, is about £2,200,000, of which £1,400,000 is for the engineering works.

In its general lines the design follows that of the Blackwall tunnel,[5] built by the same authority.

The total length of the tunnel and its approaches is 6,883 feet or 1·30 miles.

Commencing at the north end, the distance to the most northerly shaft in Broad Street is 1,705 feet, of which 1,090 feet is open approach and 615 feet cut-and-cover work. From the shaft in Broad Street to the most southerly one at Clarence Street, Rotherhithe, the tunnel is a cast-iron one and will be made with a shield, and probably compressed air will be necessary throughout the entire length of 3,689 feet.

It is believed that the clays and marls known to underlie the surface sands and gravel will be above the crown of the tunnel for almost the entire length to be constructed in iron.

These upper beds are water-bearing, and as, so far as is known, the clay beds are not of great thickness, the sand and gravel below them being in places con-

[1] The author is indebted to Maurice Fitzmaurice, C.M.G., Chief Engineer of the London County Council, and to Messrs. Price & Reeves, Contractors for the work, for permission to publish some drawings of this work.

[2] See page 312.

[3] See page 68. Some Station Tunnels of the City and South London Railway are 30 feet in diameter.

[4] See page 2. [5] See p. 180 et seq.

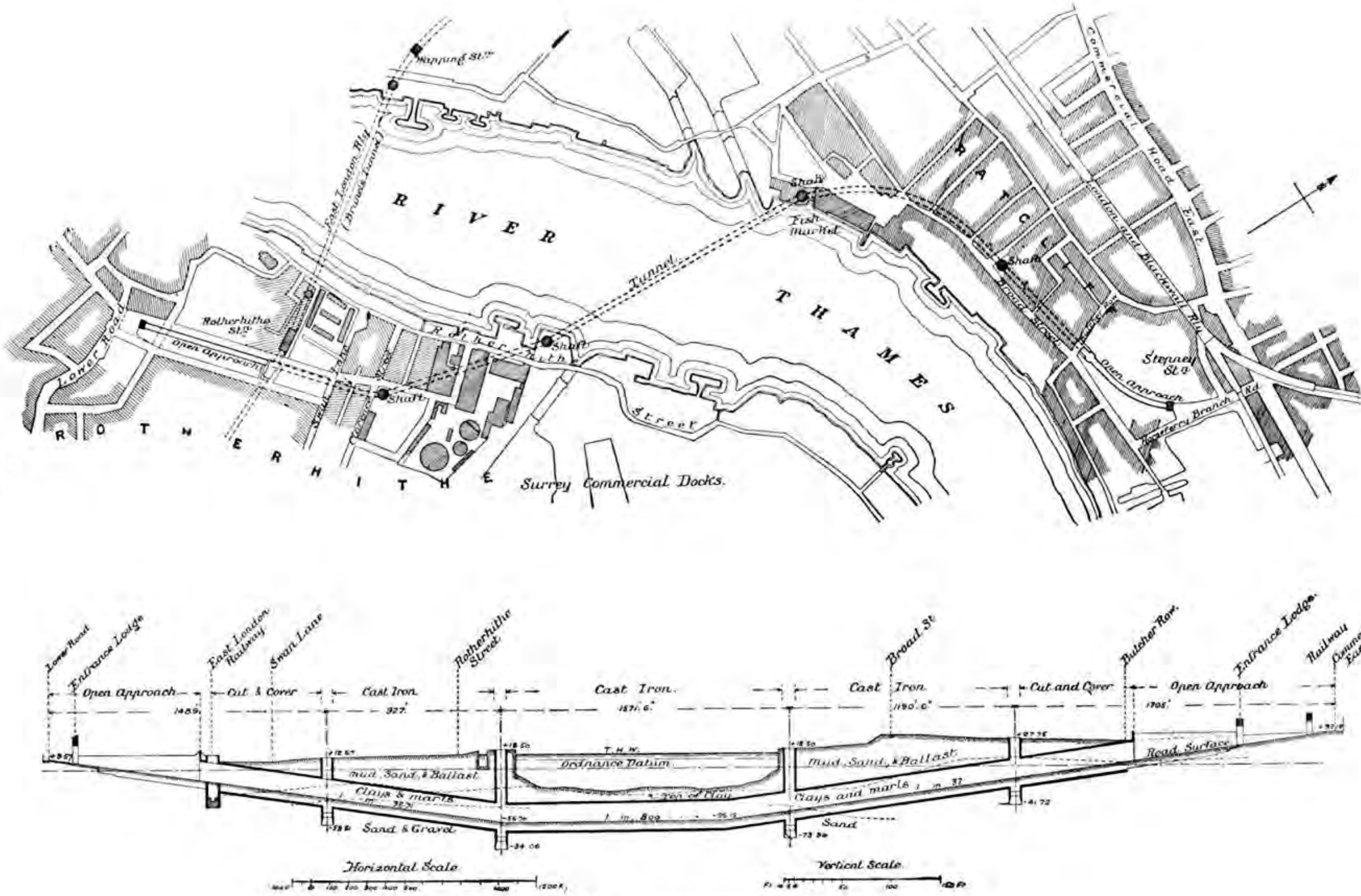


FIG. 230. ROTHERHITHE TUNNEL, LONDON.
General Plan and Section.

siderably above the invert of the tunnel, it is likely that much of the shield work will have to be done with a closed face.

The portion of the tunnel under the river has a cover of not less than 10 feet, and generally a little more. From the results of trial dredgings it is expected that

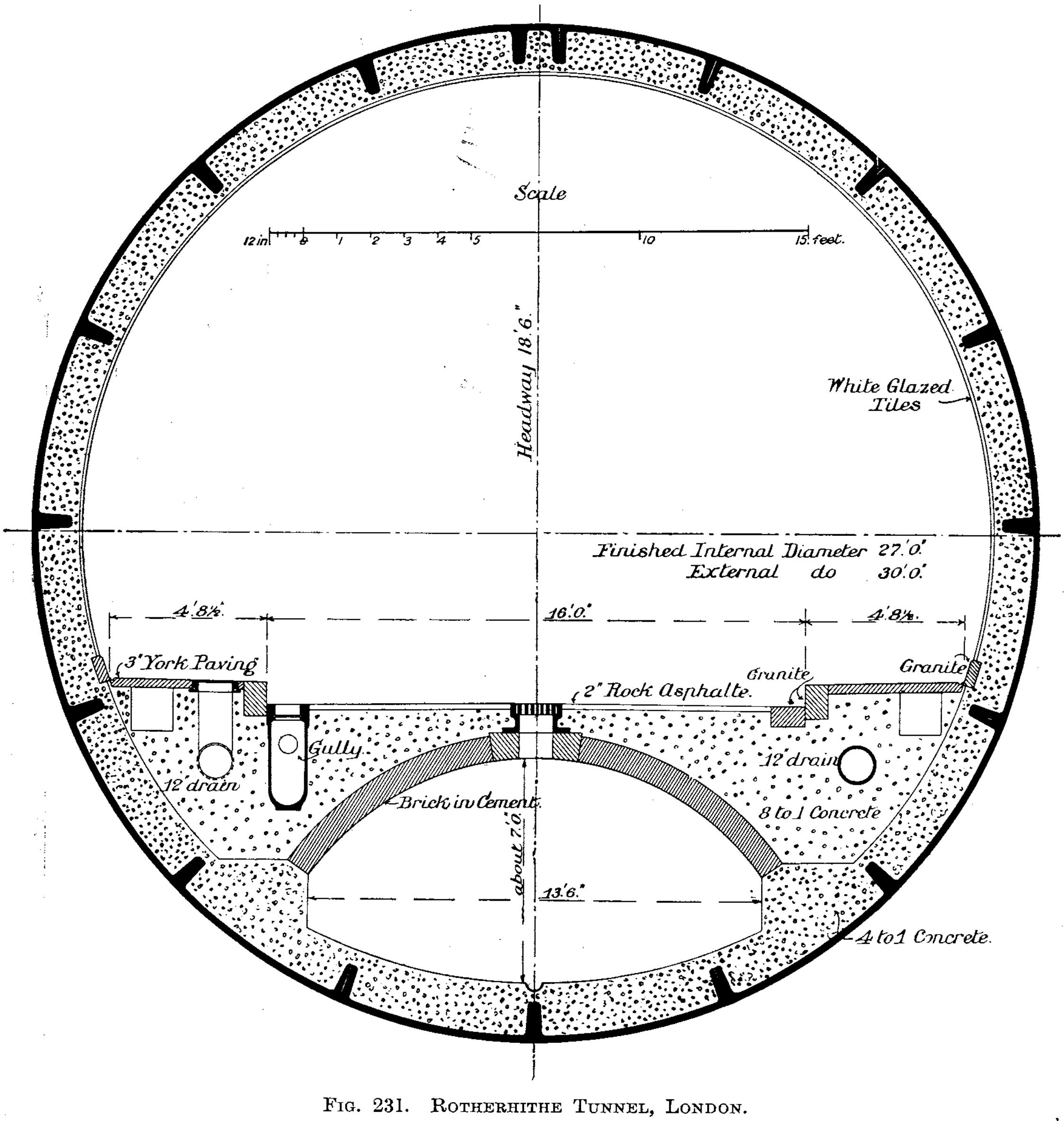


FIG. 231. ROTHERHITHE TUNNEL, LONDON.
Cross Section showing proposed arrangement of Headway.

there will be a few feet of clay or marl above the crown of the tunnel for the greater part of the length under the river.

The invert of the tunnel at the lowest point is 77 feet 8 inches below Trinity highwater mark, so that the air pressure employed is not likely to be more than 30 to 35 pounds per square inch.[1]

[1] For the conditions of work in compressed air of the contract, see page 43.

On the south side of the river the distance from the end of the cast-iron lined tunnel to the southern extremity of the approach works is 1,489 feet, of which 832 feet is open approach and 657 feet cut-and-cover work.

The roadway when made will have gradients of 1 in 37 and 1 in 36·71 on the north and south respectively, a gradient of 1 in 800 being given under the river to assist in draining the tunnel. The width of the roadway will be 16 feet, with two footways 4 feet 8 inches wide. The headway is to be 18 feet 6 inches at the centre, and 15 feet 9 inches at the kerbs (Fig. 231).

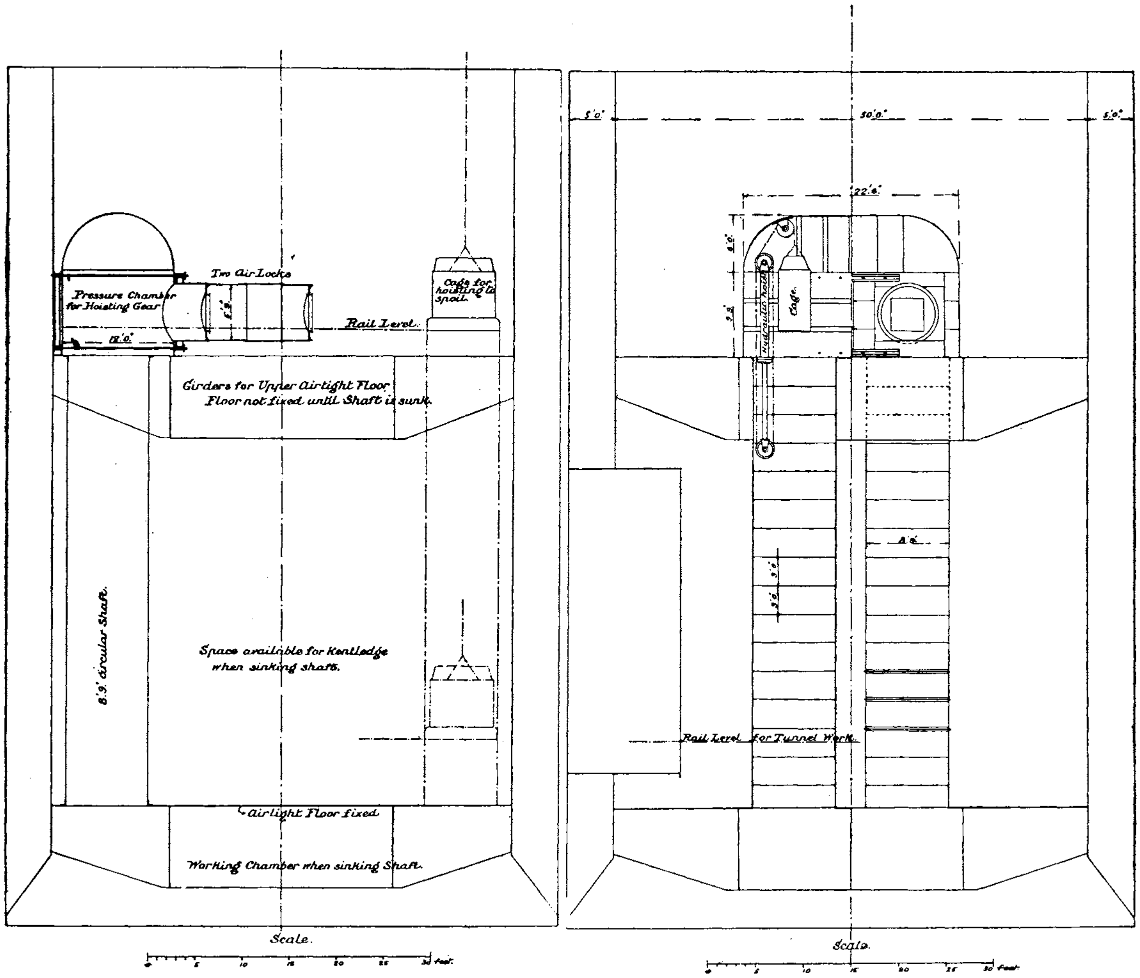


FIG. 232. ROTHERHITHE TUNNEL, LONDON.
Sections of Shaft, showing arrangement of Air-locks.

Stairways will be placed in all the four shafts.

At present [1] the sinking of the shaft on the north bank of the river near the fish market is in progress, and it is from this shaft that the tunnelling operations will commence.

The steel caissons for these shafts resemble those of the Blackwall and Greenwich tunnels,[2] and the method of sinking them is the same as at the latter work,

[1] April, 1905.   [2] See Figs. 152, 153 and 112.

a second or lower air-tight floor being provided. The arrangements of the air-locks in the shaft are on a different plan, however, and are shown in Figs. 232, 233, 234 and 235.

Figs. 232 and 233 show the locks and working shafts as arranged during the sinking of the caissons, the lower air-tight floor and the girders for the upper one being in position.

The work of excavation is carried on under pressure in the space below the lower floor, on which two circular shafts 8 feet 9 inches in diameter are fixed, terminating in a chamber or "bonnet" resting on the upper floor girders. This

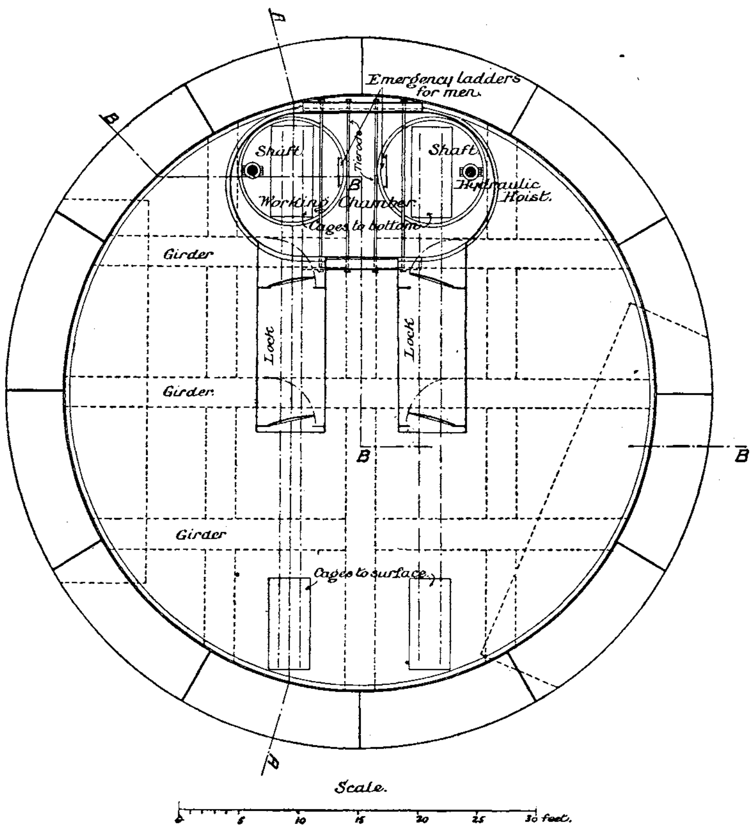


FIG. 233. ROTHERHITHE TUNNEL, LONDON.
Horizontal Section through Air-locks and Bonnet.

upper chamber has circular ends and roof, and measures 22 feet 6 inches by 12 feet, thus affording ample roof for the working of the cages, which are fitted in the working shafts, and are worked by hydraulic hoists.

From this chamber access to the outer air is gained through two horizontal locks, 14 feet 6 inches long and 5 feet 9 inches in diameter, and the skips of material brought up the shafts from the bottom of the caisson are taken through them to cages, in which they are lifted clear of the caisson in progress of erection above and around them.

This arrangement gives much more facility for rapid handling of the spoil than the lock used at Greenwich and Blackwall (figured on page 202), which had a working capacity of only eight to ten skips per hour, while the extra expense of a large "bonnet" over the cost of two smaller ones, one to each shaft, will doubt-

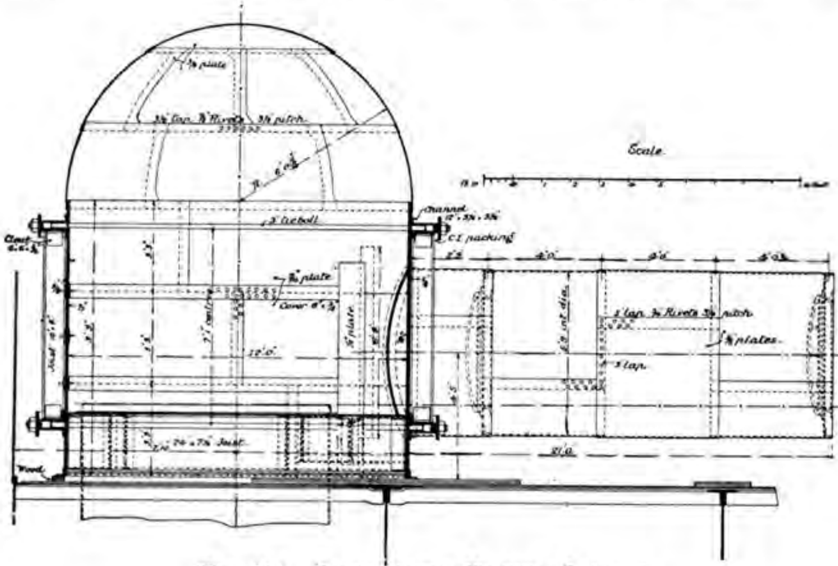


FIG. 234. ROTHERHITHE TUNNEL, LONDON.
Air-locks and Bonnet. Section on line *A A* (Fig. 233).

less be repaid by the increased ease of working due to the increased floor area.

Ladders for use on an emergency are provided in each shaft.

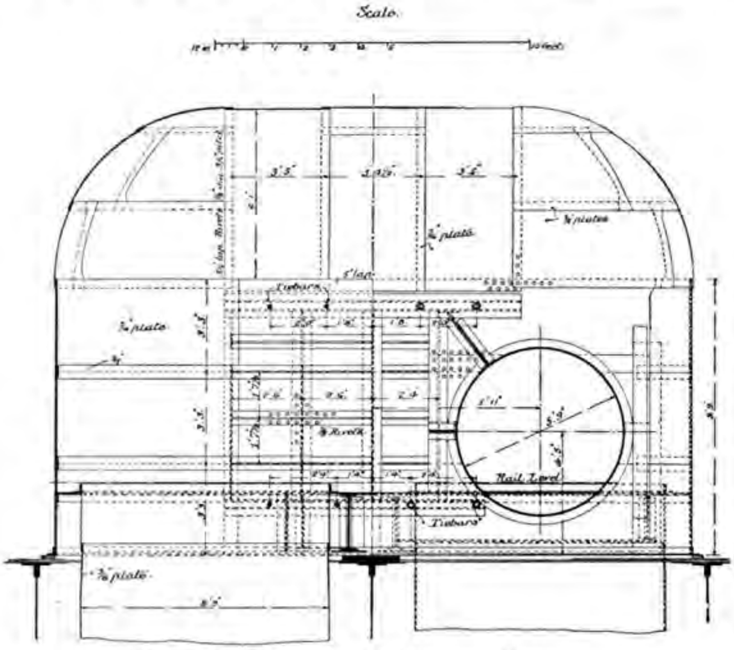


FIG. 235. ROTHERHITHE TUNNEL, LONDON.
Air-locks and Bonnet. Section on line *B B* (Fig. 233).

When the caissons are sunk to the required depth, the air pressure will be taken off, and the working shafts between the upper and lower floors removed, the cylinders composing them being subsequently utilized for the horizontal locks in the tunnel bulkhead.

When the shield is erected in the caisson at the tunnel level, the upper floor

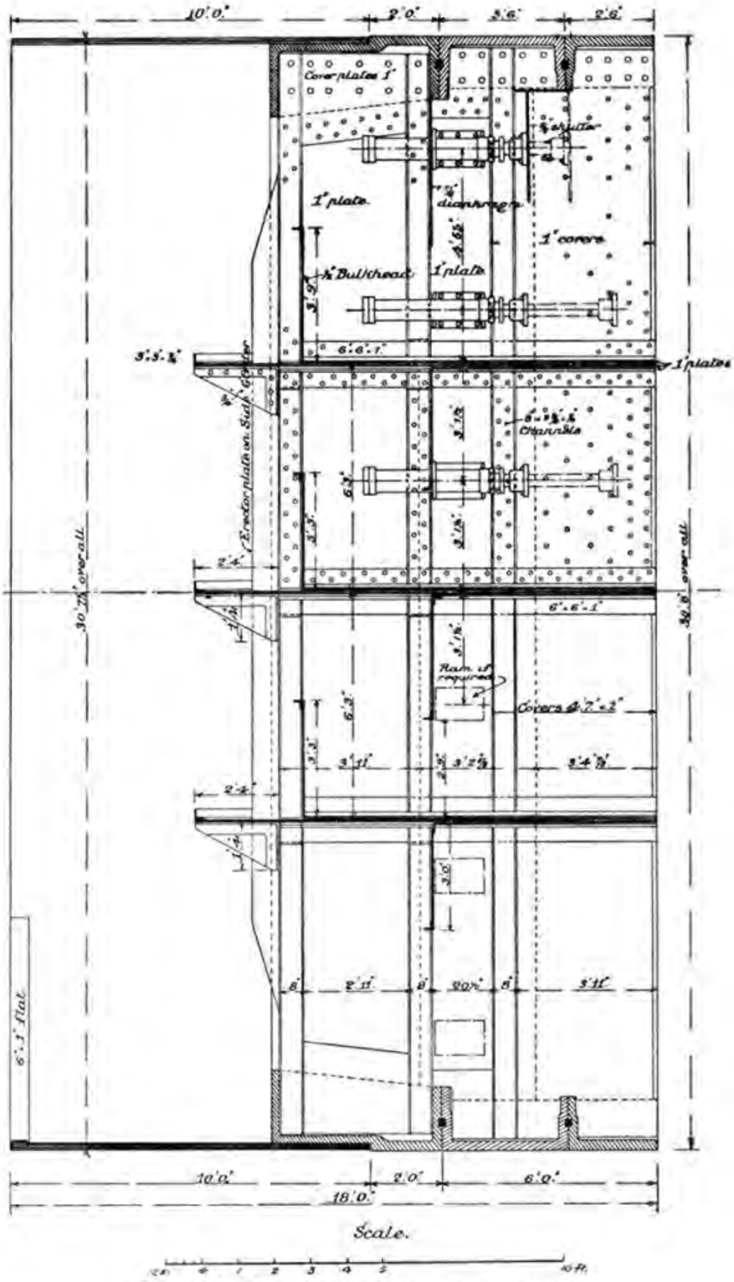


FIG. 236. ROTHERHITHE TUNNEL, LONDON.
The Shield: Longitudinal Section.

will be closed and air pressure again employed for starting the tunnel by the removal of the "plug" in the caisson.

Work will be continued by means of the locks and bonnet on the upper floor until the tunnel is sufficiently advanced to permit of the erection in it of a bulkhead with horizontal locks, when the caisson will be cleared of all the upper temporary fittings and left clear for the hoisting of material from the bottom by means of

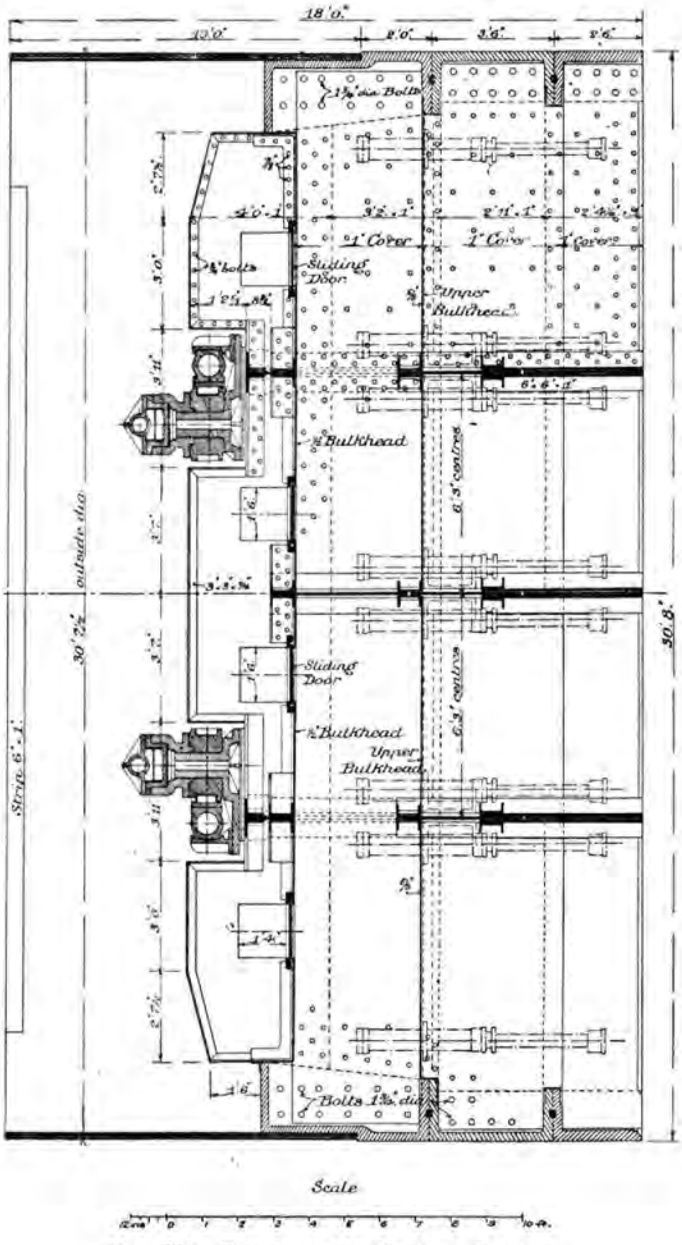


FIG. 237. ROTHERHITHE TUNNEL, LONDON.
The Shield: Horizontal Section.

the cages at first working between the top floor and the top of the caisson, as shown in dotted lines in Fig. 232.

The cast-iron lining of the tunnel is shown in Figs. 35, 36, 37 and 231, and but for its exceptional strength, due to the size of the tunnel, and its situation in waterlogged material of varying density, does not differ from the pattern employed elsewhere.

For a considerable distance on the north side of the river the tunnel is laid out on a curve of 800 feet radius, and the cast-iron lining along this portion will

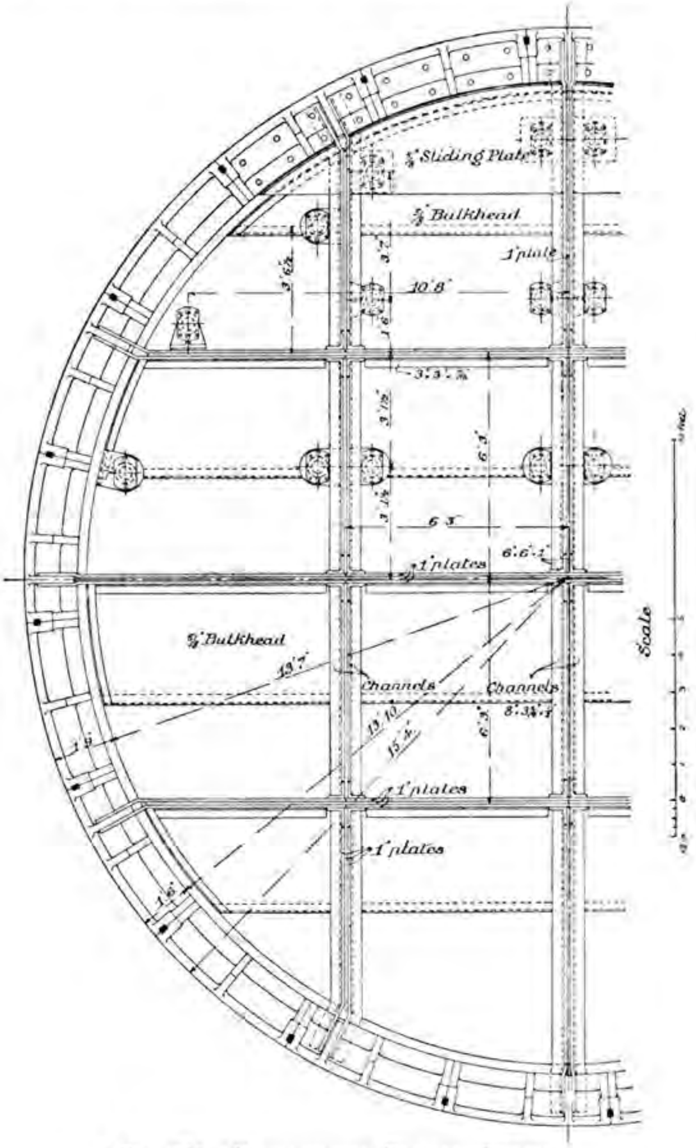


FIG. 238. ROTHERHITHE TUNNEL, LONDON.
The Shield: Half Front Elevation.

be built in special tapered rings, the difference in the width of the 20-inch rings employed being ¾ inch in the diameter of the tunnel.

It is stated in the specification of works that a special shield will be required for this portion of the tunnel. The contractors anticipate, however, that the shield they have designed for the straight portions of the work will do equally well for the curved length. As the length of the shield is only three-fifths the diameter of the tunnel, and considerable play, some 2 inches, is provided between the outside of the cast-iron lining and the tail of the shield, this opinion will probably be justified by results, unless the character of the material met with be very bad.

This shield is shown in Figs. 236, 237, 238 and 239, and presents some variation

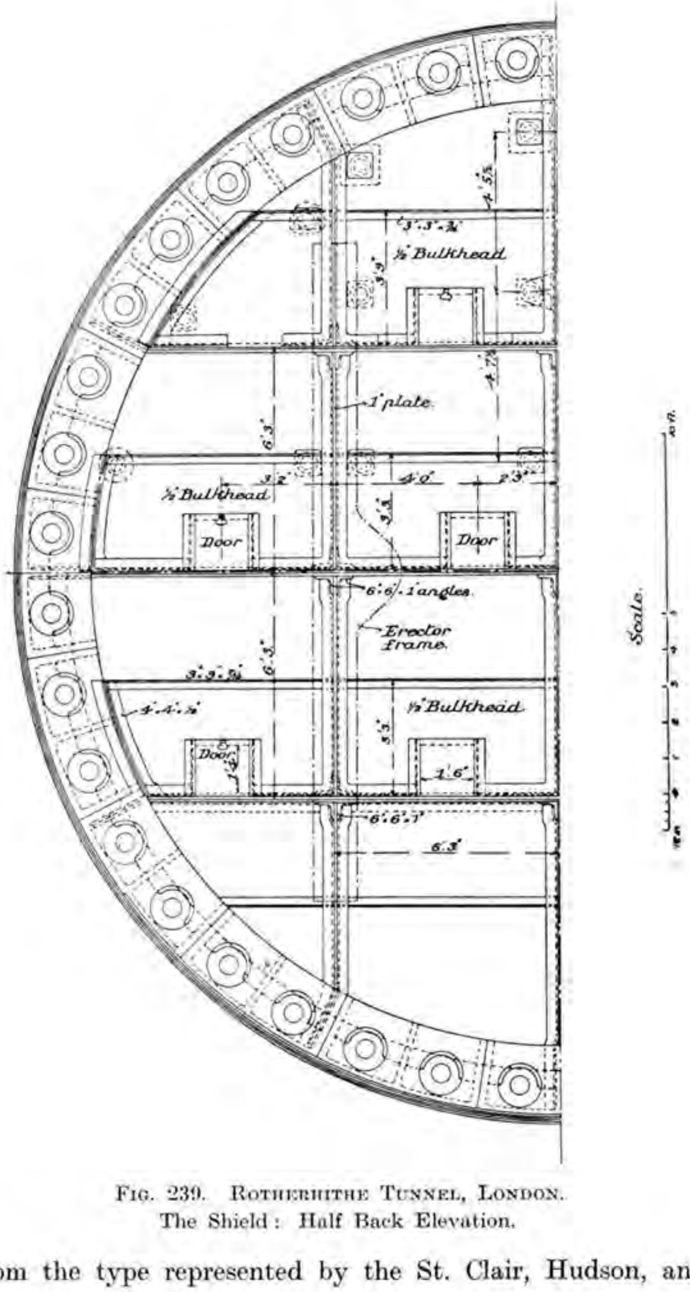


FIG. 239. ROTHERHITHE TUNNEL, LONDON.
The Shield: Half Back Elevation.

in details from the type represented by the St. Clair, Hudson, and Blackwall shields.

In length over all it is 18 feet, the external diameter of the cutting edge being 30 feet 8 inches, and of the tail plates 30 feet $7\frac{1}{2}$ inches. But the circumferential plates forming the skin do not as usual form a protecting cylinder which envelopes the entire length of the shield, but are only 10 feet long, thus leaving 8 feet of the outside cylinder composed only of three cast steel rings composed of numerous segments.

The vertical joints between these rings and the joints between the segments of which each ring is composed are planed, and are provided with machined slots in which are fitted machined steel key pieces, the effect of which is greatly to increase the resistance of the joints to shearing strain, which, without these keys, would of course be provided only by the bolts joining the segments; but the absence of the usual cylinder of skin of rolled steel plates must, one would think, materially

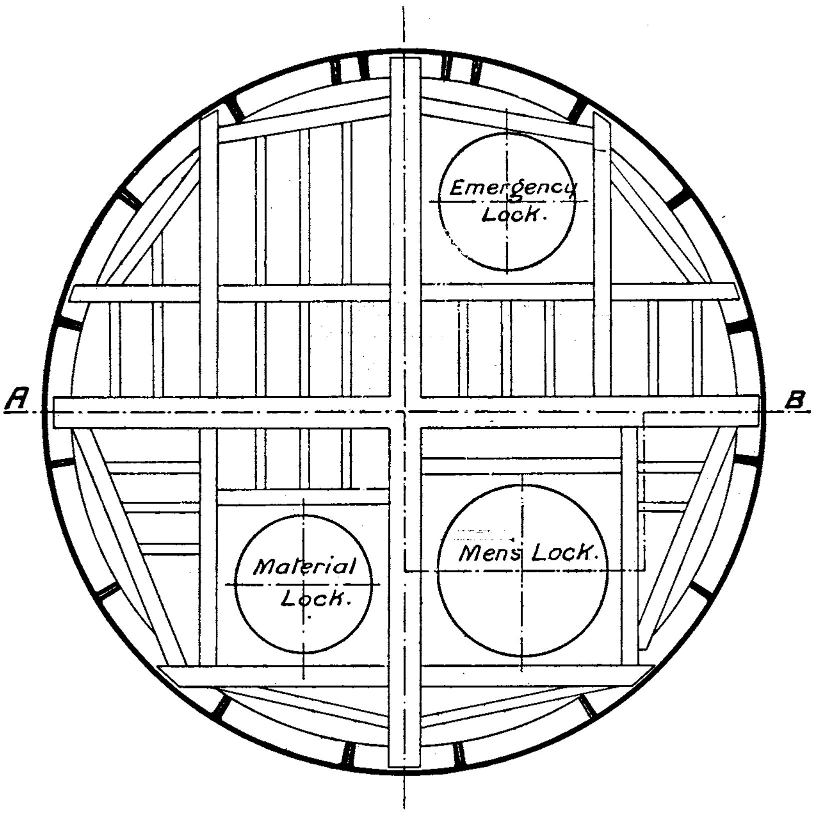


FIG. 240. ROTHERHITHE TUNNEL, LONDON.
Bulkhead: Diagram showing Disposition of Framing.

weaken the shield's resistance to tensional strain, such as is produced for instance by the cutting edge pushing against a boulder.

The existence of similar transverse joints unprotected by skin plates was, in the shields used in the St. Clair and Mersey Tunnels, found to be a source of weakness.

The frame of the shield is of exceptional strength, there being three vertical and three horizontal diaphragms, all the latter and the central vertical one extending back 10 feet 7 inches from the cutting edge, and being formed of several thicknesses of 1-inch plates rivetted together.

There are no sliding shutters of the kind which proved so useful at Blackwall, but numerous face rams, to pairs of which plates can be attached for holding up the face, are provided.

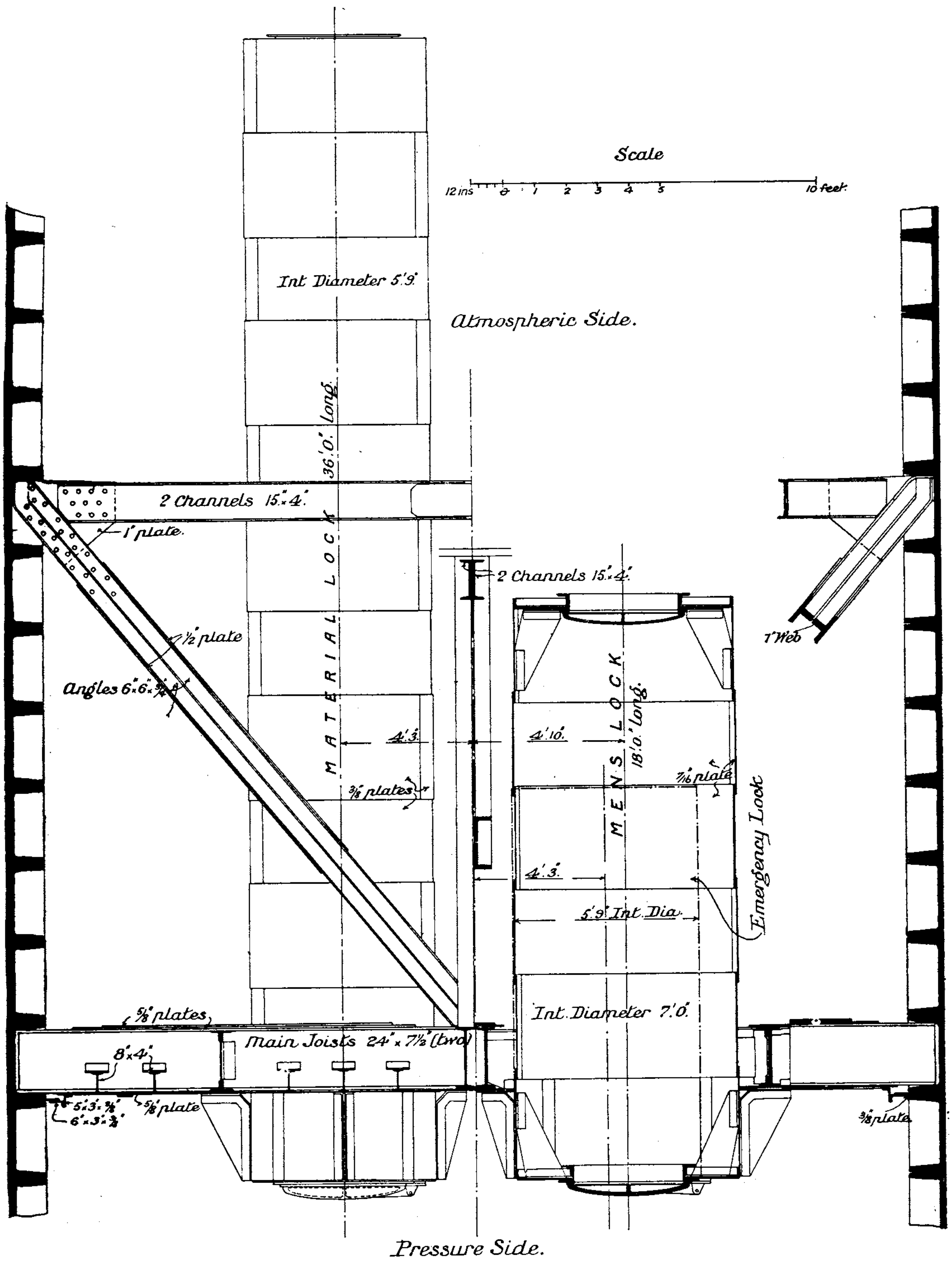


FIG. 241. ROTHERHITHE TUNNEL, LONDON.
Bulkhead: Sectional Plan on line *A B* (Fig. 240).

In addition are provided on each working floor bulkheads (removable), which are intended in some measure to act as the " trap " or water seal fittings of the Vyrnwy and Greenwich shields.

The advantage of these at different levels of an open face shield is problematic, and perhaps it would have been better had the face rams been placed nearer to the cutting edge or made with a longer stroke, so that they could reach well beyond the line of the cutting edge.

Forty rams for driving the shield are provided, and hydraulic erectors similar in type to those of the Blackwall shield will be used.

The contractors propose to substitute for the customary masonry bulkhead for the air-locks in the tunnel, a steel framed one. This, so far as the author is aware, has never been done before save in the Glasgow Harbour Tunnel,[1] which, however, was only 16 feet in diameter.

The bulkhead consists of ⅝-inch plating supported on two main girders composed each of two 24-inch joists occupying the vertical and horizontal diameters of the tunnel with smaller joists forming a framing in which are set the three locks. Fig. 240 shows this frame in outline, and Fig. 241 is a sectional plan of the bulkhead, locks and rakers supporting the bulkhead.

These rakers, four in number, bear on the bulkhead at the centre at the intersection of the main frames, their rear ends fitting into the cast-iron lining of the tunnel six and seven rings behind the bulkhead.

At these rings ties are fixed across the tunnel to prevent any spreading of the lining close to the thrust of the rakers.

The locks are placed so that practically they are for their entire length on the outer or atmosphere side of the bulkhead, thus ensuring that the cylindrical plates forming them are subject to tension only.

The River Dee Tunnel

This tunnel[2] will, when completed, form part of the main outfall sewer conveying the sewage and storm water from Aberdeen to the sea outlet at Girdleness. It is situated between Point Law on the north and Torry on the south bank of the Dee, and is designed, with the two shafts on either side of the river, to form duplicate inverted syphons to carry the sewage by gravitation across the river (see Fig. 242).

The two cast-iron shafts, each 12 feet in internal diameter, are already sunk, and no difficulty was experienced in the sinking operations, until the tunnel level was reached, where the fine alluvial clay previously met with changed to boulder clay, a bed of which, 3 or 4 feet thick, overlay gravel, which in turn extended to a depth of about 70 feet below Ordnance Datum, where rock was found. The concrete bottom of the Terry shaft is 58·35 and of the Point Law shaft 50·37 feet below Ordnance Datum.

Immediately above the boulder clay water was found in such quantities as entirely to overpower the pulsometer pumps provided, and ultimately the shafts were finished by divers, who excavated to a depth of 3 feet below the iron lining of the shafts and filled in 6 feet of 3 to 1 cement concrete, which was allowed to set

[1] See Fig. 98.

[2] Most of the facts and all the drawings relating to this work were put at the author's disposal by Mr. G. R. G. Conway, the resident engineer of the tunnel.

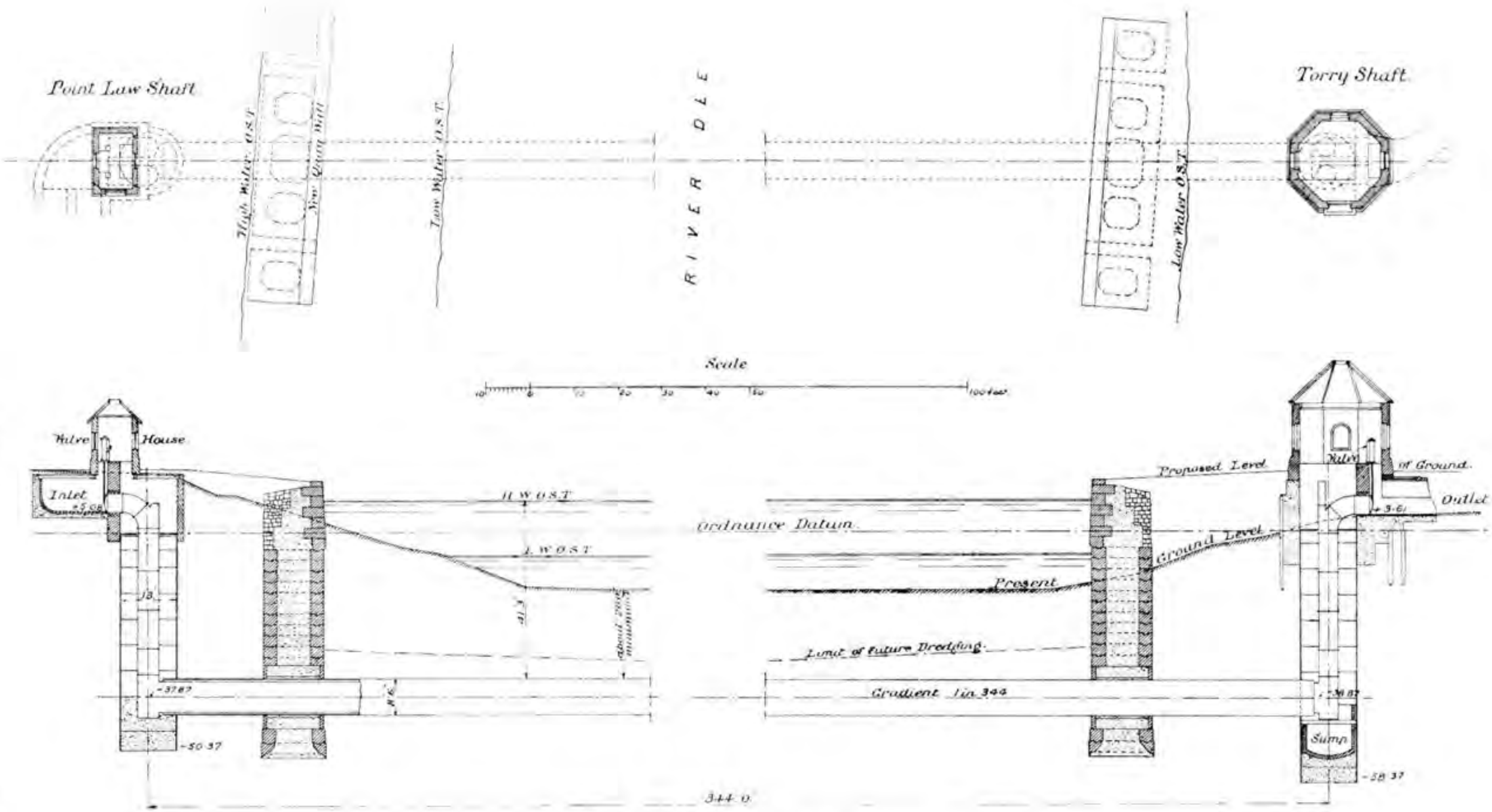


FIG. 242. DEE TUNNEL, ABERDEEN.
General Plan and Section.

for a fortnight, when the shafts were pumped dry and found to be perfectly water-tight.

Simultaneously with the sinking of the shafts, the construction of short lengths of quay walls of concrete was proceeded with.

Elsewhere these quay walls are to be of timber, but in order to prevent any interference with the tunnel at a future date, permanent quay walls were, by an arrangement come to between the Town Council and the Harbour Commissioners, built for a distance of about 60 feet on either side of the tunnel. In building these walls, which were composed of concrete cylinders sunk by excavating inside, and loading the cylinders with kentledge, openings 9 feet 6 inches in diameter were left for the passage of the tunnel.

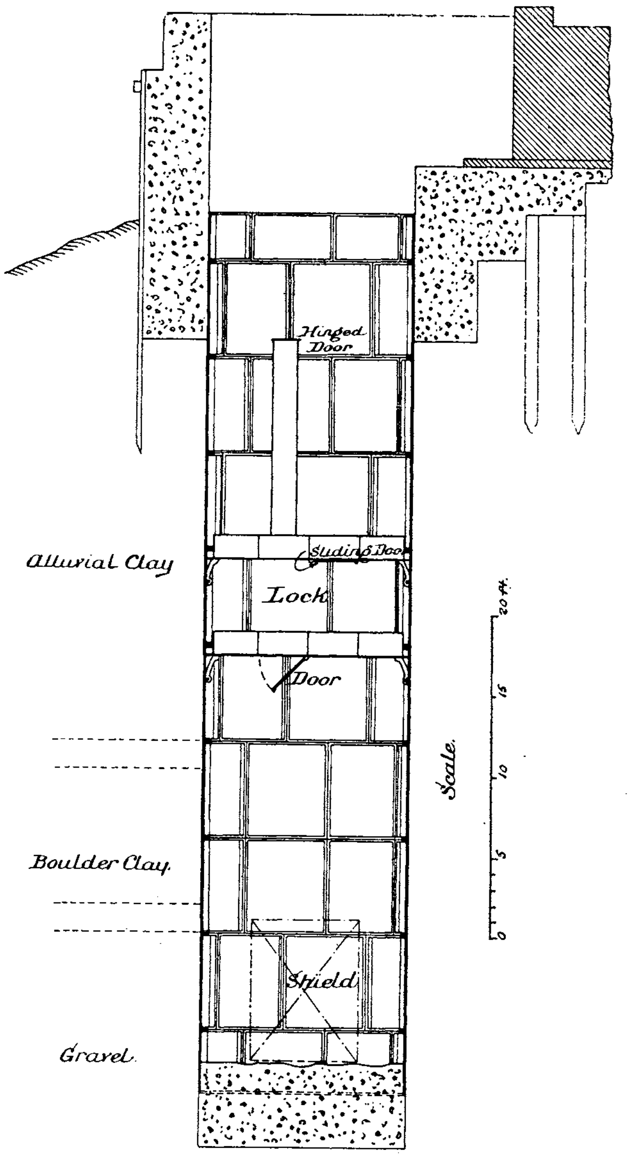


FIG. 243. DEE TUNNEL, ABERDEEN.
The Torry Shaft: Section.

As the quantity of water met in sinking the Torry shaft, from which the driving of the tunnel was to be done, made the opening out of the shaft at the tunnel level impossible without compressed air, a vertical air-lock (see Fig. 243) was fitted in the shaft about 5 feet above the top of the tunnel. This lock is only 4 feet 6 inches high, but a "chimney" or pipe is built above it, which gives sufficient space to admit of passing rails or timbers up to about 15 feet long. The work of driving the tunnel is being carried on with this lock, it being rightly thought that in a tunnel of such small diameter, and so short a length, the extra cost of substituting a horizontal lock in the tunnel would hardly be repaid by the saving in time in "locking through" which a horizontal lock would ensure. The amount of excavation per yard run of tunnel is under 7 cubic yards, an amount which, at an ordinary rate of advance, is well within the capacity of a vertical lock.

The air-compressing plant consists of two Ingersoll-Sergeant "straightline" piston inlet air compressors, having 16-inch steam and 18¼ air cylinders, the capacity of each being 37,000 cubic feet of free air per hour, and a small compressor for working the grouting pan and pumping.

5,000 cubic feet of air per man per hour is the allowance aimed at, and though the amount of CO_2 has reached as much as ·22 per cent. at the tunnel face, the usual amount is ·12 to ·14 per cent., a fairly satisfactory condition of purity.[1] A medical lock for the treatment of men affected by caisson sickness is provided on the works.

The tunnel itself is 8 feet 6 inches in external and 7 feet 8 inches in internal diameter, built of cast-iron segments, five segments and a key making a ring.

The rings are 18 inches wide, and the weight of the iron casing is 2 tons 12½ cwt. per yard forward. All the flanges of the segments are machined, a space

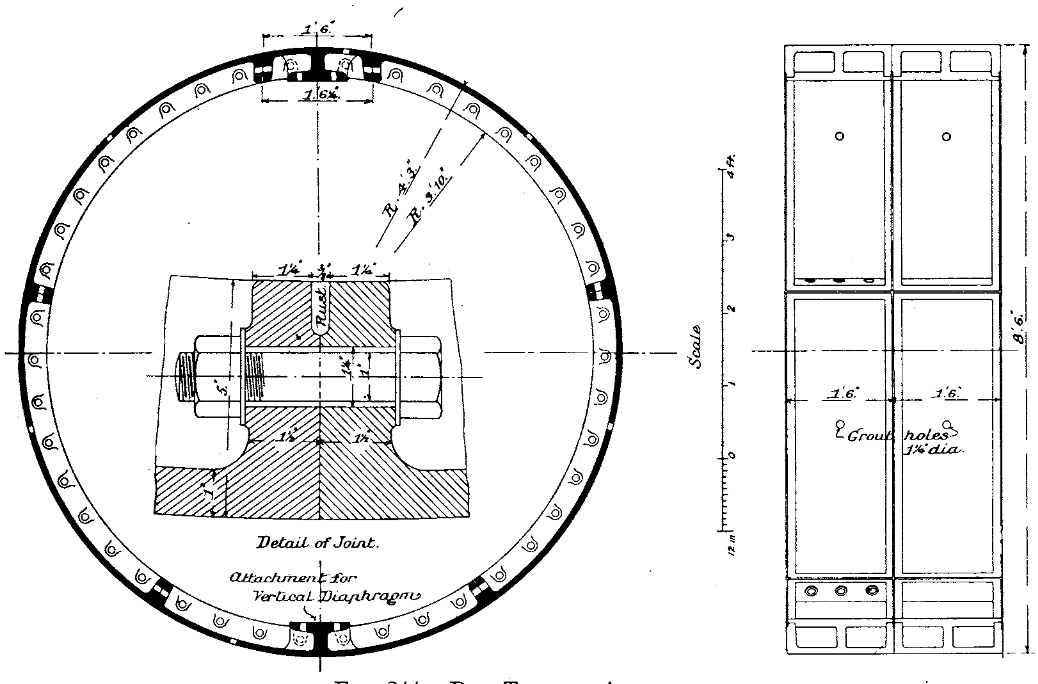


FIG. 244. DEE TUNNEL, ABERDEEN.
Cast Iron Lining.

being provided for rust jointing. The bolts, of which there are sixty to each ring, are 1 inch in diameter. Grout holes, as usual, are provided, but are not provided with screw plugs; and, special castings being required at the top and bottom of the tunnel to allow of a vertical dividing plate to be fitted later, the rings of the lining do not break joint.

The length of the completed tunnel will be 344 feet centre to centre of shafts, and it is being constructed at a depth of about 41 feet below highwater mark, to allow of a cover of about 4 feet above it in the event of the river channel ever being deepened to the level shown on Fig. 242.

The gradient is 1 in 344 towards the Torry shaft.

After the air-lock was fitted in the Torry shaft, the tunnel was commenced by opening out the cast-iron lining, and constructing a chamber from which to

[1] See pages 41 and 43.

start, the shield having been erected in the well of the shaft previously to the fixing of the air-lock.

The shield is of the ordinary Greathead type, and differs little from those used in clay tunnelling elsewhere. The double plates of the vertical diaphragm arranged to break joint make a very rigid frame in spite of the doorway being larger in proportion to the shield than usual (see Fig. 245).

In this diaphragm are thirteen holes, 2 inches in diameter, closed with screw plugs when not required. These are to allow the working of drills from the back of the shield in the event of the cutting edge encountering large boulders in its course, granite blocks being frequently found in the alluvial clay of the district.

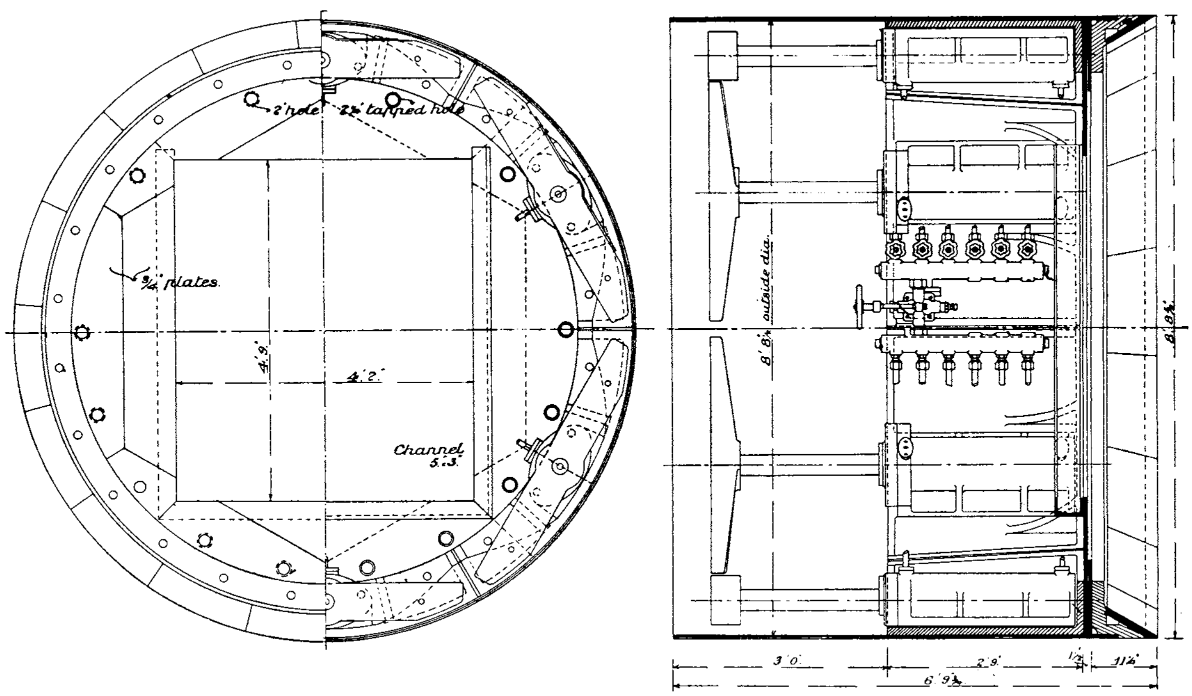


FIG. 245. DEE TUNNEL, ABERDEEN.
The Shield.

The working of the shield follows the usual lines of clay working, which is, no doubt, sufficiently secure, as there is, at the minimum, a cover of 20 feet presumably of clay over the crown of the tunnel.

A heading, 5 feet 6 inches by 3 feet 6 inches, is driven in front of the shield and is timbered with close-set side props and headtrees, no polings being used, and no timber being left in. The principal risk in working in this manner under the river is that, with the considerable amount of clay opened up in front of the shield, a blow, if such occurred, would probably be of such dimensions that the small amount of air in a tunnel of such small diameter would escape entirely and the pressure drop almost instantaneously.

The tunnel work has now [1] proceeded for a distance of 120 feet from the quay wall, the average rate of progress being about 4½ feet per day of twenty-four hours.

When the tunnel is completed an upright steel diaphragm will be bolted to

[1] April, 1905.

the top and bottom segments, on which special flanges are provided for this purpose, as shown in Fig. 244, and the whole lined with 4 to 1 cement concrete. The tunnel will thus be divided into two distinct passages, each of which will be connected with vertical pipes, 4 feet 6 inches in diameter in each shaft, thus forming two independent syphons.

The necessary machinery, penstocks, valves, pumps, etc., will be provided within small valve-houses erected over the shafts.

Paris Metropolitan Extension (1905)[1]

It was stated above[2] that the results obtained by the employment of shields in the construction of masonry tunnels for a double line of railway in the first section of the Paris Metropolitan Railway, comprising the line from Vincennes to the Porte Maillot, did not appear to have been sufficiently good to ensure a further trial of the system on the second section of the line, under the Outer Boulevards, as no shields were employed on this portion.

There has recently,[3] however, been put to work, on the section of the line between Vincennes and the Place d'Italie, a roof shield of entirely novel design which gave satisfactory results for a time, and the ultimate failure of which was due to conditions which would probably prove fatal to any shield of the same size.

The shield commenced its course in close sand, and according to M. Biette, the engineer of the line, very satisfactory results were obtained for a distance of about 660 yards, of which 80 yards was on a curve of 330 feet. The rate of progress was often 20 feet per day, and although some tendency to sink was observed, this may perhaps be in part explained by the loosening of the ground under the centres by the driving of a central gullet below them for the easier removal of the spoil.

After this promising commencement it was somewhat unfortunate that the line of the tunnel, on leaving the sand, passed through ground completely faulted by the irregular settlement of ancient underground quarries, which are numerous in the southern quarter of Paris.

The uneven support given by the underlying material, consisting in part of the solid rock left to support the quarry roofs, and in part of the débris which had filled the old workings, proved too much for the system of centering on which the shield moved; the centres settled unequally, as did those behind supporting the finished tunnel arch, and after some trial the shield work was abandoned.

But in some respects, notably in the greatly increased area over which the weight was distributed, the shield appears more satisfactory than some of its predecessors on the same line, and a further trial of the machine in undisturbed soil may very well be expected to give good results.

The shield is called by the name of its designer, M. Raquet, one of the contractors for the railway, and the principal feature which differentiates it from other roof shields employed on the same railway earlier is the manner in which the centres for carrying the masonry tunnel behind the shield are first made to support the shield itself. All the tunnelling systems described in chapters VIII and IX have in common a framed shield advancing on a prepared path or tram lines, behind which is erected a series of centres on which a masonry arch is turned.

[1] The author is indebted to M. Biette, chief engineer of the railway, for the drawings illustrating this description.

[2] Page 338.

[3] April, 1905.

The Raquet shield, however, has no framework beneath the roof: it is, in

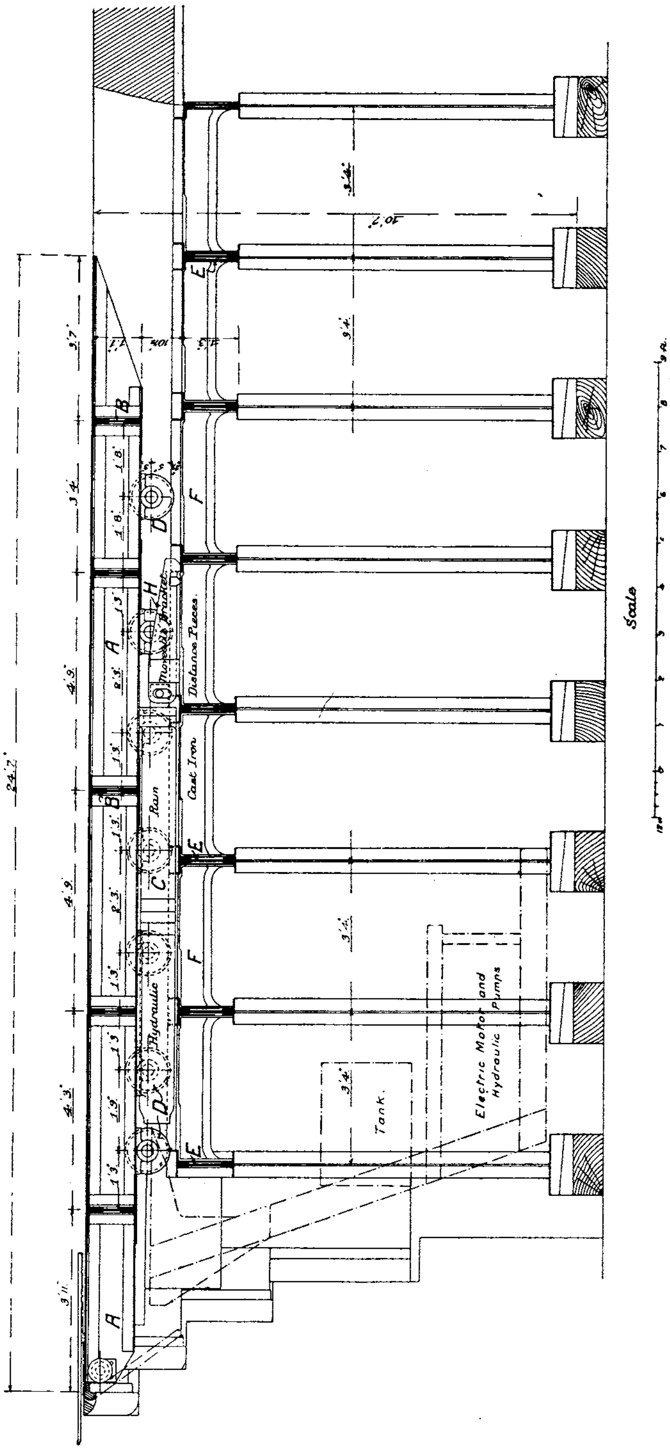


FIG. 246. PARIS METROPOLITAN RAILWAY.
Raquet Shield; Longitudinal Section.

truth, a roof and nothing more, and travels by means of rollers on tracks formed of the distance pieces between centres erected, not behind the shield, but beneath it, the first operation on a length of excavation being removed for the shield to advance being to erect a centre on which it bears as it moves forward.

Figs. 246 and 247 give respectively longitudinal and cross sections of the

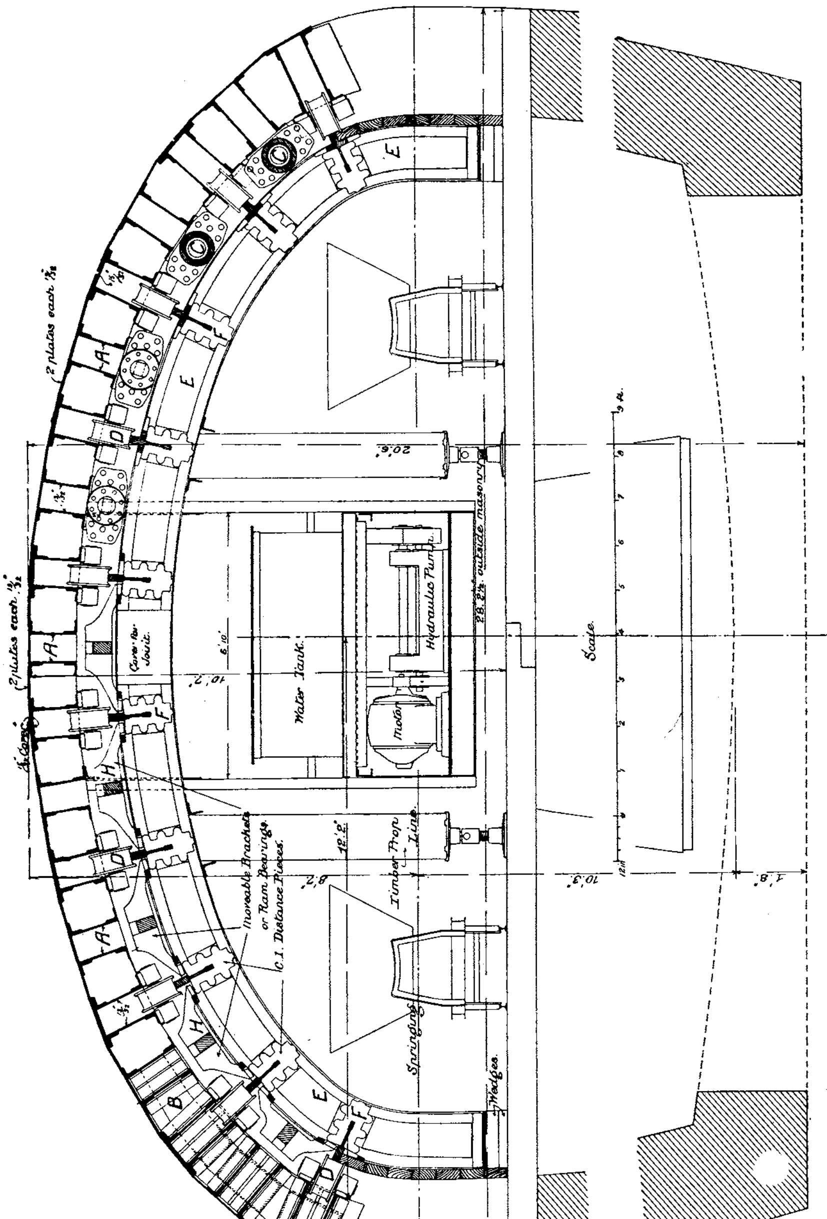


Fig. 247. Paris Metropolitan Railway. Raquet Shield. Cross Section.

shield. In them the roof is shown composed of plates supported by girders, *A*, *A*, nineteen in number, and formed of twin webs with angle iron flanges running the full length of the shield, and braced transversely at intervals varying from 3 feet

4 inches to 4 feet 9 inches in length by built frames, *B, B, B*. Beneath alternate girders are fixed nine rams, *C, C, C*, and ten sets of rollers, *D, D, D*, each 10 inches in diameter.

E, E are the centres supporting the shield, and *F, F, F* the cast-iron distance

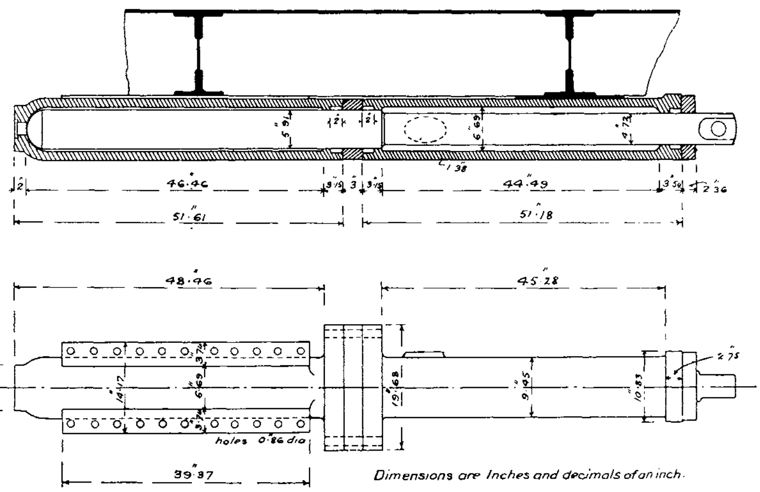


FIG. 248. PARIS METROPOLITAN RAILWAY.
Raquet Shield. Details of Double-ended Shield Ram.

pieces between them. These distance pieces have secured to the top flange a 2½-inch path to receive the rollers *D* carrying the roof.

These distance pieces have at either end their upper flanges widened out so as to receive the feet of the moveable bearings *H, H* of the hydraulic rams, which,

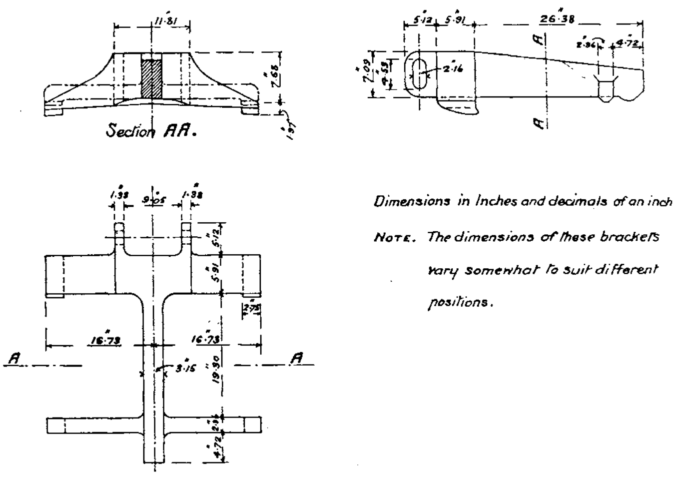


FIG. 249. PARIS METROPOLITAN RAILWAY.
Raquet Shield: Details of Bearings, *H, H*, of Rams shown in position in Figs. 246 and 247.

as shown in Fig. 247, are placed midway between adjacent distance pieces. The moveable bearings *H, H*, which are shown in more detail in Fig. 249, are ingeniously arranged for throwing the thrust of the rams on to the line of the distance pieces, and for easy removal from one piece to another as the shield advances.

The rams themselves are of the two-ended pattern, the greater length which this type involves enabling the bearing of the rams on the roof to be spread over a larger surface than a single reversing ram would provide.

In Fig. 246 the shield is shown in the position which it occupies relatively to the leading centre at the end of an advance of one metre (3 feet 4 inches). When the excavation of the face has proceeded far enough to permit of the erection of another centre, this is completed with its distance pieces, and the roof pushed forward on to it. The pin securing the piston of the ram to the bearing H is taken out, and pressure put in the rear half of the ram which draws in the piston, and so enables the ram-bearing piece H to be advanced one centre, when it is again ready to take the thrust of the ram.

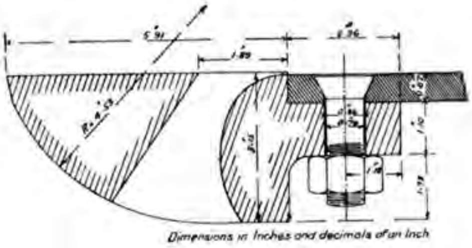


FIG. 250. PARIS METROPOLITAN RAILWAY.
Raquet Shield: Cutting Edge.

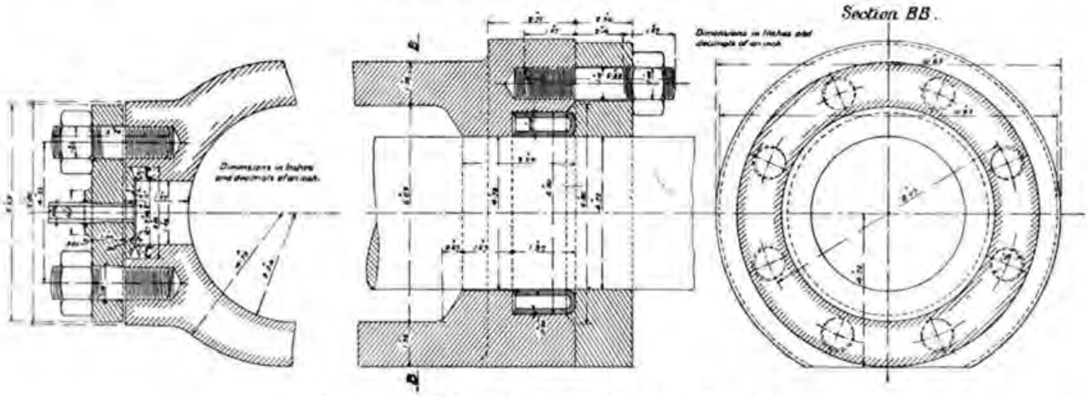


FIG. 251. PARIS METROPOLITAN RAILWAY.
Raquet Shield: Details of end of Cylinders of Hydraulic Ram.

The pumps for the hydraulic power are fixed in a hanging platform which

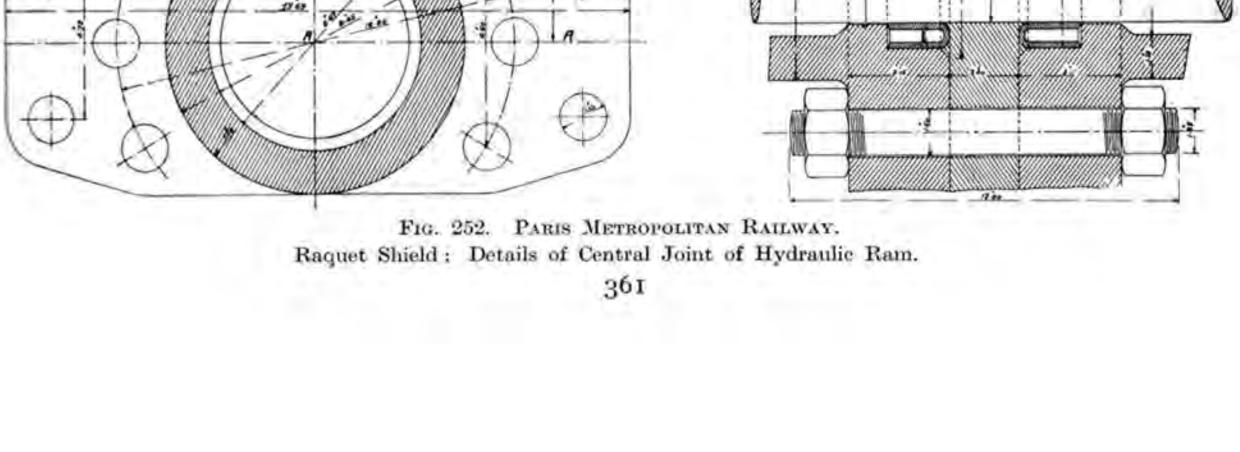


FIG. 252. PARIS METROPOLITAN RAILWAY.
Raquet Shield: Details of Central Joint of Hydraulic Ram.

occupies the centre of the space under the shield. The pipe connexions are not shown, but it will be seen from Figs. 248 and 251 that the main pressure pipe for driving the shield is attached to the nose of the ram, a somewhat unusual position, while the reversing pipe enters the rear cylinder at the side. (Fig. 253.)

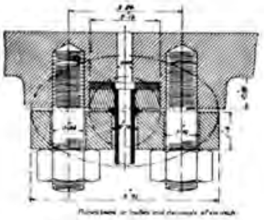


FIG. 253. PARIS METROPOLITAN RAILWAY.

Raquet Shield: Details of joint of Pressure Pipe and Glands in Cylinder of Hydraulic ram.

A minor feature of interest is the manner in which the cutting edge is perforated to allow of poling boards outside the shield being pulled forward by light chains to hold up the roof of the excavation in front of the cutting edge.

This arrangement would perhaps hardly be found satisfactory except in very compact uniform material, when, however, the poling boards would not be essential.

The general arrangements for working the tunnel do not appear to differ from the earlier work on the same railway.

The details of the hydraulic rams shown in Figs. 251 and 252 represent the most recent patterns of this class of work made in France.

The Brackenagh Tunnel [1]

In connexion with an extensive scheme for supplying the city of Belfast, Ireland, with water from the Mourne Mountains, it was necessary to drive a tunnel

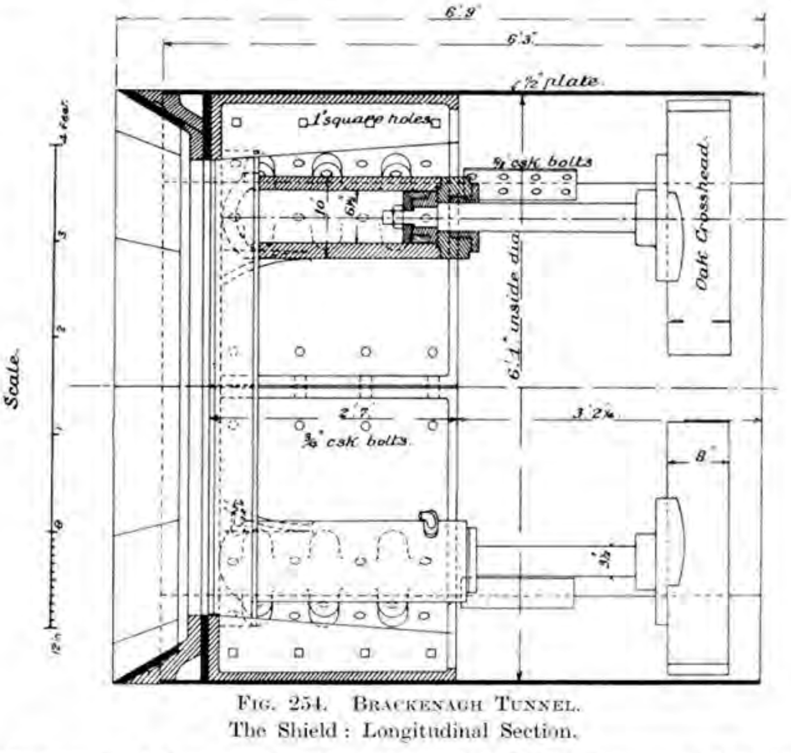


FIG. 254. BRACKENAGH TUNNEL.
The Shield: Longitudinal Section.

for the main aqueduct through the flank of one of the hills, known as the Brackenagh Tunnel.

[1] The author is indebted to Sir. A. R. Binnie for the drawing of this shield.

For the greater part of its length, this tunnel was constructed in concrete, but for a length of 220 yards it traversed a depression in the solid beds forming the hill-side, which was filled with a glacial deposit, much of which was water-bearing with some running sand.

After an unsuccessful attempt to drive the tunnel through this material in the ordinary manner, and with a concrete ring, a cast-iron lining 5 feet 4 inches in internal and 6 feet in external diameter was adopted instead of the concrete, but the ground proved too difficult for even this construction without the assistance of a shield and of compressed air. With their help, however, the tunnel was successfully driven through the running sand (1903).

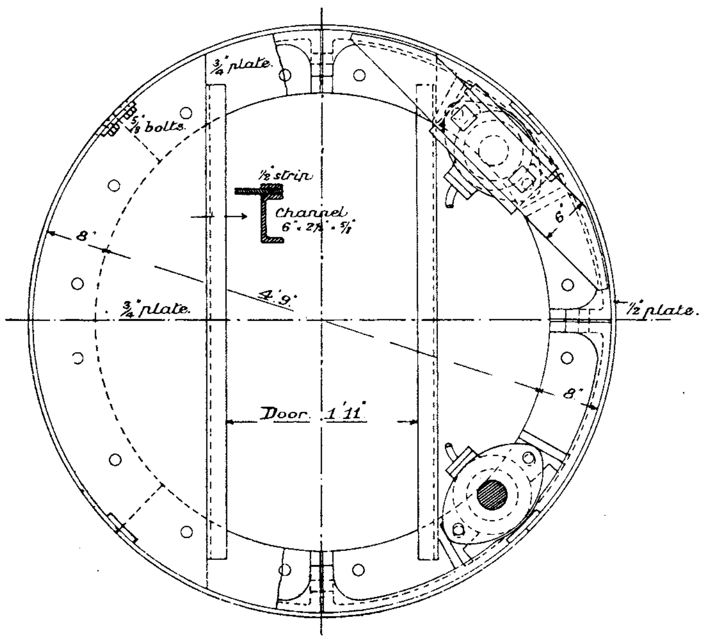


Fig. 255. Braokenagh Tunnel.
The Shield: Cross Sections.

The shield employed is shown in Fig. 225 and was of the ordinary Greathead type, the smallness of the tunnel rendering any face protection unnecessary, and indeed almost impossible.

The maximum depth of the tunnel below ground was about 95 feet.

Hilsea Creek Tunnel

This tunnel[1] has now been constructed for the borough of Portsmouth Water Works Company, and is for the purpose of carrying the water mains under Hilsea Creek near the village of Cosham, Hampshire, into the district of Portsmouth.

A shaft is sunk on each bank of the creek, and the tunnel has been driven (working from one shaft) at a depth of about 43 feet below high-water mark to the crown of tunnel, the total length from centre to centre of the shafts being 600 feet (see Fig. 256).

[1] The author is indebted to Mr. J. Quick and Mr. R. W. Hoggett, the engineer and resident engineer respectively, of the work for this brief description and drawings accompanying it.

The shafts, 21 feet 2 inches in external diameter, are of cast iron built up in rings 3 feet deep, each ring consisting of eight segments. They are carried down to a hard chalk foundation, the bottom being in each case about 62 feet below high water. The material passed through consisted for the most part of loose chalk through which water came freely. This was kept under by pumping, the plant employed consisting of two " Evans " mining pumps and a No. 8 pulsometer, with a total capacity of about 130,000 gallons per hour.

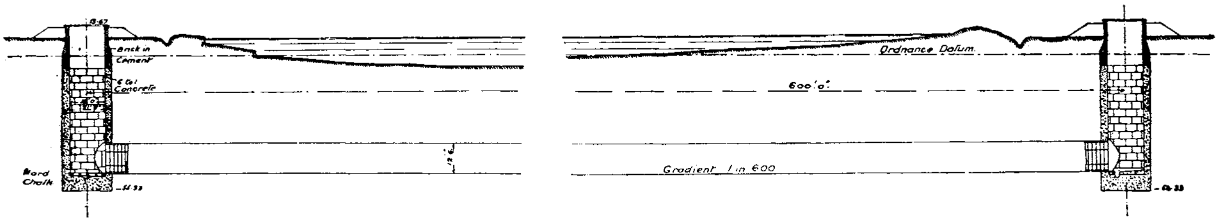


FIG. 256. HILSEA CREEK TUNNEL, HAMPSHIRE.
Longitudinal Section.

The shafts were excavated to the required depths and the lining built up from the concrete foundations.

A cast-iron false bottom (cast in sections and furnished with key pieces) was attached to the shaft ironwork, and the floor finished with an inverted concrete bottom. Within the cast-iron lining, concrete, as shown on the drawing, Fig. 259, was placed, the finished work being 15 feet internal diameter.

The opening for the tunnel was made in special castings, built in at commencement, and was sufficiently large to permit of the passage of the Greathead shield employed in the tunnel. The tunnel itself is 12 feet 6 inches in external and 11 feet 10 inches in internal diameter, the iron lining consisting of rings 1 foot 8 inches

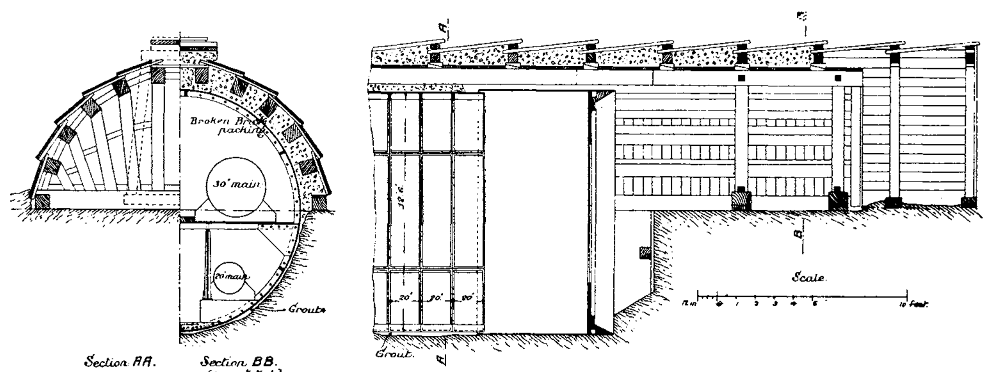


FIG. 257. HILSEA CREEK TUNNEL, HAMPSHIRE.
Details of Timbering.

wide and composed of six segments and a key, and weighing about 3 tons per yard of tunnel.

The shield is of the ordinary Greathead type and is used very much in the manner adopted in the Glasgow tunnels described in chapter V ; that is, its main function is to serve as a temporary centering within which to erect the cast-iron rings, the excavation being done in front of it.

The method of working was as follows : A timber heading with settings 4 feet apart and close poled was first driven and then opened out for a distance of 12 feet in front of the shield, but only down to the horizontal axis of the tunnel. This chamber was supported on crown bars 9 inches square supported by props on cills 12 inches square, which rested on the undisturbed ground in the lower half of the tunnel. This lower portion was only removed for a length equal to one tunnel ring at a time, and the shield then moved forward again, thus avoiding the necessity of timbering the lower half of the chamber (Fig. 257).

This appears to be a useful variation on the system employed at Glasgow, and is no doubt rendered possible by the fact that the material passed through was loose chalk, and therefore not liable to run as would have been the case had it been the sand and gravel met with at Glasgow.

The quantity of water dealt with on the average amounted to 100,000 gallons per hour, but on several occasions this quantity was considerably exceeded.

The rate of progress has naturally been slow compared with tubes of the same size constructed in the London Blue Clay, but after the system of timber crown bars had been adopted the progress was about 30 feet per week, or 5 feet per day of twenty-four hours.

Chapter XI

COST OF THE SHIELD

First Cost of Shield—Examples—Cost of Tunnelling per Yard Forward, and per Cubic Yard of Content—Tables Giving Details of Quantities and Prices—Comparison of Cost of Small Tunnels in Masonry or Brickwork and Cast Iron—Increase of Cost due to Compressed Air—Gangs of Miners—Rates of Pay—Numbers of Men

THE cost of tunnelling operations with a shield with or without compressed air is dependent on so many circumstances outside of the mere cost of the machine, and choice of the material for the tunnel lining, that the experience of past work can only be accepted as a guide to a limited extent. In the case of cast-iron lined tunnels, fairly accurate details are available as to the cost of works already executed; in estimating for masonry tunnels to be built with a shield, little help can be derived from previous experience, as no exact information is yet available relative to the actual cost of the more important works.

In considering the cost per yard run of a tunnel the charge due to the first cost of the shield is an important item, and this charge obviously is greater or less according to the length of the tunnel, the longer the travel of the shield the less being the charge per yard forward.

An ordinary Greathead shield about 12 feet in diameter weighs complete about 18 tons, and costs £450 or about £25 per ton; the larger shield (Fig. 74) of the Kingsway Subway under Holborn, 16 feet in diameter, cost £1,600; the station tunnel shield (Fig. 71) of the London "Tube" Railways weighs complete 85 tons, and cost £2,400 or about £28 per ton.

Of the shields used in water-bearing material, the Mersey Tunnel Shield, 10 feet in diameter (Figs. 145 and 146), cost (with alterations) £1,100; the Greenwich Tunnel Shield, 12 feet 6 inches in diameter, weighed complete 75 tons, and cost (with alterations), £2,340, or about £31 per ton; the Blackwall Tunnel Shield, 27 feet 8 inches in diameter (Fig. 115), weighed 220 tons and cost about £10,000, or about £45 per ton.

Of shields used in masonry tunnels the Tremont Street (Boston) Shield with a width over all of 29 feet 4 inches (Fig. 207), weighed 22 tons, and cost £1,200, or £55 per ton.

The cost of the Boston Harbour Shield (Fig. 211) at the same cost per ton would amount to £3,300.

These prices include all the hydraulic rams, etc., and the connexions on the shield, but not the service pipes in the tunnel, the cost of which obviously varies with the distance travelled by the shield and with the nature of the power supply.

COST OF THE SHIELD

It will be seen that the cost per ton of the shields above named varies from £25 to £55, and on dividing up the cost of each machine by the length of the tunnel driven, the cost of the work per yard forward due to this alone results in the case of the Greenwich and Blackwall Tunnels as nearly £6 in the former and over £9 in the latter case.

The cost of repairs to shields, save in the event of a serious accident causing crippling of the skin, is not usually heavy, being limited to renewals of the packings and glands of the hydraulic machinery and connexions.

Cost of Tunnelling with Shield

The subjoined tabular statements I and II set forth the actual prices (inclusive of shield and all plant) of some typical tunnels, and in III these figures are summarized together with some figures relating to earlier works.

For purposes of comparison the unit taken in Statement III is the cost per cubic yard of content of the tunnel, or in other words the cost per square yard of effective or inside area per yard forward.

This is preferable to taking the cost per cube yard of actual excavation, as owing to the great difference in the thickness of a masonry as compared with a cast-iron lining, a comparison between the two systems based on that as a unit would be misleading.

Statement I

Quantities and Cost per Lineal Yard of Iron-lined Tunnels Constructed with a Shield in London Clay

Note.—The figures do not include the cost of pointing (as distinct from caulking where necessary) the joints of the lining, concrete lining, or any other internal finishing.

(a) *Tunnel* 10 *feet* 6 *inches in internal diameter* :—

		Quantity.	Price.	£	s.	d.
Excavation including removal and finding shoot or tip	cubic yards	11·3	18*s*.	10	3	5
Cast Iron lining with planed end joints	tons	2·5	£6	15	0	0
Wrought Iron in Bolts, etc.	cwt.	1·75	18*s*.	1	11	6
3 to 1 Lias Lime Grouting	square yards	12	2*s*.	1	4	0
Price per yard forward				£27	18	11

Price per square yard of effective sectional area, per yard forward—
$=£27{\cdot}9 \div 9{\cdot}62 = £2{\cdot}9$

(b) *Tunnel* 11 *feet* $8\frac{1}{4}$ *inches in internal diameter* :—

		Quantity.	Price.	£	s.	d.
Excavation including removal and finding shoot or tip	cubic yards	14	18*s*.	12	12	0
Cast Iron lining with planed end joints	tons	2·83	£6	16	19	7
Wrought Iron in Bolts, etc.	cwt.	1·94	18*s*.	1	14	11
3 to 1 Lias lime grouting behind iron	square yards	13	2*s*.	1	6	0
Price per yard forward				£32	11	6

Price per square yard of effective sectional area, per yard forward—
$=£32{\cdot}575 \div 12 = £2{\cdot}714$

(c) *Tunnel* 12 *feet* 6 *inches in internal diameter* :—

		Quantity.	Price.	£	s.	d.
Excavation, etc.	cubic yards	16	18*s*.	14	8	0
Cast Iron, etc.	tons	3·1	£6 2*s*.	18	18	3
Wrought Iron	cwt.	1·94	18*s*.	1	14	11
Lime Grouting	square yards	14	2*s*.	1	8	0
Price per yard forward				£36	8	2

Price per square yard of effective sectional area, per yard forward—
=£36·4 ÷ 13·63 = £2·67

(d) *Tunnel* 15 *feet in internal diameter* :—

		Quantity.	Price.	£	s.	d.
Excavation, etc.	cubic yards	22·2	18*s*.	20	0	0
Cast Iron, etc.	tons	5·7	£6 2*s*.	34	15	4
Wrought Iron	cwt.	3·5	18*s*.	3	3	0
Lime Grouting	square yards	17	2*s*.	1	14	0
Price per yard forward				£59	12	4

Price per square yard of effective sectional area, per yard forward—
=£59·63 ÷ 19·63 = £3·03

(e) *Tunnel* 21 *feet* 2½ *inches in internal diameter* :—

		Quantity.	Price.	£	s.	d.
Excavation	cubic yards	45·16	18*s*.	40	12	10
Cast Iron	tons	8·5	£6 5*s*.	55	5	0
Wrought Iron	cwt.	6·5	18*s*.	5	17	0
3 to 1 Lias Lime Grouting	square yards	23·5	2*s*.	2	7	0
Price per yard forward				£104	1	10

Price per square yard of effective sectional area per yard forward—
=£104·09 ÷ 43 = £2·42

(f) *Tunnel* 30 *feet in internal diameter* :—

		Quantity.	Price.	£	s.	d.
Excavation	cubic yards	92	18*s*.	82	16	0
Cast Iron	tons	20	£6 10*s*.	130	0	0
Wrought Iron	cwt.	12	18*s*.	10	16	0
3 to 1 Lias Lime Grouting	square yards	34	2*s*.	3	8	0
Price per yard forward				£227	0	0

Price per square yard of effective sectional area per yard forward—
=£227 ÷ 78 = £2·91

(g) *Shield Chambers, approximate cost of short lengths of iron-lined tunnels to serve as : not including cost of headwalls if used* :—

15 feet diameter Chamber for 11·8¼ Tunnel	£220	0	0
,, ,, 21·0 ,,	£1200	0	0

COST OF THE SHIELD

Statement II

Quantities and Cost per Yard Forward of Subaqueous Tunnels built with a Shield and Compressed Air.

Note.—The figures do not include the cost of pointing (as distinct from caulking when necessary) the joints of the lining, concrete lining, or any other internal finishing.

(h) *Blackwall Tunnel under River Thames* (1892)

	Unit	Quantity.		Price.		£	s.	d.
Excavation in compressed air (measured net external diameter of iron tunnel tubing) at the proper pressure and without attempting to dry the surrounding soil, and as far as possible without excavating more soil than the net area occupied by iron tubing, so that there is no settlement, and for which the contractor is liable, and cart or barge away, including finding shoot for same. The contractor must provide and include, in his price for excavation, for forcing at sufficient pressure and by means of suitable appliances through holes in iron tubing with and including lias lime, Portland cement or other approved composition, and for all models, medical attendance, etc.. .	cubic yards	63·6	..	47*s*.	..	149	9	2

Note.—The ground line is about 45 feet average above crown of tunnel. The bottom of river at least height is only 6 feet above crown of tunnel.

	Unit	Quantity.		Price.		£	s.	d.
Cast-iron lining 2 inches thick in fourteen segments with flanges 12 inches wide $2\frac{7}{8}$ inch metal, including patterns and weighing 19 tons 9 cwt. 1 quarter per yard lineal	No.	1 1	..	£9 15*s*.	..	189	15	2
Ditto in No. 1 key piece, including pattern, and weighing 8 cwt. 3 quarters 11 pounds . . .	No.	0 1	..	£9 9*s*.	..	4	6	4
Machining and coating joints of segments 12 inches wide and making joint perfectly watertight in an approved manner—circumferential joint	lineal feet	98	..	1*s*. $10\frac{1}{2}$*d*.	..	9	3	9
Ditto, longitudinal joint	lineal feet	45	..	1*s*. $10\frac{1}{2}$*d*.	..	4	4	3
Clearing and forming holes in $2\frac{1}{2}$ inch metal	No.	$175\frac{1}{5}$	..	$1\frac{1}{2}$*d*.	..	1	1	11
Ditto, in $2\frac{7}{8}$ inch	No.	$175\frac{1}{5}$	..	$1\frac{1}{2}$*d*.	..	1	1	11
Drilling and tapping for $1\frac{1}{2}$ inch plugs . . .	No.	18	..	8*d*.	..	0	12	0
$\frac{3}{16}$ inch washers	No.	$368\frac{2}{5}$	..	$\frac{3}{4}$*d*.	..	1	3	0
$1\frac{1}{2}$ inch screw plugs	No.	18	..	9*d*.	..	0	13	6
$1\frac{1}{2}$ inch bolts $10\frac{1}{2}$ inch long over all, weighing about 9 pounds each, including making watertight in an approved manner	No.	0 $175\frac{1}{5}$	..	1*s*. $10\frac{1}{2}$*d*.	..	16	8	6
Total per yard lineal of tunnel						£377	19	6

(j) *Greenwich Footway Tunnel* :—

Cost of Tunnelling per Yard Forward.

	Unit	Quantity		Price		£	s.	d.
Excavation in compressed air, including grouting at back of lining	cubic yards	$14\frac{1}{4}$	..	40*s*.	..	28	10	0
Cast-iron lining	tons	$4\frac{1}{8}$	..	£15 12*s*.	..	64	7	0
Wrought iron in bolts and washers . . .	cwt.	$7\frac{1}{2}$	..	24*s*.	..	9	0	0
Lead washers	No.	273	..	$1\frac{1}{2}$*d*.	..	1	14	$1\frac{1}{2}$
Grouting holes	No.	$14\frac{1}{4}$	...	10*d*.	..	0	11	$10\frac{1}{2}$
Forming watertight joint	lineal yards	31	..	2*s*. 9*d*.	..	4	5	3
Total per yard lineal of tunnel						£108	8	3

Statement III

Comparative Statement of Cost of Iron-lined Tunnels built with a Shield.

Note.—The cost of internal lining is not included.

Tunnel.	Date.	Internal Diameter. Feet.	Cost per Lineal Yard of Tunnel. £	Cost per square Yard of internal section per yard forward £	Remarks.
"Tube" Railways in London	1900–1905				
As per Detail (*a*) .	,,	10·50	27·90	2·90	In London Clay.
,, ,, (*b*) .	,,	11·68	32·575	2·714	,, ,,
,, ,, (*c*) .	,,	12·50	36·40	2·67	,, ,,
,, ,, (*d*) .	,,	15·00	61·216	3·03	,, ,,
,, ,, (*e*) .	,,	21·20	104·09	2·42	,, ,,
,, ,, (*f*) .	,,	30·00	227·00	2·91	,, ,,
Glasgow District Subway	1892	11·00	40·00	3·78	In general in good material, but with some subaqueous lengths in which compressed air was used.
Greenwich Tunnel .	1899	11·75	108	9·00	In waterbearing material. Compressed air used. Very heavy lining.
Glasgow Harbour Tunnel	1890	16·00	85	3·35	In water-bearing sand and gravel, compressed air used.
Hudson River Tunnel	1889	18·00	300	10·61	In almost fluid silt. Compressed air used.
St. Clair River Tunnel	1888	19·83	200	5·81	In clay under River. Compressed air used.
Blackwall Tunnel .	1892	25·00	378	6·93 [1]	In water-bearing gravel under River. Compressed air used.
		25·33	315	5·62 [1]	

Note.—The figures do not include cost of pointing joints (as distinct from caulking), concrete lining, or any internal finishing.

It will be seen that, as regards the tunnels in London Clay, the cost per cubic yard of content is, as might be expected, remarkably uniform, gradually decreasing from rather less than £3 in the smaller tunnels to less than £2 9*s*. in the 21-foot tunnel, rising again to nearly £3 for the 30-foot one, the increase being probably due to the more expensive shield for this tunnel having a shorter travel in proportion than the others.

The figures relating to the Glasgow District Subway Tunnels [2] are not very informing, the general contract price of £40 per yard run including a considerable amount of work under compressed air, though the major portion of the shield work was in fairly good material.

[1] The two prices and diameters are due to two different sections of lining being employed.

[2] See page 139.

COST OF THE SHIELD

The cost of the tunnelling work in the Greenwich Subway [1] giving a result of £9 per cubic yard of content is greater than appears necessary, but the cast-iron lining (see Figs. 30, 31, 32) was made of exceptional strength, and the special washers, etc., in the joints added to the expense. In the light of the experience gained in carrying out the work the Author is of opinion that a tunnel of the same size in similar conditions could be built for £7 10*s*. per cubic yard of content.

The Glasgow Harbour Tunnels, which were below the Clyde for almost their entire length, cost about £3 7*s*. per cube yard of content, a price which appears very low compared with the Greenwich results, but at Glasgow the tunnels were driven for the greater part of the distance in boulder clay, and consequently in much more favourable conditions, a portion being constructed without the use of compressed air, and for a certain length it was possible to build a brick lining.[2] At Greenwich at no time could the air pressure have been dispensed with, and for a long distance the work was in open ballast which extended upwards to the river bed.

For the Hudson and St. Clair Tunnels, the diameters of which are nearly the same, the figures (approximate only) show considerable divergence, as might be expected from the description of the works given in Chapter VI. The former work presented difficulties exceptional even in subaqueous work; the latter, in more favourable circumstances was built with a rapidity which is so far unequalled for a subaqueous tunnel of the same size.

It will be seen that the cost per cubic yard of content—£5 16*s*.—of the St. Clair Tunnel is less than that of the Blackwall Tunnel, where the heavier lining was used—£6 18*s*.,—and 4*s*. more than that of the lighter lined lengths of the same tunnel, and it may be added that the new Rotherhithe Tunnel under the Thames will, it is estimated, cost about £6 per cube yard of content.

The cost of Brunel's Thames Tunnel is of interest in this connexion. Per cubic yard of excavation it cost about £12 8*s*., and per cubic yard of content £25, including the cost of the shafts at each end.

From the above figures, which cover only the structural work of the tunnel and do not include anything in the nature of inside lining, formation of roadway, or fittings for the special purpose for which each tunnel is designed, nor the cost of approaches, whether shafts or embanked inclines, it appears that in estimating for iron-lined tunnels in London Clay, £3 per cubic yard of content is a sufficiently safe price, and for tunnels in difficult water-bearing material about £7 per cubic yard of content is a safe covering figure.

For tunnelling in material of fair consistency, without compressed air and in which but little timbering in front of the shield is required, and when the amount of water met with can be dealt with without laying down an excessive pumping plant, about £3 10*s*. to £4 per cubic yard of content is a fair inclusive estimate for an iron-lined tunnel, the diameter of which is not greater than 15 or 16 feet.

Above that size, the great increase in face timbering for, and in the weight of a shield for working in, loose material charged with water, makes estimating very difficult, and £5 per cubic yard of content is probably not too high a figure.

A comparison of the relative cost of a masonry tunnel built in timbered lengths, and of an iron tunnel built with a shield, is of value to a certain extent only.

Tunnels in open water-bearing material, whether actually under waterways or not, are best built with a shield, and the larger the tunnel the more the superiority of the new system is shown, even if any other be practicable at all. But in tunnels

[1] See page 231. [2] See page 152.

in good material where any water met with can be dealt with without the use of compressed air, and either shield work or timber-work is possible, the choice of method will be determined by considerations of cost and convenience.

In one important and increasing class of tunnel work, to which the previous sentence applies, it is especially probable that the shield and iron lining will be employed largely in the future—namely, in tunnels under or in the vicinity of large cities, where any interference with property or interruption of street traffic, such as is inseparable from the older system of working, is now so strongly resented that it is, when permitted at all, hedged round with such stringent conditions as to be economically almost impossible.

Although it is not probable that elsewhere the construction of deep level "tube" railways will be undertaken on such an extended scale as the last ten years have witnessed in London, in all great centres of population it may be useful to employ the shield and iron-lined system of tunnelling in the building of sewers above a certain diameter.

Speaking generally the brick tunnel for diameters up to 10 feet (internal) is cheaper than an iron one, with brick lining, in good material. Above 10 feet diameter the cost of either method is about the same up to 15 feet diameter, above which the advantage in price is with the iron-lined tunnel. But in all cases the latter has the advantage in speed of construction and freedom from risk of serious settlement.

A contract for a brick sewer 9 feet in internal diameter in good material has recently been let in London at £23 per lineal yard, or £3 5*s.* per cubic yard of content (exclusive of cost of shafts). This price is a low one for brick tunnelling, and is much lower than that of a same sized sewer having an iron casing of 10 feet internal diameter. This, taking the cost of the iron casing at £3 per cubic yard of its content and adding £5 10*s.* for the masonry lining,[1] would cost £30 13*s.* per yard forward, or £4 7*s.* 6*d.* per cubic yard of content (complete).

If a concrete lining only were employed, an iron tunnel with a finished internal diameter of 9 feet would cost about £27 5*s.* on the same basis.

Drawings were actually prepared of such alternative designs by the engineer carrying out the work and the estimates based on them, the prices taken being current London contract ones worked out at £30 for the iron tunnel with a concrete and brick finish and at £25 for the iron tunnel finished with concrete only.

It will be seen that, however calculated, the price of an iron tunnel of the diameter (finished) of 9 feet is 20 per cent. above that of one constructed entirely in brick.

Simultaneously almost with the above, a contract for a brick sewer 11 feet 6 inches in diameter was let by contract at a price of £45 per lineal yard or £3·9 or £3 18*s.* per cubic yard of content, and in this case the ground was known to consist of disintegrated chalk, gravel, and loose material containing some water.

In this case the contractor found that the construction of a brick tunnel was out of the question, at any rate at anything like the price at which he had taken

[1] This is obtained as under

			£	*s.*	*d.*
4 to 1 Concrete	1·6 cubic yards	at 24*s.*	1	18	4
Brickwork	1·24 ,, ,,	,, 50*s.*	3	2	0
Extra on blue brick invert	5 sup. yards	,, 2*s.* 6*d.*	0	12	6
			£5	12	10

the work, and he was permitted to substitute an iron one of 12 feet 6 inches internal diameter.

Again, applying the cost per cubic yard of content as obtained from the statement on page 370, and adding the value of the masonry lining, the cost of such a tunnel comes out at £46 15*s.*, or £4·05 per cubic yard of content per lineal yard.

That this is an approximate estimate of the cost of the work was curiously corroborated by the fact that among the tenders originally sent in was one which offered as an alternative to the brick sewer specified an iron one, the difference between the two prices sent in by the firm tendering being only about 6 per cent. in favour of the brick sewer.

Concerning the cost of brick or masonry tunnels constructed with a shield, but little information is available. The tunnels built in this manner on the Paris Metropolitan Railway appear to have been not too fortunate in the design and manipulation of the machines employed to furnish any statistics of value, and no detailed figures are available of the very successful work carried out in this manner on the Boston Underground Railway.

M. Legouëz [1] gives the contract price per lineal metre of the Collecteur de Clichy [2] extra muros and the Collecteur de Clichy intra muros, both built in masonry under shields, at 1,016 francs and 770 francs respectively, or about £37·33 and £28·25 per lineal yard.

Taking the same unit as before, the cost of the first was £1·33, and of the second £1 per cubic yard of content. The latter of these prices was confessedly low, and the work was undertaken with a perhaps too sanguine estimate of the capabilities of the new shield, and even the higher price of the section "extra muros" does not appear sufficient to return a profit to the contractor. But even were the price doubled there would be apparently a very considerable advantage in favour of the masonry tunnel built with a shield as compared with that of the iron-lined system.

But in neither case does M. Legouëz give any information as to the financial result to the Contractor of work done at the prices of the tenders, and even allowing for the somewhat cheaper rates of wages in Paris, it is not easy to think the prices quoted are remunerative.

M. Legouëz has made calculations which he considers demonstrated that the use of a shield in masonry tunnels results in an economy of from 20 to 400 francs per lineal metre.[3]

In general the cost of working with a shield in compressed air is about 100 per cent. more than, or double, the cost of the same sized tunnel where compressed air is not required.

In tunnelling in the London Clay, compressed air is sometimes employed as a precautionary measure in the vicinity of heavy and valuable buildings, all the other tunnelling operations remaining unchanged. In such cases the cost of the work in compressed air is somewhat less than double that of ordinary work.

Where the amount of air required is large, the cost of compressing it is not less than twopence per thousand feet of free air even when very large quantities are used,[4] over a considerable period, and double or treble that for small installations.

[1] *Le Bouclier*, pp. 309, 328.
[2] See Fig. 183.
[3] *Bouclier*, p. 425.
[4] Mr. Moir, *Proc. I.C.E.*, vol. cl. p. 54.

The wages paid to the shield gang are in London at the present date :—

	In Ordinary Tunnelling.	In Compressed Air Tunnelling.
	s. d.	s. d.
Ganger per hour	1 0	1 6
Miner, ditto	9	1 3
Miner's Labourer, ditto	7½	1 1½
Ordinary Labourer, ditto	7	1 0
Boy, ditto	4	—
Shield Driver, ditto	9 [1]	1 0
Locksman, ditto	—	1 0

In addition to these wages, a bonus for each ring erected per week over a fixed minimum is usually paid. This bonus is generally paid on an ascending scale, the amount per ring increasing with each ring.

The miners in ordinary work have one 10-hour shift per day ; in compressed air work, 8-hour shifts are usual when the pressure is not more than 30 to 35 lb. per square inch.[2]

The number of men employed with some shields used in recent English work is given below, the list including in the case of ordinary tunnelling the men employed between the face and the first "turnout" of the tramway, and in compressed air work all the men inside the lock.

COMPOSITION OF TUNNEL GANGS.

Men.	Central London Railway.		Charing Cross and Hampstead.	Greenwich Tunnel.
	11 ft. 8 in. Shield.	22 ft. 6 in. Shield.	Price's Excavator 12 ft. 6 in. diam.	12 ft. 6 in. Shield.
Ganger	1	1	1	1
Miners	4	8	2	2
Miners' Labourers	4	8	2	2
Ordinary Labourers	4	4	4	5
Boy	1	1	1	—
Shield Driver	—	1	—	1
Locksman	—	—	—	1
	14	23	10	12

Note.—About sixty men were in ordinary circumstances employed in the Blackwall Tunnel. At the Baker Street and Waterloo Railway Tunnel under the Thames the gang numbered thirteen.

In addition to the ordinary gang, it is usually advisable in iron-lined tunnels to have one or two extra men employed some distance behind the shield (50 to 60 rings) to tighten up the bolts of the cast-iron lining, when the rate of progress exceeds five or six rings per day.

[1] A shield driver is only employed with large shields.

[2] Four-hour shifts were worked at the Forth Bridge when the pressure was 37 lb. per square inch.

APPENDIX A

A CHRONOLOGICAL LIST OF EVENTS CONNECTED WITH TUNNELLING BY MEANS OF A SHIELD OR OF COMPRESSED AIR

1818. Brunel's shield patent (see page 1).

1825. The Thames tunnel commenced by Brunel (see page 3).

1828. Dr. Colladon said to have recommended the use of compressed air to Brunel in his tunnel enterprise.

1830. Sir Thomas Cochrane's patent for constructing shafts and tunnels in water-bearing strata by means of compressed air (see page 23).

1839. Compressed air first actually used in sinking a shaft at Chalonnes in the Loire Valley, France (see page 27).

1841. About this time the Potts system of vacuum working was first tried.

1842. The Thames tunnel completed.

1849. A Mr. Dunn patented a tunnelling machine, patent No. 12632 of 1849 (see page 7).

1857. M. Guibal's shield used for shaft sinking (see page 8).

1861. M. Foley at Argenteuil, France, recommended, for the first time, re-immersion in cases of compressed air sickness (see page 36).

M. Rhizas introduced his system of movable iron tunnel centres from which the working face was supported (see page 8).

1864. Mr. Barlow's shield patent, No. 2207 of 1864 (see page 8).

1868. Mr. Beach of New York patented a shield resembling the Barlow shield of 1864 (see page 14).

Mr. Barlow provisionally patented another shield, which patent, however, was abandoned (see page 9).

1869. The Tower Subway of cast iron constructed by means of a shield under the River Thames by Mr. Greathead (see page 11).

The Broadway Subway constructed by means of a shield commenced by Mr. Beach (see page 14).

1870. The Beach shield tried in Cincinnatti and Cleveland, Ohio (see page 16).

1873. The Woolwich tunnel projected by Mr. Greathead. A feature of his scheme was the use of compressed air in conjunction with a shield (see page 16).

1879. A small tunnel at Antwerp constructed of cast iron by M. Hersent, in which for the first time compressed air was used in a tunnel (see page 17).

The Hudson Tunnel.

The tunnel under the Hudson River, New York, of brick was commenced by an American syndicate, Haskin's compressed air system being employed (see page 159).

1880. Andersen's patent pilot tunnel system used at the Hudson River tunnel (see page 165).

APPENDIX

1885. A small footway tunnel constructed at Stockholm by means of iron centres and the use of a freezing machine, the face of the tunnel being further protected by means of small iron plates serving as polings (see page 275).

1886. Mr. Greathead commenced the **City and South London Railway.**

On this work, in which the tunnels were of cast iron, compressed air was for the first time used in conjunction with a shield in water-bearing strata.

Diameter of tunnels 10 feet 2 inches and 10 feet 6 inches (see pages 88 and 137).

1888. The **Mersey or Fidler's Ferry Tunnel**, under the River Mersey, commenced. This was constructed with a cast-iron lining by means of a shield and compressed air.

Diameter of tunnel 9 feet (see page 224).

The **St. Clair for Sarnia Tunnel** was built under the St. Clair River with cast-iron lining, with shield and compressed air.

Length of tunnel built with shield, 6,000 feet. Diameter of tunnel, 19 feet 10 inches (see page 172).

1889. A small tunnel with cast-iron lining and driven by means of a shield was made at Blackton, in connexion with Middlesbrough Water Works.

Diameter of tunnel, 13 feet 6 inches.

The Hudson tunnel works, abandoned for some years, were recommenced, the tunnels being constructed in cast iron by means of a shield and compressed air.

Diameter of tunnels, 18 feet (see page 167).

1890. **Glasgow Harbour Tunnel.** In this work three tunnels were driven side by side under the River Clyde. They were lined with cast iron, and shields and compressed air were employed in their construction.

Length of each tunnel, 700 feet. Diameter of tunnels, 16 feet (see page 152).

1891. **Glasgow Subway.** This work is a circular underground railway in Glasgow, 6½ miles in length, of two tunnels with cast-iron linings. Nearly the entire length was built by means of Greathead shields, and compressed air was used in the subaqueous portions where the tunnels pass under the River Clyde.

Diameter of tunnels (single line), 11 feet (see page 139).

A small tunnel was driven under the Thames at Kingston by the Southwark and Vauxhall Water Company. This tunnel was of 8 feet 4 inches diameter, and was for its entire length of 540 feet in the London Clay. A second tunnel was driven near the first in 1901.

1892. The **Blackwall Tunnel under the River Thames.** Shield and compressed air employed.

Length of tunnel built with shield, 3,116 feet. Diameter of tunnel, 25 feet (see page 180).

The **Siphon de Clichy**, a portion of the main drainage system of Paris, was made under the River Seine, near Clichy, by means of a shield of the Greathead pattern, and with a lining of cast iron.

Length of tunnel, 1,522 feet. Diameter of the tunnel, 8 feet 2¼ inches (see page 157).

Baltimore Belt Line.

An attempt was made to construct a short length of tunnel by means of shields, but was abandoned almost immediately.

APPENDIX

East River Gas Tunnel, New York

This is a tunnel constructed under the East River between Seventy-first Street, New York, and Ravenswood, Long Island, for the convenience of gas mains. Portions of the tunnel were built with an iron lining, and a large proportion of the total length was built with a shield and in compressed air.

Total length of tunnel, 2,516 feet. Diameter of iron-lined tunnel, 10 feet 2 inches (see page 216).

A roof shield, made to travel on side walls previously built, was tried on a tunnel under Howard Street, Baltimore, U.S.A.

1893. **The Mound tunnels at Edinburgh** were constructed in connexion with some railway extensions of the North British Railway Company.

They were built under compressed air and with a shield, and lined with cast iron.

Length of each tunnel, 750 feet. Diameter of tunnels, 16 feet 4 inches (see page 156).

The Melbourne Tunnel

The Melbourne (Australia) tunnel, which formed a part of the drainage system of that city, was built in cast iron, brick and timber linings, by means of a shield of the Greathead type, and with compressed air.

This tunnel is notable for the serious accident which occurred in April, 1895, by which seven men lost their lives.

Diameter of tunnel, 11 feet (see *Engineering*, November 11, 1898).

Emmersburg Tunnel

This tunnel, near Schaffhausen in Switzerland, is a small iron-lined tunnel built by the aid of a shield of rudimentary character, consisting of little more than a roof plate or hood which slid over the iron lining.

Diameter, about 5 feet vertical, about 3 feet 6 inches horizontal.

The Waterloo and City Railway, London

This work consists of two single-line tunnels, connecting the Waterloo terminus of the South-Western Railway with the City of London. All the tunnels are constructed in cast iron, and by means of shields of the Greathead type. In certain parts of the line compressed air was employed, and shields of a special design were used.

Length of railway, 1 mile 46 chains. Diameter of tunnels, 12 feet $1\frac{3}{4}$ inches, 12 feet 9 inches ; diameter of station tunnels, 23 feet (see page 143).

1895. Tunnel under the Spree at Berlin

An experimental length of tunnel was driven under compressed air by shields designed by M. Mackensen, the lining being of wrought iron, with joints reinforced by plates projecting outside of the tunnel circumference, somewhat in the manner of the Andersen pilot tunnel.

Diameter of tunnel, 13 feet 2 inches.

The Collecteur de Clichy " Extra Muros "

This main sewer, forming part of the drainage system of Paris, was constructed at a depth of a few feet only under the streets of Paris in a busy district by means of a shield designed by M. Chagnaud. The shield was the first roof shield or " carapace " employed, and for the first time also a masonry lined tunnel was constructed behind any shield.

The sewer was elliptical in shape, being about 19 feet 8 inches in inside horizontal diameter and 16 feet 5 inches high, the masonry being nowhere more than 2 feet thick.

Length of tunnel, 5,715 feet. Dimensions inside masonry, 19 feet 8 inches by 16 feet 5 inches (see page 278).

The Collecteur de Clichy "Intra Muros"

This was a continuation of the preceding work, and in dimensions and form of construction was the same. The shield used, however, was of the older type, completely enclosing the tunnel behind it.

Length of tunnel, 8,450 feet (see page 285).

The Siphon de la Concorde

This siphon under the River Seine is like the Siphon de Clichy, a part of the main drainage of Paris, and, like it, was constructed by a Greathead shield, and with a circular cast-iron lining.

Length of siphon, 780 feet. Diameter of tunnel, 8 feet $2\frac{1}{2}$ inches (see page 158).

1896. The Central London Railway [1]

This railway, $6\frac{1}{2}$ miles in length, connects the western suburbs of London with the city, and consists of two single-line tunnels lined with cast iron, with larger tunnels at the stations. Greathead shields were used throughout, and at certain points, as under the Holborn Viaduct and in front of the Bank of England, compressed air was used, as a precaution against settlement of the heavy structures above.

Diameter of tunnels, 11 feet $8\frac{1}{4}$ inches; stations, 22 feet $2\frac{1}{2}$ inches (see page 104).

Tremont Street Tunnel, Boston

This is a masonry tunnel for two lines of railway, and forms part of the Boston Underground Railway. It was built with a roof shield, of novel construction, and moving in concrete side walls built in advance headings, the arch built within the shield being of brick. In the brickwork were embedded cast-iron rods to take the thrust of the shield rams.

Width of tunnel, 23 feet. Length built under shield, 550 feet (see page 303).

Tunnel under the River Spree, Berlin

In connexion with a tramway, a tunnel with a composite lining of cast iron and concrete was built with a hooded shield and compressed air under the Spree. It was not finished until 1899.

Diameter of tunnel, 13 feet 2 inches. Length, 1,490 feet.

The Ripley Tunnel, U.S.A.

The water supply of Ripley in New York State, U.S.A., has on its main service pipe a tunnel constructed with compressed air and in brick, and for a short length with a shield worked by hand screws.

Length of the tunnel built with shield, 60 feet. Diameter, 3 feet 6 inches.

1897. Siphon de l'Oise, France

This consists of a shaft and tunnel on the line of a discharge sewer for irrigation works in connexion with the main drainage system of Paris. The tunnel passes

[1] From this date onward, numerous "tube" railways have been constructed in the London Clay. Tunnelling work by means of a shield has, in fact, been going on continuously in London since 1896.

under the River Oise near its junction with the Seine. It was built for part of its length with a shield, and under compressed air.

The permanent lining consists of concrete enclosed in a thin steel plate casing, this latter being built in rings after the manner of cast-iron tunnels. The concrete was built up on removable steel plate centres, and compressed in position by the rams of the shield.

Length of tunnel built with shield, 919 feet. Diameter of tunnel, 6 feet 8 inches (see page 291).

1898. Collecteur de Bievre, Paris

In connexion with the extension of the Orleans Railway along the quays of the Seine, a considerable alteration in the system of main sewers in the district was necessary, and the diversion of the Bievre outfall sewer, one of the main arteries, was carried out in masonry by means of roof shields.

This sewer for a part of its length was elliptical in section, the dimensions inside the masonry being: horizontal axis, 16 feet 2 inches; vertical axis, 10 feet 10 inches. For this section a roof shield (of the Chagnaud type) was used.

The remainder was circular in section, the internal diameter being 13 feet 2 inches, two roof shields being used, the one of the Chagnaud type and the other of the Dieudonnat[1] pattern.

Total length of sewer, 8,025 feet.

1898. Aqueduct of the Rivers Loing and Lunain, France

In making this aqueduct, a tunnel with concrete lining was constructed, and a shield somewhat of the type used in the Paris sewers was employed, but with very unsatisfactory results, the tunnel ultimately being completed in timbered lengths in the ordinary manner.

Diameter of tunnel, 8 feet $2\frac{1}{2}$ inches.

The Meudon Tunnel, France

This double-line tunnel on the Western Railway of France is situated between Issy and Viroflay, and was driven from its two extremities at the same time. From the Issy end, ordinary tunnel timbering was used, from the other the tunnel was driven by means of a roof shield similar in construction to those used in the Orleans and Metropolitan Railways of Paris.

The arch of the tunnel is made of concrete bricks, the side walls are of concrete faced with concrete blocks, and the invert of concrete. The shield work was, after some sixteen months, abandoned entirely, a very small proportion of the tunnel having been driven, and the work was finished in the ordinary manner.

Width of tunnel, 29 feet 6 inches. Height of tunnel, 24 feet.

Paris Extension of the Orleans Railway

In the construction of this line, which lies under the quays on the south bank of the Seine between the Pont d'Austerlitz and the Pont de Solferino, three roof shields were employed, the aggregate length of tunnel so constructed being about 4,000 feet. The tunnel is a double-line one.

No compressed air was used, only the invert being in water-bearing material.

Width of tunnel, 29 feet 6 inches. Height of crown above rails, 15 feet 7 inches (see page 295).

Waterloo and Baker Street Railway, London

This railway, 3 miles 1 furlong in length, connects the terminal station of the

[1] This shield resembles the Lamarre shield figured on page 335.

South-Western Railway in London with the northern districts, and consists of two single-line tunnels with larger tunnels at the stations.

The greater portion of the line was built with the ordinary Greathead shield, only the length under the Thames in water-bearing gravel being driven with "trap" shields, and under compressed air.

Diameter of tunnels, 12 feet; at stations, 23 feet (see page 265).

1899. The Greenwich Footway Tunnel

This tunnel passes under the River Thames at Greenwich, and was built with a "trap" shield and under compressed air. Access to it is obtained by lifts and stairways placed in shafts 35 feet in diameter, and about 60 feet deep.

Length of tunnel, 1,217 feet. Diameter of tunnel, 11 feet 9 inches (see page 231).

Metropolitan Railway of Paris

Only a small portion of this extensive system was built by means of shields of the usual French type, and for the most part the machines employed were unsatisfactory. The shields were exclusively used for masonry tunnels for two lines of railway (see pages 324 and 357).

Chicago U.S.A., Intercepting Sewers

In these sewers, a shield known as the Hastings shield was used in 1899 (*Engineering News,* August 7, 1899) for the construction of a brick-lined tunnel about 20 feet in internal diameter.

Later another shield was used in the Thirty-ninth Street Conduit, with compressed air. This seems to have resembled the Hudson and Blackwall types (*Engineering News*, May 28, 1903).

Sewer at Worcester, Massachusetts, U.S.A.

A small sewer was constructed in this year in brickwork through quicksand by means of compressed air. At one point, where the sewer passed under a railway, a lining made of pressed steel plates was employed.

Boston (U.S.A.) Harbour Tunnel

This tunnel, constructed under Boston Harbour, and forming part of the Boston Underground Railway, is a masonry one for two lines of railway. Between Sumner Street East, Boston, and Commercial Street, Boston, it was built under compressed air, a roof shield being employed, which travelled on concrete side walls built in advance headings.

Width of tunnel, 23 feet 4 inches. Length of tunnel built under shield, 5,000 feet (see page 312).

1901. Lea River Tunnel

In connexion with an extension of the main drainage of London, a tunnel of cast iron, constructed with a "trap" shield and by means of compressed air, was driven under the River Lea.

Length of tunnel constructed with shield and compressed air, 1,100 feet. Diameter of tunnel, 11 feet (see page 259).

Chelsea Tunnel

A small tunnel similar to that constructed under the Thames at Kingston was built from Chelsea on the north to Wandsworth on the south to connect up the pipe systems of the New River Water Company, and of the Southwark and Vauxhall Water Company.

APPENDIX

New York " Rapid Transit " Works (in course of construction)

The extension of the underground railway system of New York in this year included the construction of two tunnels (now in progress) under the East River and Harlem River respectively.

The subaqueous portions of both consist of two single-line circular tunnels, cast-iron lined, and 15 feet 6 inches in internal diameter.

In the East River tunnel a shield with compressed air is employed, the total length of double tunnel being 6,650 feet, and the maximum depth of the rails below mean high water, 94 feet.

The Harlem River tunnel has a length of 640 feet of double iron tunnel, and was constructed by means of McBean's system of piled timber subaqueous caissons and compressed air.

See *Engineering Record*, August 22, September 5, December 19 and 26, 1903; March 5 and 12, August 20, 1904; *Engineering News*, October 1 and 8, 1903; October 13 and November 10, 1904.

East River Tunnel of Pennsylvania Railway, New York (in course of construction)

The portion of this tunnel under the East River between First Avenue, Manhattan Island, and East Avenue, Queens, consists of two cast-iron tunnels similar to the East River Tunnel of the New York Rapid Transit Lines.

1903. **Hilsea Creek Tunnel**

This tunnel was constructed under the Hilsea Creek for the line of pipes supplying water to Portsmouth.

A shield was used in its construction, and it is lined with cast-iron segments. Internal diameter of tunnel, 11 feet 10 inches. Length, 600 feet (see page 363).

Brackenagh Tunnel

A portion of this tunnel, which forms part of the aqueduct supplying Belfast with water from the Mourne Mountains, was built with a shield and compressed air, and lined with cast iron.

Internal diameter of cast-iron tunnel, 5 feet 4 inches. Length of tunnelling in compressed air, 660 feet (see page 362).

1904. **Rotherhithe Tunnel** (works commenced only)

This, the largest tunnel of its kind yet undertaken, is to be driven under the River Thames at Stepney, London.

Diameter of tunnel, 30 feet (external) (see page 340).

The Holborn Tunnels

In connexion with the construction of the new street, Kingsway, connecting Holborn with the Strand, the London County Council constructed a tramway subway, which passes under Holborn in two single-line tunnels, circular, with cast-iron linings, and 250 feet in length.

They were built with a shield, the material passed through being mainly London Clay, a little sand and gravel showing in the upper part of the face.

Diameter of tunnels, 15 feet (see page 122).

River Dee Tunnel (in course of construction)

This forms a part of an extension scheme for the drainage system of Aberdeen. The tunnel under the River Dee is now in course of construction by means of a shield and compressed air. It is circular, with a cast-iron lining of the usual type.

Diameter of tunnel, 7 feet 8 inches, Length, 344 feet (see page 352).

1905. **Metropolitan Railway of Paris (Southern section)**

A shield known as the Raquet shield was employed for a short distance on an extension of this railway near the Place d'Italie on the south side of the Seine (see page 357).

APPENDIX B

Some English Patents relating to Tunnelling with Shield and Compressed Air, 1818 to 1904.[1]

No. 4204 of 1818. M. J. Brunel.
The shield.

No. 6018 of 1830. T. Cochrane.
Tunnelling by the aid of compressed air.

No. 12632 of 1849. S. Dunn.
A shield in one piece, having the front entirely closed, and intended to drive through the ground, no material being excavated through the tunnel.

No. 2207 of 1864. P. W. Barlow.
A shield in one piece, combined with cast-iron lining to the tunnel, which is to have grouting behind.

No. 770 of 1866. R. Morton.
(Provisional protection only.)
A shield in one piece, with closed pointed face and hydraulic rams, combined with cast-iron tunnel lining (no drawing).

Provisional Patent (no number), 1868. P. W. Barlow.
A shield similar to the patent 2207 of 1864, but with a vertical diaphragm.

No. 688 of 1870. W. R. Lake.
A shield or movable frame which can travel on the bed of the waterway in which the tunnel or other work is to be laid, and in which is an expanding cloth or canvas which can be opened out under the shield, thus making an air space in which the miners can work.

No. 2221 of 1873. G. T. Bousfield.
A compressed air-lock like that used continually from 1845 onwards.

No. 1738 of 1874. J. H. Greathead.
A shield having a closed face, the soil in front of which is to be disintegrated by water jets, and by protruding tools. The tunnel to be lined with cast iron, or with moulded artificial blocks. Grouting to be injected behind the tunnel lining.

No. 2585 of 1876. T. Clapham and W. Clapham.
A mechanical erector for tunnel plates.

[1] The list includes all those English patents relating to shields and to the use of compressed air in working chambers or caissons which the author has been able to find, but none of the numerous patents involving the use of compressed air as a motive force for mining machinery are inserted.

APPENDIX

No. 5,665 of 1884. J. H. Greathead.
A shield, etc., as in No. 1738 of 1874 with some modifications.

No. 5221 of 1886. J. H. Greathead.
The grouting pan. A shield similar to those of No. 1738 of 1874 and 5665 of 1884.

No. 13,215 of 1887. J. H. Greathead.
A shield with alternatively a central rotary cutter, with wedges for breaking down the face, washing out pipes, and wedges only, etc.

No. 195 of 1889. J. H. Greathead.
A shield with revolving cutter.

No. 919 of 1889. Louis Coiseau.
A shield divided into compartments forming separate air chambers in conjunction with a bulkhead and air-lock in the tunnel.

No. 19550 of 1889. M. J. Jennings.
Roof needles.

No. 7374 of 1890. J. J. Nobbs.
A shield moving forward in sections, and having an envelope composed of narrow longitudinal plates, capable of being advanced separately.

No. 18,267 of 1891. S. Pearson & Son.
A shield having compartments forming separate air chambers, and having in front shutters capable of movement by means of hydraulic rams.

No. 717 of 1893. G. Talbot.
An improvement in timbering in front of a shield by the use of a movable rib.

No. 1445 of 1893. J. J. Robins.
A combination of a shield with a rotary cutter concentrically fixed in it.

No. 12273 of 1894. F. H. Poetsch.
A method of sinking shafts with a vertical shield and rotary cutter.

No. 12575 of 1894. P. Kraus.
A shield with hood advancing on rollers, and bearing on iron centres which support the tunnel behind.

No. 18565 of 1895. F. C. Glaser.
A shield having a projecting roof, the face being closed, and a vertical diaphragm in the rear enabling work to be carried on with compressed air.

No. 622 of 1896. H. H. Dalrymple Hay.
A hooded shield, to be worked in conjunction with the use of clay filling in front.

No. 13907 of 1896. J. Price.
A rotary cutter to work with an ordinary Greathead shield.

No. 16970 of 1896. H. H. Dalrymple Hay.
Gauge for guiding shields.

No. 865 of 1897. T. Thomson.
A ladder excavator to work with an ordinary Greathead shield.

No. 6608 of 1897. C. Redlich.
A system of constructing tunnels in lengths, each length being built above ground, and sunk into position in an air-tight caisson.

No. 9549 of 1897. G. Burt.
A rotary cutter, and conveyor to work in an ordinary Greathead shield.

No. 26,804 of 1898. W. J. E. Binnie.
Construction of a tunnel in mass concrete behind a shield by means of movable centering of cast iron.

APPENDIX

No. 11219 of 1899. T. H. Murphy.

Construction of a masonry tunnel behind a shield by building in the first place a heavy timber skin within the shield, forming a temporary tunnel lining, and affording an abutment to receive the thrust of the shield, instead of this latter bearing on green masonry.

No. 11220 of 1899. C. G. Hastings and T. H. Murphy.

A shield with air-tight bulkheads, and having a mechanical erector behind. The tail of the shield to consist of separate flexible strips of metal instead of one cylindrical plate.

No. 8748 of 1900. A. W. Manton.

A rotary cutter for tunnel work.

No. 16981 of 1900. C. G. Hastings.

A shield having compartments fitted with face shutters composed of movable slats.

No. 10045 of 1901. A. W. Farnsworth.

A shield with concentric rotary cutter.

No. 26153 of 1901. C. M. Jacobs.

Construction of tunnels in soft material such as silt, by supporting lengths of cast-iron tunnel stiffened with longitudinal girders on piers sunk through the soft material to underlying solid foundations.

No. 17227 of 1902. J. Breuchaud.

Construction of tunnels by means of a shield and compressed air, the shield being made to allow of the construction underneath it of pile or other foundations on which it advances, and on which the tunnel is subsequently constructed.

No. 18423 of 1902. J. F. O'Rorke.

Construction of tunnels in soft or water-bearing material by caissons in which successive lengths are built.

No. 23417 of 1902. T. Cooper.

A shield with diaphragms to form a water-seal.

Nos. 6828, 6830, and 6831. D. D. McBean.

A method of constructing tunnels under water in timber casing with compressed air.

INDEX

INDEX

INDEX

INDEX

INDEX

BUTLER & TANNER,
THE SELWOOD PRINTING WORKS,
FROME, AND LONDON.