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Underexcavating the Tower of Pisa: Back to Future

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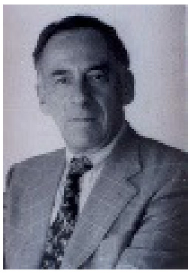

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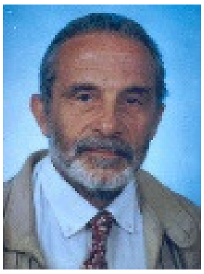

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SYNOPSIS: The stabilization of the Tower of Pisa is a very difficult challenge for geotechnical engineering. The tower is founded on weak, highly compressible soils and its inclination has been increasing inexorably over the years to the point at which it is about to reach leaning instability. Any disturbance to the ground beneath the south side of the foundation is very dangerous; therefore the use of conventional geotechnical processes at the south side, such as underpinning, grouting, etc., involves unacceptable risk. The internationally accepted conventions for the conservation and preservation of valuable historic buildings, of which the Pisa Tower is one of the best known and most treasured, require that their essential character should be preserved, with their history, craftsmanship and enigmas. Thus any intrusive interventions on the tower have to be kept to an absolute minimum and permanent stabilization schemes involving propping or visible support are unacceptable and in any case could trigger the collapse of the fragile masonry.

In 1990 the Italian Government appointed an International Committee for the safeguard and stabilization of the Tower. It was conceived as a multidisciplinary body, whose components are: experts of arts, restoration and materials; structural engineers; geotechnical engineers. After a careful consideration of a number of possible approaches, the Committee adopted a controlled removal of small volumes of soil from beneath the north side of the foundation (underexcavation). The technique of underexcavation provides an ultra-soft method of increasing the stability of the tower which is completely consistent with the requirements of architectural conservation.

The paper reports the analyses and experimental investigations carried out to explore the applicability of the procedure to the stabilization of the leaning tower of Pisa. All the results being satisfactory, a preliminary stage of underexcavation of the tower has been carried out in 1999; the results obtained are presented and discussed.

1. INTRODUCTION

A cross section of the Leaning Tower of Pisa is reported in Figure 1. It is nearly 60m high and the foundation is 19,6 m in diameter; the weight is 141.8 MN. In the early 90's the foundation was inclined southwards at about 5,4° to the horizontal. The average inclination of the axis of the tower to the vertical is somewhat less, due to its slight curvature resulting from corrections made by masons during the construction, to counteract the inclination already occurring.

The seventh cornice overhangs the first one by about 4.1 m. Construction is in the form of a hollow cylinder. The inner and outer surfaces are faced with marble and the annulus between these facings is filled with rubble and mortar within which extensive voids have been found. A spiral staircase winds up within the annulus. Figure 1 clearly shows that the staircase forms a large opening on the south side just above the level of the first cornice, where the cross section of the masonry reduces. The high stress within this region was a major cause of concern since it could give rise to an abrupt brittle failure of the masonry.

Figure 2 shows the ground profile underlying the tower. It consists of three distinct horizons. Horizon A is about 10 m thick and primarily consists of estuarine deposits, laid down under tidal conditions. As a consequence, the soil types consist of rather variable sandy and clayey silts. At the bottom of Horizon A there is a 2m thick medium dense fine sand layer. Based on sample descriptions and piezocone tests, the materials to the south of the tower appear to be more silty and clayey than to the north and the sand layer is locally thinner.

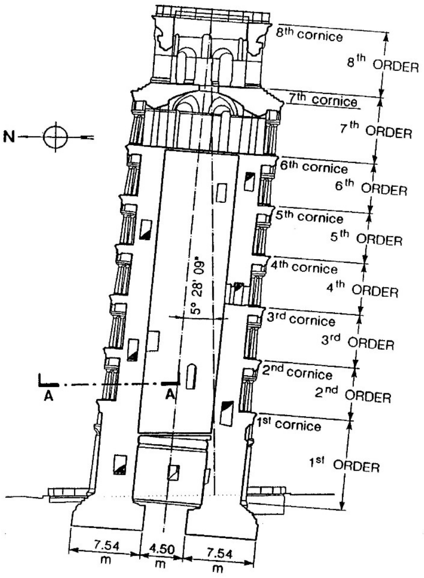


Figure 1 Cross section through the tower of Pisa in the plane of maximum inclination (very nearly coincident with the north-south plane)

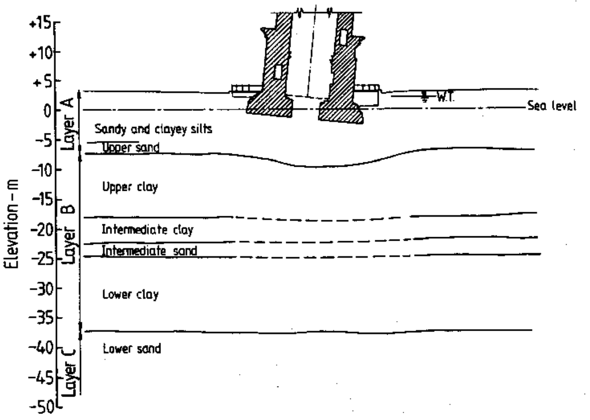


Figure 2 Soil profile beneath the tower

Horizon B consists primarily of marine clay, which extends to a depth of about 40 m. It is subdivided into four distinct layers. The upper layer is soft sensitive clay locally known as the Pancone. It is underlain by an intermediate layer of stiffer clay, which in turn overlies a sand layer (the intermediate sand). The bottom layer of horizon B is normally consolidated clay known as the lower clay. Horizon B is laterally very uniform in the vicinity of the tower.

Horizon C is a dense sand (the lower sand) which extends to considerable depth.

The water table in horizon A is between 1 m and 2 m below the ground surface. Pumping from the lower sand has resulted in downward seepage from horizon A with a pore pressure distribution with depth through horizon B which is slightly below hydrostatic.

The many borings beneath and around the tower show that the surface of the Pancone clay is dished beneath the tower, from which it can be deduced that the average settlement of the monument is approximately 3 m.

Fuller details about the tower and its subsoil, including a wide list of references, are reported by Burland et al. (1999)

In 1990 the Italian Government appointed an International Committee for the safeguard and stabilization of the Tower. It was conceived as a multidisciplinary body, whose components are: experts of arts, restoration and materials; structural engineers; geotechnical engineers.

The Committee recognised the need for temporary and fully reversible interventions, aimed at an improvement of the safety against the risk of structural collapse or overturning by foundation failure of the tower. The temporary measures gave to the Committee the time to complete the investigations and analyses necessary to conceive and implement the final stabilisation measures.

In the summer of 1992 the safety of the masonry was temporarily improved by applying lightly pre-stressed steel strands around the tower in the vicinity of the first cornice. At present the masonry is being consolidated by grouting and the temporary circumferential strands will soon be removed. The observation that the northern side of the tower foundation had been steadily rising for most of this century led to the suggestion of applying a north counterweight to the tower, as a temporary measure to improve the safety against overturning by reducing the overturning moment. Accordingly, a design was developed consisting of a pre-stressed concrete ring cast around the base of the tower for supporting a number of lead ingots. This intervention was successfully implemented in 1993. The Committee has developed a detailed understanding of the history of the inclination of the tower, and in particular of the movements it has experienced last century. These have been observed by a very comprehensive monitoring system, installed on the tower since the beginning of the 20 century and progressively enriched. The behaviour of the tower clearly indicates that its equilibrium is affected by leaning instability, a phenomenon controlled by the stiffness of the subsoil rather than by its strength (Gorbunov Possadov, Serebrjany, 1961; Habib, Puyo, 1970; Schultze, 1973; Hambly, 1985; Cheney et al, 1991; Lancellota, 1993; Desideri, Viggiani, 1994; Desideri et al, 1997). The analysis of the problem, taking into account the non-elastic and non-linear restraint exerted by the foundation shows that a limited decrease of the inclination of the tower would greatly increase its safety and arrest the progress of inclination.

The Committee has been exploring a variety of approaches to permanently stabilising the tower. The fragility of the masonry, the sensitivity of the underlying clay and the very marginal stability of the foundations impose severe restraints. Any measures involving the application of concentrated loads to the masonry or underpinning operations beneath the south side of the foundation have thus been ruled out. Moreover conservation considerations require that the impact of any stabilising measures on the formal, historical and material integrity of the monument should be kept to an absolute minimum.

After a long and heated discussion, the Committee decided to give priority to so called "very soft" solutions, aimed at reducing the inclination of the tower by up to half a degree (i.e. by about 10% the present inclination) by means of an induced settlement beneath the north side of the foundation, without even touching the structure of the tower. Besides improving the stability of the foundation, such an approach allows also a reduction of masonry overstressing, thus contributing to reducing to a minimum the work needed to consolidate the tower fabric itself.

The Committee gave careful consideration to a number of possible approaches, such as the construction of a ground pressing slab to the north of the tower, coupled to a post-tensioned concrete ring constructed around the periphery of the foundations and loaded by tensioned ground anchors, or the consolidation of the Pancone Clay by means of electro-osmosis. Eventually the choice was that of a controlled removal of small volumes of soil from beneath the north side of the foundation (underexcavation).

Underexcavation was originally proposed by Terracina (1962) as a method to increase the stability of the tower of Pisa. Recently the method has been successfully employed in Mexico (Tamez et al., 1989; Santoyo et al., 1989); among many cases, an important application was aimed at mitigating the impact of the very large differential settlements which affected the Metropolitan Cathedral of Mexico City (Tamez et al., 1995). The principle of the method is to extract a small volume of soil at a desired location, leaving a cavity. The cavity gently closes due to the overburden pressure, causing a small surface subsidence. The process is repeated at various chosen locations and very gradually the inclination of the tower is reduced.

The present paper reports the analyses and experimental investigations carried out to explore the applicability of the procedure to the stabilisation of the leaning tower of Pisa. All the results being satisfactory, a preliminary stage of underexcavation of the tower has been carried out in 1999; the results obtained are also presented and discussed.

2. SMALL SCALE lg TESTS

Edmunds (1993) performed a number of small scale physical tests on a model tower resting on a bed of fine sand, to study the effect of underexcavation on a tower close to the collapse for leaning instability. A sketch of the experimental setup is reported in Figure 3. A model tower with a diameter of 102 mm was placed at the top of a very loose fine sand bed, and loaded through a hanger at height of 126 mm over the base. The ratio 126/102 is approximately equal to the ratio of the height of the centre of gravity of the tower of Pisa to the diameter of its foundation.

Loading the model tower produced a settlement and a rotation α. A total of 8 load tests were carried out; the load at failure varied between 120 and 190 N. Failure in all cases was by toppling with the lowest edge of the model tower's base sinking into the sand as the tower rotates toward horizontal.

The individual plots of α varying with load give somewhat scattered results, but when combined into one plot, as in Figure 4, a well defined envelope of results emerges. The envelope shows a pronounced change in curvature at a load of 160 to 165N, where the inclination averages 0.09 ($\alpha = 5^o$).

After this preliminary investigation the underexcavation tests were performed starting with a load of 165 N and a rotation of 5.5°. These conditions are believed to be representative of a tower on the verge of leaning instability. Underexcavation was performed by inserting a stainless steel tube with an outer diameter of 6 mm, and inside it an inner suction tube connected to a vacuum pump. The inner tube, with an outer diameter of 2.1 mm, removes the sand from inside the larger tube that is thus advanced into the soil by a form of self-boring, without significant disturbance of the surrounding soil. The whole probe is advanced to the desired location and then retracted, leaving a cavity that closes instantaneously.

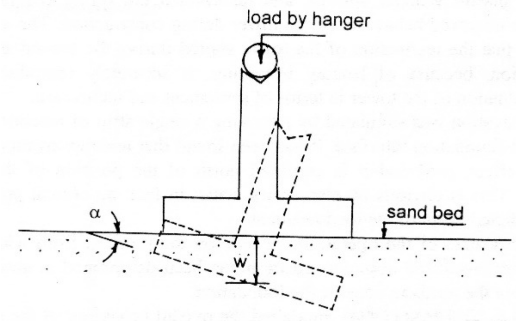


Figure 3 Experimental set up for small scale physical test (Edmunds, 1993)

The underexcavation tubes are held in position by external guides and penetrate the sand at an angle of 18° 26' (3/1). Five radial tubes have been adopted, covering a sector of 90° centered on the north side of the model tower.

A total of 14 underexcavation tests with different combinations of probe positions and penetration sequence have been performed. The most important indications emerging from those tests are as follows:

- underexcavation can be used to reduce the tilt of the model in a controllable manner. Reductions of tilt up to 1° have been obtained;
- the movement of the tower can be steered using probes inserted at a range of positions around the tower;
- the results are reproducible, at least qualitatively;
- a critical point exists some 10 mm north of the central axis of the tower, in the ground beneath it, beyond which ground removal aggravates the tilt, but behind which underexcavation produces a decrease in tilt;
- repeated use of one probe in isolation rapidly ceases to significantly affect the tower's tilt;

Most of these indications are believed to apply qualitatively to the case of the tower of Pisa.

3. PRELIMINARY SIMPLIFIED ANALYSES

Thilakasiri (1993) modelled the subsoil of the tower as a set of elastic- perfectly plastic Winkler springs, and determined the spring constants by fitting the observed behaviour of the tower during construction. The analysis confirms that the inclination of the tower started during the second stage of construction, because of leaning instability; it accurately reproduces the present situation of the tower in terms of settlement and inclination. Underexcavation was simulated by removing a single strip of reaction stress at the soil-foundation interface. It has been found that underexcavation has a positive effect, provided it is confined north of the position of the load resultant. This is obvious by elementary statics; in fact, no critical point has been predicted north of the load resultant.

The effectiveness of the operation depends on the position from which the stress is removed; the optimum position has been determined at about half radius from the northern edge of the foundation.

Desideri & Viggiani (1994) modelled the overall behaviour of the subsoil and the tower foundation by an elasto-plastic strain hardening restraint, and simulated the underexcavation intervention by a reduction in overturning moment with constant vertical force. Desideri et al. (1997) modelled the subsoil as a bed of Winkler type elastic-strain hardening plastic springs; they found that the overall behaviour of the tower and the subsoil can be described by a set of yield loci eventually merging into a failure locus, and by an associative flow rule. All these spring models do not predict the occurrence of a critical line.

Como et al. (1999) simulate the subsoil as a bed of elastic-perfectly plastic Winkler springs, and assume that the effects of underexcavation may be simulated by a reduction of stiffness and strength of a part of these springs. According to such a model, the occurrence of a critical line is connected to a contraction of the yield locus of the foundation, due to the strength reduction in the soil. They claim that no critical line can be found if an elastic model is assumed for the subsoil.

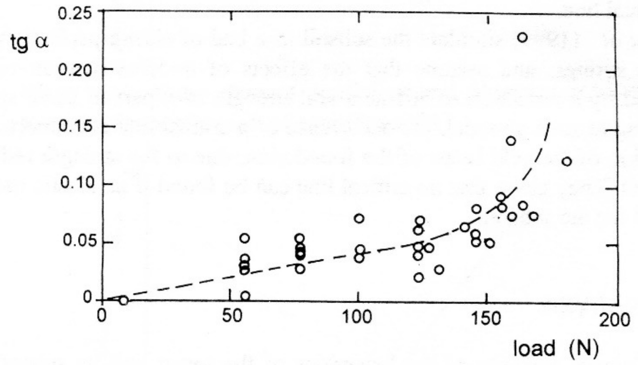


Figure 4 Inclination α of the model tower vs. applied vertical load

4. FEM ANALYSIS

Finite element analyses of the behaviour of the tower and its subsoil have been carried out using a finite element geotechnical computer program developed at Imperial College and known as ICFEP (Potts & Gens, 1984). The constitutive model is based on Critical State concepts and is non-linear elastic work hardening plastic. Fully coupled consolidation is incorporated, so that time effects due to the drainage of pore water in the soil skeleton are included.

The prime object of the analysis was to improve the understanding of the mechanisms controlling the behaviour of the Tower (Burland & Potts, 1994). Accordingly, a plane strain approach was used for much of the work, and only later was three dimensional analyses used to explore certain detailed features.

The layers of the finite element mesh matched the soil sub-layering that had been established from soil exploration studies, as reported in § 2.2 above. Figure 5a shows the adopted mesh, while Figure 5b reports the detail of the mesh in the immediate vicinity of the foundation. In Horizon B the soil is assumed to be laterally homogeneous; however a tapered layer of slightly more compressible material was incorporated into the mesh for layer A as shown by the shaded element in Figure 5b. This slightly more compressible region represents a more clayey material found beneath the south side of the foundation; in applied mechanics terms this slightly more compressible tapered layer may be considered as an "imperfection". The overturning moment generated by the lateral movement of the centre of gravity of the tower was incorporated into the model as a function of the inclination of the foundation, as shown in Figure 5.

The construction history of the tower was simulated by a series of load increments applied to the foundation at suitable time intervals. The excavation of the catino in 1838 was also simulated in the analysis. Calibration of the model was carried out by adjusting the relationship between the overturning moment generated by the centre of gravity and the inclination of the foundation. A number of runs were carried out with successive adjustments being made until good agreement was obtained between the actual and the predicted present day value of the inclination.

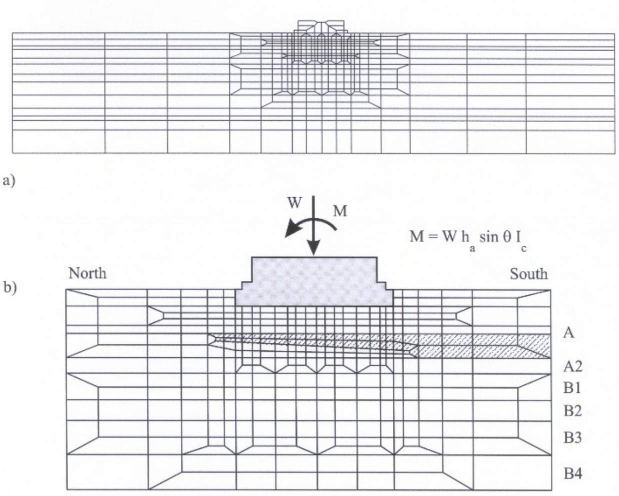


Figure 5 Finite element model, a) General mesh, b) Mesh in the vicinity of the tower foundation

Figure 6a shows a graph of the predicted changes in inclination of the tower against time, compared with the deduced historical values. From about 1272 onwards there is a remarkable agreement between the model and the historical inclination. Note that it is only when the bell chamber was added in 1360 that the inclination increases dramatically (Figure 6b). Also of considerable interest is the excavation of the catino in 1838 which results in a predicted rotation of about 0.75°. It should be noted that the final imposed inclination of the model tower is 5.44° which is slightly less than the present day value of 5.5°. It was found that any further increase in the final inclination of the tower model resulted in instability: a clear indication that the tower is very close to falling over.

The analysis has demonstrated that the lean of the tower results from the phenomenon of settlement instability due to the high compressibility of the Pancone Clay. The principal effect of the layer of slightly increased compressibility beneath the south side of the foundation is to determine the direction of lean, rather than its magnitude. The main limitation is that the model does not deal with creep. Nevertheless the model provides important insights into the basic mechanisms of behaviour and has proved valuable in assessing the effectiveness of various proposed stabilisation measures.

As reported before, a lead ingot counterweight was installed on the north side of the tower between May 1993 and January 1994; the observed behaviour of the tower is reported in Figure 7. On 29th February 1994, one month after completion of loading, the northward change of inclination was 33"; by the end of July it had increased to 48". On 21st February 1994 the average settlement of the tower relative to the surrounding ground was about 2.5 mm.

Figure 8 shows a comparison of the Class A prediction and measurements of (a) the changes in inclination and (b) the average settlement of the tower during the application of the lead ingots. The computed settlements are in good agreement with the measured values; the predicted changes in inclination are about 80% of the measured values.

The movements observed during the counterweight application have been used to further refine the model. After such a refinement, that involved a small reduction of the value of G/p'$_0$ in horizon A, a better overall agreement between computed and observed values has been obtained (Figure 9).

The re-calibrated model has been used to simulate the extraction of soil from beneath the north side of the foundation. It should be emphasised that the finite element mesh had not been developed with a view of modelling underexcavation; the individual elements are rather large for representing regions of extraction. Thus the purpose of the modelling was to throw light on the mechanisms of behaviour rather than attempt a somewhat illusory "precise" analysis.

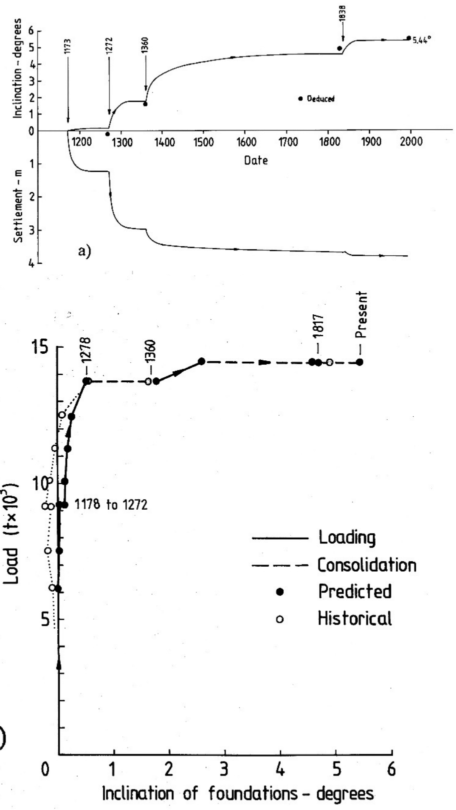


Figure 6 Comparison between the history of the tower and the results of the finite element model, a) Inclination and settlement versus time, b) Relationship between the weight and the inclination of the tower

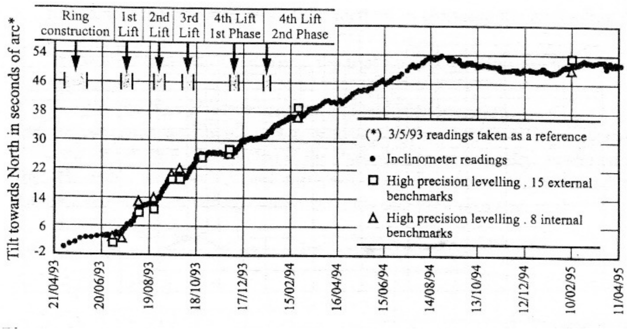


Figure 7 Variation of the inclination of the tower in response to placement of the counterweight

The soil extraction has been simulated by reducing the volume of any chosen element of ground incrementally, so as to achieve a predetermined reduction in volume of that element.

The first objective of the numerical analysis was to check whether the concept of a critical line, whose existence was revealed by the small scale tests by Edmunds (1993) was valid. Figure 10 shows the finite element mesh in the vicinity of the tower. Elements numbered 1, 2, 3, 4 and 5 are shown, extending southwards from beneath the north edge of the foundation. Five analyses were carried out in which each of the elements was individually excavated to give full cavity closure and the response of the tower computed. For excavation of elements 1, 2 and 3 the inclination of the tower reduces, so that the response is positive. For element 4 the response is approximately neutral, with an initial slight reduction in inclination which, with further excavation, was reversed. For element 5 the inclination of the tower increased as a result of excavation.

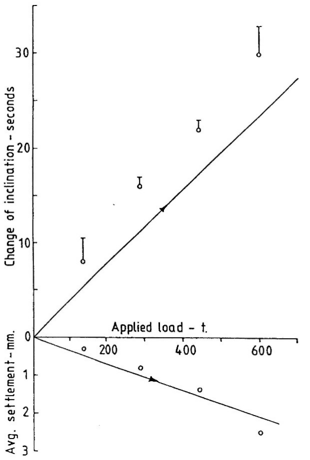


Figure 8 Plane strain finite element prediction and observed response of the tower to the application of counterweight

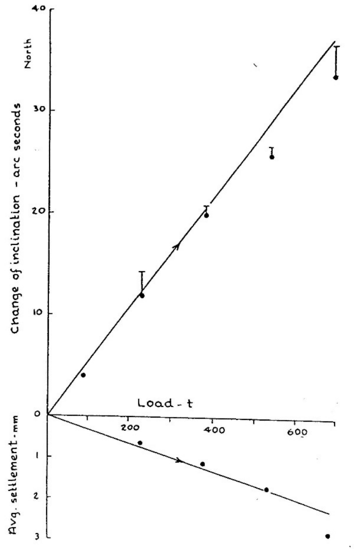


Figure 9 Comparison of the observed response of the tower to the counterweight with the recalibrated plane strain model prediction

The above analyses confirm the concept of a critical line separating a positive response from a negative one. For the plane strain computer model the location of the critical line is towards the south end of element 4 which is at a distance of 4.8 m underneath the foundation of the tower, i.e. about one half the radius of the foundation.

It was noted that, as the location of excavation moved further and further south beneath the foundation, the settlement of the south side steadily increases as a proportion of the settlement of the north side. Excavation of elements 1 and 2 give a proportion of less than one quarter.

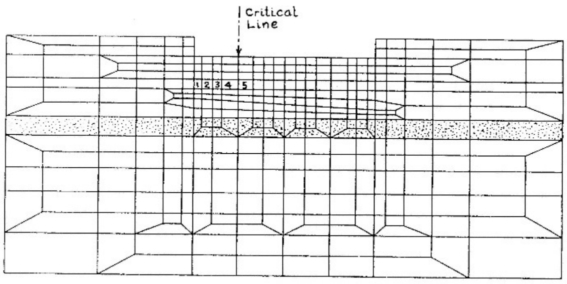


Figure 10 Finite element mesh in vicinity of tower foundation showing elements which were individually excavated to investigate the existence of a critical line

Having demonstrated that localised soil extraction gives rise to a positive response, the next stage was to model a complete underexcavation intervention aimed at safely reducing the inclination of the tower by a significant amount.

A preliminary study was carried out of extraction using a shallow inclined drill hole, extracting soil from just beneath the foundation. Although the response of the tower in terms of decrease of inclination was favourable, the stress changes beneath the foundation were large; consequently a deeper inclined extraction hole was investigated.

The insert in Figure 11 shows the finite element mesh in the vicinity of the foundation on the north side. The elements numbered 6 to 12 were used for carrying out the intervention and are intended to model an inclined drill hole. It should be noted that element 12 lies south of the critical line established by localised soil extraction as described above. The procedure for simulating the underexcavation intervention was as follows:

- the stiffness of element 6 is reduced to zero;
- equal and opposite vertical nodal forces are applied progressively to the upper and lower faces of the element until its volume reduces by about 5%. The stiffness of the element is then restored;
- the same procedure is then applied successively to the elements 7, 8, 9, 10 and 11 thereby modelling the progressive insertion of the drill probe. For each step the inclination of the tower reduces;
- when element 12 is excavated the inclination of the tower increases, confirming that excavation south of the critical line gives a negative response. The analysis is therefore re-started after excavating element 11;
- the retraction of the drill probe is then modelled by excavating elements 10, 9, 8, 7 and 6 successively. For each step the response of the tower is positive;
- the whole process of insertion and retraction of the drill probe is then repeated. Once again excavation of element 12 gives a negative response.

The computed displacements of the tower are plotted in Figure 11. The sequence of excavation of the elements is given on the horizontal axis; the upper diagram shows the change of inclination of the tower due to underexcavation; the lower diagram shows the settlement of the north and south sides of the foundation.

As underexcavation progresses from elements 6 through 11 the rate of change of northward inclination increases as do the settlements. As the drill is retracted the rate decreases. At the end of the first cycle of insertion and retraction of the drill the inclination of the tower is decreased by 0.1°. The settlement of the south side is rather more than one half of the north side. For the second cycle a similar response is obtained but the change of inclination is somewhat larger. After the third insertion of the drill the resultant northward rotation was 0.36°. The corresponding settlements of the north and south sides of the foundation were 260 mm and 140 mm respectively.

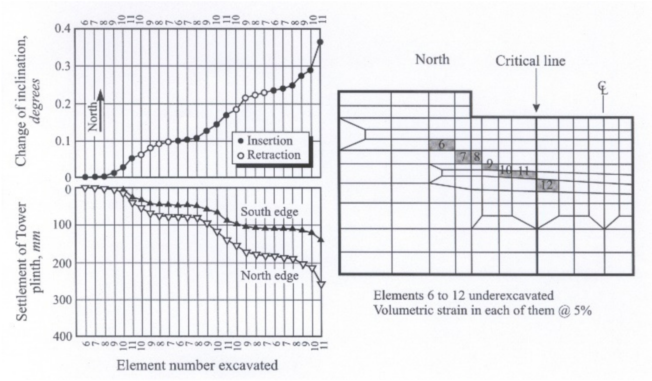


Figure 11 Predicted response of the tower to underexcavation beneath the north side by means of an inclined drill hole. The volumetric reduction for each element was approximately 5%

As for the contact stress distribution, the process results in a slight reduction of stress beneath the south side. Beneath the north side, some fluctuations in contact stress take place, as it was to be expected, but the stress changes are small. In general the stress distributions after retraction of the drill are smoother than after insertion.

5. CENTRIFUGE TESTS

Centrifuge modelling of the tower and its subsoil has been carried out at ISMES, with the aim of exploring the present stability conditions of the tower and their possible evolution with time. The results obtained are reported and discussed by Pepe (1995).The tests gave further insight into the mechanisms of the instability and confirmed the elastoplastic character of the restraint exerted by the foundation and the subsoil on the motion of the tower.

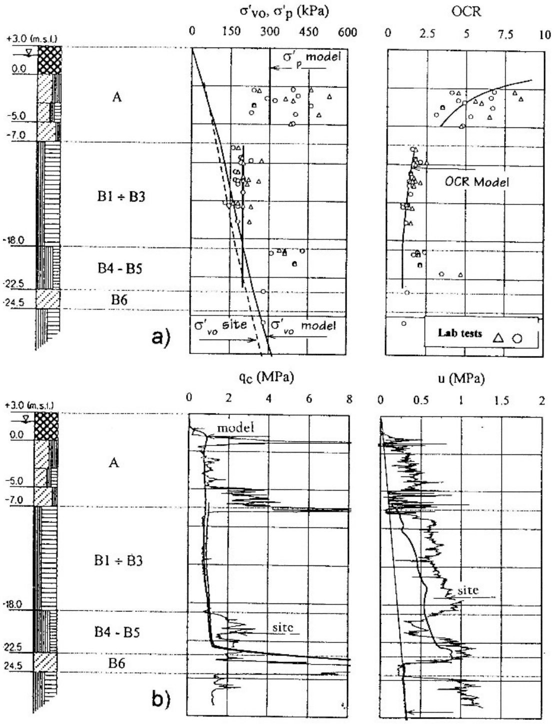


Figure 12 Comparison between the properties of the subsoil of the tower and those of the centrifuge model, a) Overconsolidation of clay layers, b) Piezocone profiles

In Figure 12 the properties of the foundation soils of the tower are compared with the properties obtained in the small scale model after consolidation under geostatic load in the centrifuge; the main features of the soil profile are satisfactorily reproduced in the model.

Figure 13 reports the simulation of the construction of the tower, as obtained by one of the centrifuge tests. It may be seen that both the settlement and the rotation of the tower are in good overall agreement.

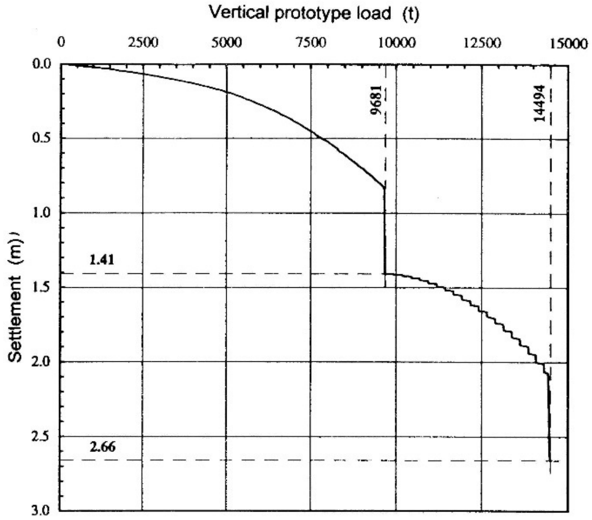


Figure 13 Centrifuge simulation of the construction of the tower; test Y/E15

The centrifuge was also used to assess the effectiveness of underexcavation as a means to stabilise the tower. The process of soil extraction was modelled by inserting into the ground beneath the model tower flexible tubes with wires inside, prior to the commencement of the experiment. Once the model tower had come to equilibrium at an appropriate inclination under increased gravity, the wires were pulled out of the flexible tubes by an appropriate amount, while the model was in flight, causing the tubes to close simulating the closure of the cavity produced by a drill probe.

Figure 14 reports the results of a typical experiment. The test results confirmed the existence of a critical line and showed that soil extraction north of this line always gave a positive response.

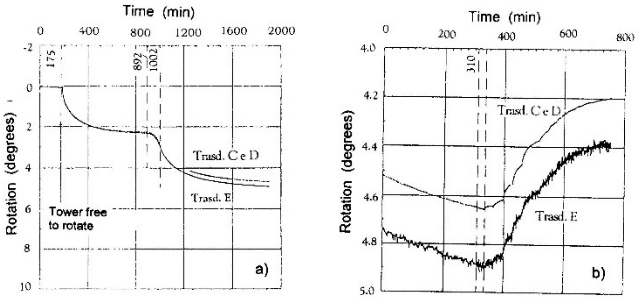


Figure 14 Centrifuge simulation of the underexcavation, a) Construction of the tower, b) Underexcavation

6. LARGE SCALE FIELD EXPERIMENT

The results of the physical and numerical modelling work on underexcavation were sufficiently encouraging to undertake a large scale development trial of the field equipment. The objectives of the trial were:

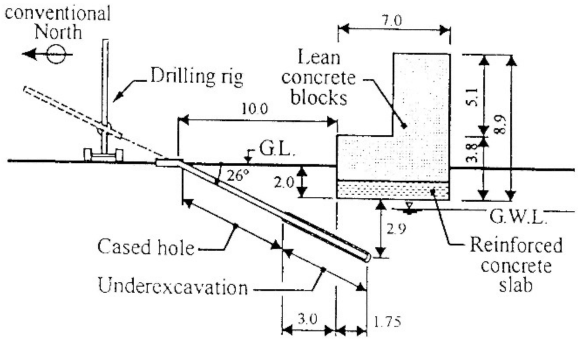
- to develop a suitable method of forming a cavity without disturbing the surrounding ground during drilling;
- to study the time involved in the cavity closure;

- to measure the changes in contact stress and pore water pressures beneath the trial footing;
- to evaluate the effectiveness of the method in changing the inclination of the trial footing;
- to explore methods of "steering" the trial footing by adjusting the drilling sequence;
- to study the time effects between and after the operation.

For this purpose a 7 m diameter eccentrically loaded circular reinforced concrete footing was constructed in the Piazza north of Baptistry, as shown in Figure 15. Both the footing and the underlying soil were instrumented to monitor settlement, rotation, contact pressure and pore pressure.

Figure 15 Underexcavation trial field

After a waiting period of a few months, allowing the settlement rate to come to a steady value, the ground extraction commenced by means of inclined borings, as schematically shown in Figure 16. Drilling was carried out using a hollow stemmed continuous flight auger inside a contra-rotating casing.



Drawing not to scale - all dimensions in meters

Figure 16 Underexcavation trial field; cross section

The trial has been very successful. When the drill is withdrawn to form the cavity, an instrumented probe located in the hollow stem is left in place to monitor its closure (Figure 17). A cavity formed in the Horizon A material has been found to close smoothly and rapidly.

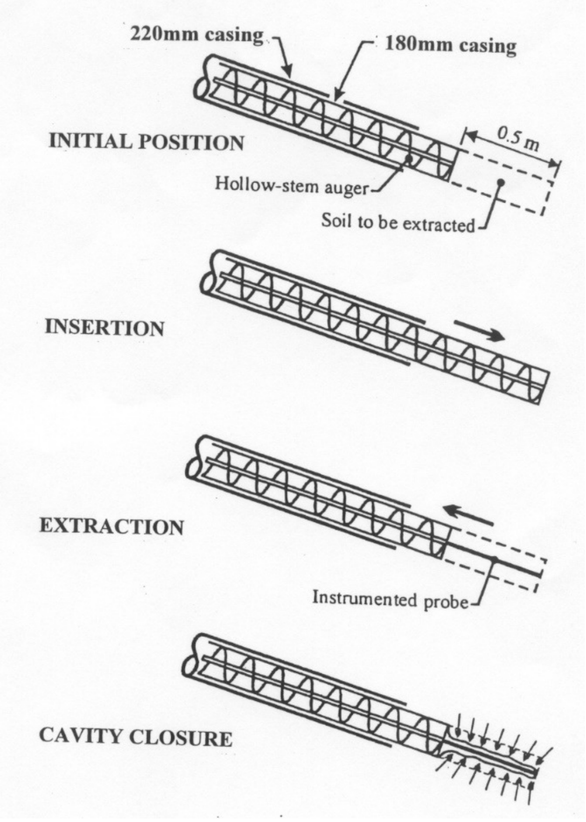


Figure 17 Soil extraction process

Figure 18 reports the measurements of the contact stress at the soil-foundation interface along the north - south axis, before underexcavation (19.09.95) and after a substantial rotation of the footing (01.12.95).

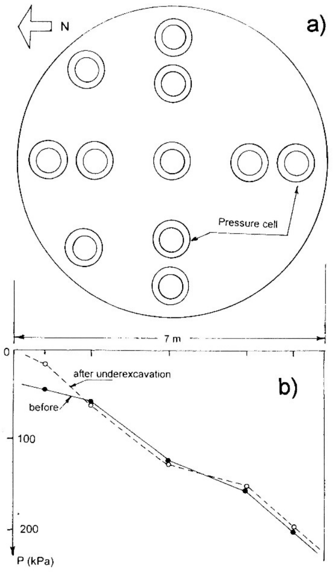


Figure 18 Stress variations at the soil-foundation interface during the large scale underexcavation trial, a) Layout of the pressure cells, b) Pressure distribution along the north-south axis at two different dates

The stress changes beneath the foundation were found to be very small. The trial footing was successfully rotated by about 0.25° and directional control was maintained even though the ground conditions were somewhat non-uniform. Rotational response to soil extraction was rapid, taking a few hours. At the completion of the underexcavation, in February 1996, the plinth came to rest and since then it has exhibited negligible further movements (Figure 19). Very importantly, an effective system of communication, decision taking and implementation was developed.

It is of importance to note that, early in the trial, over enthusiastic drilling resulted in soil extraction from excess penetration beneath the footing causing a counter rotation (Figure 19). Therefore the trial also confirmed the concept of a critical line.

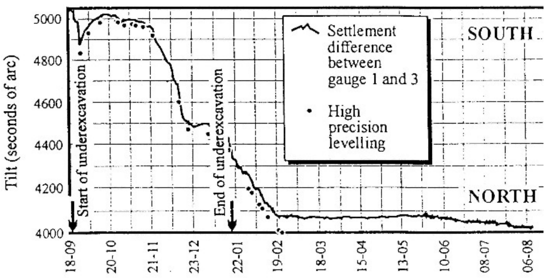


Figure 19 Underexcavation large scale field experiment: rotation of the plinth in the north-south plane

7. PRELIMINARY UNDEREXCAVATION OF THE TOWER

The results of all the investigations carried out on the underexcavation were positive, but the Committee was well aware that they might be not completely representative of the possible response of a tower affected by leaning instability. Therefore it was decided to implement preliminary ground extraction beneath the tower itself, with the objective of observing its response to a limited and localised intervention. This preliminary intervention consists in 12 holes (Figures 20 and 21) to extract soil from Horizon A to the north of the tower foundations, penetrating beneath the foundation not more than 1 m. The goal was to decrease the inclination of the tower by a significant amount, in order to check the feasibility of underexcavation as a means to permanently stabilise the tower, and to adjust the extraction and measurement techniques.

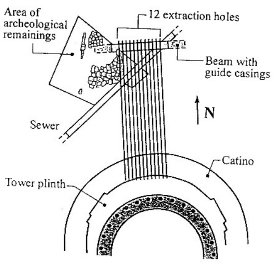


Figure 20 Preliminary underexcavation experiment beneath the tower: layout

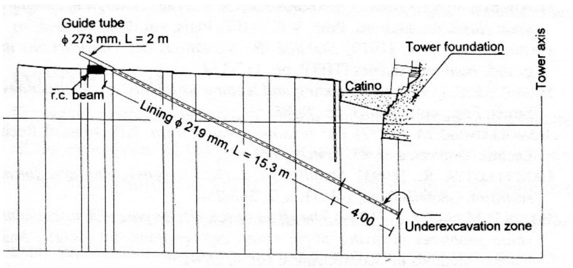


Figure 21 Preliminary underexcavation experiment beneath the tower: cross section

To protect the tower from any unexpected adverse movement during this or any other interventions aimed at the final stabilisation of the monument, a safeguard structure was considered mandatory. The structure finally chosen consists of two sub-horizontal steel stays connected to the tower at the level of the third order and to two anchoring steel frames located behind the building of the Opera Primaziale, to the north of the tower. The scheme of the safeguard structure is reported in Figure 22; it was installed and connected to the tower in December 1998.

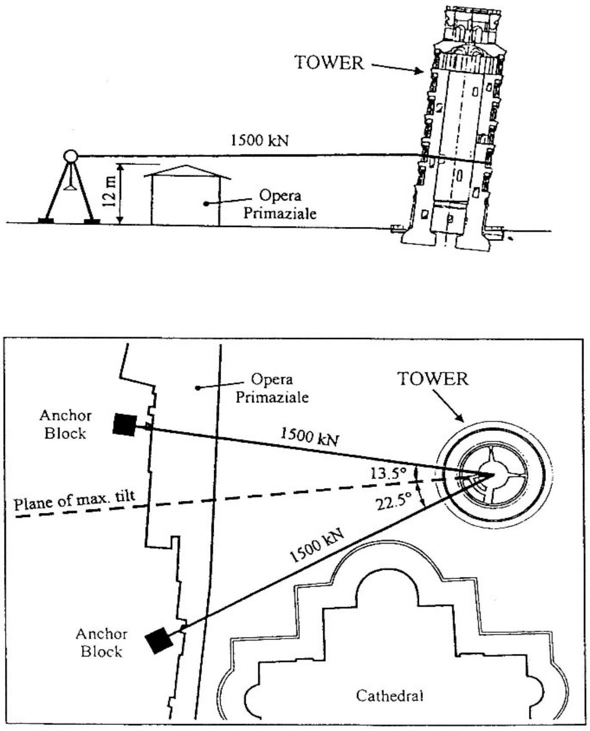


Figure 22 Cable stay provisional structure, a) cross section, b) Layout in plan

Each stay is capable of applying a maximum force of 1500 kN, with a safety factor equal to 2. The force may be applied by dead weights or by hydraulic jacks; the value of the applied load is continuously monitored. At present, the load applied to each stay is equal to about 72 kN, just enough to keep it in position.

The underexcavation experiment has been carried out between February and June, 1999. The results obtained are reported in Figure 23. During the underexcavation period, the tower rotated northwards at an increasing rate, as the extraction holes where drilled gradually ahead near the north boundary of the foundation and below it. At the beginning of June 1999, when the operation ceased, the northwards rotation of the tower was 90"; by mid-September it had increased to 130". At that time three of the 97 lead ingots (weighing about 10 t each) acting on the north side of the tower were removed; since then the tower has exhibited negligible further movements. As a matter of fact, the preparatory operations for the final underexcavation (removal of the 12 guide casings of the preliminary undexcavation, installation of the 41 guide casings for the final underexcavation) have produced a slight further northward rotation, bringing the overall decrease of inclination in March, 2000 to 135".

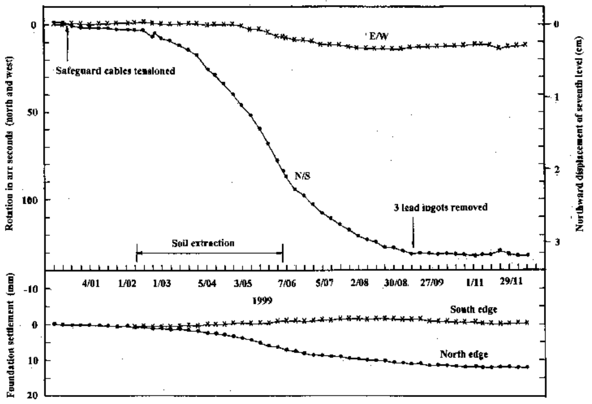


Figure 23 Results of the preliminary underexcavation experiment a) Variation of the inclination, b) Settlement of the north (N) and south (S) edges of the foundation

The rotation in the east - west plane has been much smaller, reaching a final value of about 10" westwards, as intended.

Due to underexcavation, the north side of the tower foundation underwent an overall settlement equal to 1,3 cm; in the meantime the south side first raised up to 2 mm, and then gradually settled by the same amount, showing that the axis of rotation is located between the two points.

To put these results in perspective, the evolution of the tilt of the tower base since 1993 is reported in Figure 24. The effect of the underexcavation experiment largely overwhelms that of counterweight and the seasonal cyclic movements.

A longer time perspective is gained by the diagram in Figure 25, reporting the inclination since 1935 as measured by a pendulum inclinometer installed at that time. It may be seen that the effect of the preliminary underexcavation has been to bring the tower "back to future" by over 30 years.

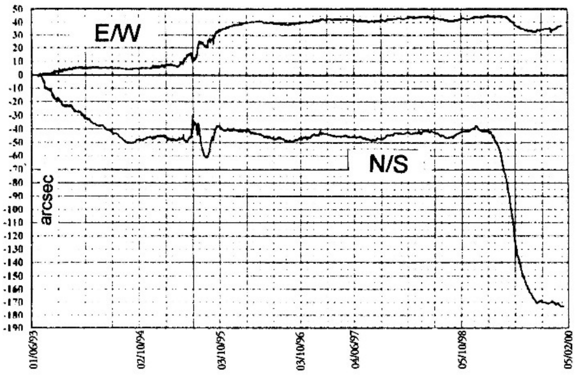


Figure 24 Results of the preliminary underexcavation experiment in terms of variation of the inclination, as measured by the pendulum inclinometer

8. CONCLUDING REMARKS

The stabilisation of the Tower of Pisa is a very difficult challenge for geotechnical engineering. The tower is founded on weak, highly compressible soils and its inclination has been increasing inexorably over the years to the point at which it is about to reach leaning instability. Any disturbance to the ground beneath the south side of the foundation is very dangerous. Therefore the use of conventional geotechnical processes at the south side, such as underpinning, grouting, etc., involves unacceptable risk. The internationally accepted conventions for the conservation and preservation of valuable historic buildings, of which the Pisa Tower is one of the best known and most treasured, require that their essential character should be preserved, with their history, craftsmanship and enigmas. Thus any intrusive interventions on the tower have to be kept to an absolute minimum and permanent stabilisation schemes involving propping or visible support are unacceptable and in any case could trigger the collapse of the fragile masonry.

The technique of underexcavation provides an ultra-soft method of increasing the stability of the tower which is completely consistent with the requirements of architectural conservation. Different physical and numerical models have been employed to predict the effects of soil removal on the stability. It is interesting to point out that some mechanisms (as, for instance, the occurrence of a critical line beyond which the underexcavation becomes dangerous) are predicted by physical modelling and by the FEM analyses, while are missed by the simplified Winkler type models.

The preliminary underexcavation intervention, undertaken after having been satisfied by comprehensive numerical and physical modelling together with a large scale trial, has demonstrated that the tower responds very positively to soil extraction.

There is still a long journey ahead for the Tower, requiring detailed communication and control and the utmost vigilance, but indeed the first step has been taken in the permanent geotechnical stabilisation.

As a postscript it should be mentioned that this paper was first published in 2000 before full underexcavation of the Tower was carried out. Work on the Tower has now been successfully completed and an up-date on the behavior of the Tower can be found in Burland et al (2009).

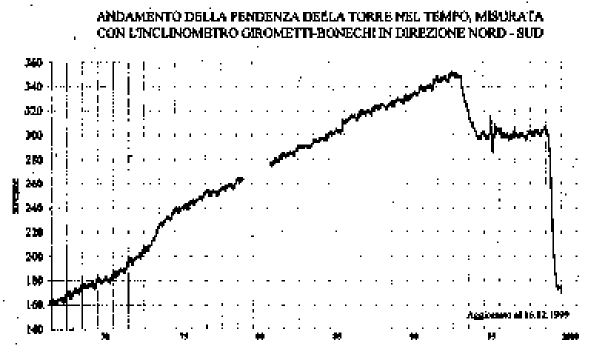


Figure 25 Results of the preliminary underexcavation experiment in terms of variation of the inclination, as measured by the pendulum inclinometer

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