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INTERACTION BETWEEN STRUCTURAL AND GEOTECHNICAL ENGINEERS

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Interaction between structural and geotechnical engineers

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Synopsis

There are many situations for which interaction between structure and ground has to be considered. This involves important interactions between specialist structural and geotechnical engineers. During his career the author has encountered profound differences in approach between structural and geotechnical engineers often leading to a lack of understanding and difficulties in communication. This paper explores these differences and the reasons for them.
The term modelling is used extensively. It is defined as the process of idealising a real-life project including its geometry, material properties and loading in order to make it amenable to analysis and hence assessment for fitness of purpose. It is demonstrated that traditional structural modelling is very different from geotechnical modelling.
In this paper extensive reference is made to Hambly's three and four legged stool, termed by Heyman16 as 'Hambly's paradox'. Hambly used the simple example of a four-legged stool to show that structural design calculations are frequently wide of the mark when it comes to analysing real-world structures. It is concluded that concepts such as ductility and robustness underpin the success of both structural and geotechnical modelling and more explicit recognition of these is needed. Case histories are given where ductility has been utilised and where lack of ductility has led to failure. The importance of gaining a clear understanding of mechanisms of behaviour prior to detailed analysis is also illustrated by means of case histories.

Introduction

Interaction always takes place between a structure and its foundation ... whether or not the designers allow for it'. In some situations interaction can be minimised e.g. by founding the building on rigid piles. Such an approach can be very costly and is often not feasible. If structure-ground interaction is to be taken into account, structural and geotechnical engineers themselves have to interact.
There have been many occasions when I have both witnessed and experienced difficulties in communications between structural and geotechnical engineers and it has been a continuing source of interest to me as to why this should be so. It is a matter of outstanding importance because poor communication and lack of understanding can lead to poor engineering and even failures. The invitation to prepare this paper and deliver the 2006 IStructFJ10E Joint Lecture is for mc, not only a great honour, but it has also provided me with an opportunity to explore the interactions between the structural engineer and the geotechnical engineer.

I have come to the conclusion that, at the heart of the problem, there are differences in the day to day approach to modelling structural and geotechnical behaviour. I will try not to side with

either discipline – the objective is to improve understanding between the two disciplines of the way the ‘average' practitioner tackles design. My hope is that, by identifying these differences there is a much better chance of moving towards more integrated approaches to designing for soil-structure interaction.
The term modelling will be used extensively in this paper. It is intended to describe the process of idealising the real-life project (or part of it) including the geometry, material behaviour and loading in order to make it amenable to analysis, carrying out that analysis, reviewing it and then assessing the design for ‘fitness for purpose'. Thus the process of modelling is very much more than carrying out the analysis itself.

Structural modelling

In 1994 the late Edmund Hambly, a most innovative structural engineer who obtained Kis PhD in Soil Mechanice, published a
book Structural Analysis by Example2. It was intended as a handbook for undergraduates and professionals who like to use physical reasoning and of the-shelf computer modelling to understand structural form and behaviour. Fifty examples are given of structural problems of increasing complexity ranging from simple frames, through beams, columns and slabs, to shear lag and torsion, and then on to whole structures such as offshore platforms and spiral staircases. The book represents an admirable summary of the range of problems and types of analysis that a structural engineer encounters in day to day practice.
In terms of modelling, it is evident that the geometry of most structures is well defined and reasonably easy to idealise. Rather simple linear elastic material behaviour is usually assumed with a limiting stress imposed. The major idealisations in the modelling process are in the loading, although in Hambly's book this is specified, as is usually the case in cxxdes of practice and standards. It is evident that the process of routine structural modelling mainly consists of idealising the structural form (often termed the ‘conceptual model') and carrying out analysis — usually on the computer. Recently The Institution of Structural Engineers3 and MacLeod[4] have set out more formal procedures for the structural modelling process.

Limitations to structural modelling

Using Hambly's book as an exemplar, it is evident that structural engineers think primarily in terms of the forces and stresses (or equivalent elastic displacements) that are the outputs from the structural models that they use in day to day practice. Yet most studies on real whole structures (especially buildings) show that the measured strains and displacements bear little semblance to the calculated oness. The classic experiments on large-scale steel structures carried out in the early 1930s under the direction of Lord Baker revealed that the measured stresses under working loads bore very little relation to the calculated values6. The National Building Studies Research Paper No 28 records that the biggest change of strain in the steel beams of the Ministry of Defence Building in Whitehall was caused by the shrinkage of the concrete after the floors had been sast — this was larger than that induced by the loading of the floors subsequently[7]. Much more recently I have found that the thermal and seasonal movements of buildings are often as large as the movements induced by tunnelling and yet these are overlooked when assessing the response of buildings to foundation movements. Thcee limitations have been appreciated for a long time but are easily forgotten. The fact is that the uncertainties of modelling real projects are dealt with in good practice, not only by factors of safety, but also by incorporating appropriate levels of ductility and robustness.

Ductility and robustness

Ductility may be defined as the ability to un ergo inelastic deformations without significant less of strength while robustness can be defined as the ability to absorb damage withaut collapse.
On page 1 of' Hambly's book referense is made to the Safe Design fiheorem which, of course, derives from the lower bound theorem of plasticity.This theorem states that:
A structure should be able to carry its design loads safely if:

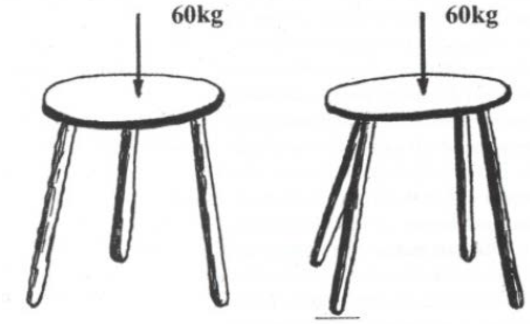
- The calculated system of forces is in equilibrium with the loads and reactions, and throughout the structure.
- Fach component has strength to transmit its calculated force and ductility to retain its strength while deforming.
- The structure has sufficient stiffness to keep deflections small and to avoid buckling before design loads are reached.

If the real structure deforms under load with a different flow of forces to that calculated it should still be safe as long as the materials are ductile (like steel) and not brittle (like glass). The equilibrium check ensures that any underestimate of the force flowing through one part of the structure is balanced by an overestimate in the force in another part. Then ductility ensures that the component that is over-stressed retains its strength while deforming, and sheds the excess force to the parts which have available capacity as a result of the equilibrium check. It is the ductility of structures which ensures the success of current design methods. This is frequently overlooked and, in my experience, many structural engineers still seem to believe that their structures behave as calculated – a belief that powerful computer programs and prescriptive codes of practice tend to reinforce. Recently both Heyman[9] and Mann[10] have written on this topic and stressed the need to ensure that the structural details are ductile – also a prerequisite for earthquake design. The inherent ductility and robustness of steel structures is well known and gave rise to modern methods of plastic analysis. Recently Beeby[11.12] summarised the developments in the concepts of ductility in traditional reinforced concrete design and stressed the importance of designing for robustness.

It is important to note that the majority of structural failures result from defects at joints and connections[13]. Engineers do of course carry huge responsibility for ensuring that local instabilities cannot develop – particularly in temporary works and propping systems. For steel structures Burdekin[14] has drawn attention to how important it is for designers to be aware of the factors that give rise to brittle fracture and fatigue.

The three and four-legged stool (Hambly's paradox)

A simple but profound physical model can be used to illustrate what we have been discussing so far. Fig 1 shows two stools, one with three legs and one with four legs's[15]. Imagine that each must support a milkmaid who weighs 60kg, and who always sits with her centre of gravity directly over the middle of the stool. The problem is to determine how much load must be carried by each leg of the three-legged stool and the four-legged stool.
The three-legged stool is straight forward in that one third of the milkmaid's weight must go down each leg i.e. 20kg. For the four-legged stool the answer of 15kg is wrong!



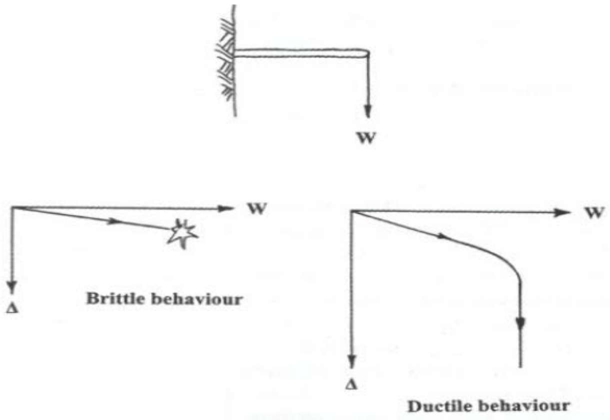


Fig 1.
Tree- and four legged stools
– Hamby's paradox

Fig 2.
Brittle and ductile behaviour of stool leg

Careful inspection of Fig 1 shows that one of the four legs does not quite touch the ground, either because the leg is slightly short or because the ground is uneven, consequently the leg is not carrying any load. The opposite leg will also not be carrying any load because its load must balance that in the short leg when equilibrium of moments is considered about the diagonal through the other two legs. Thus we find that all of the weight is carried by two legs, i.e. 30kg per leg, instead of being shared by the four legs. Hence the paradox 16 - the addition of a fourth leg to a three-legged stool can increase, rather than decrease, the force for which each leg has to be designed. So what load **should** the legs be designed to carry?

It is here that concepts of ductility and robustness come in and the illustrative model can be extended to include material properties. Fig 2 shows the load-displacement properties of a leg, either when acting as a cantilever or in axial compression. In one case very brittle behaviour is illustrated such that at a certain load the strength of the leg is lost completely as it would be if it were made of glass. In the second case the member exhibits ductile behaviour and retains its strength once yield has occurred.

If brittle material is used for the three-legged stool then accidental overload, due perhaps to a very heavy milkmaid or the cow kicking out at the stool, can easily result in total collapse. Clearly high factors of safety are required to deal with this design. It may be decided to opt for four legs but this may be of little help. The design load for each leg would have to be 1.5 times higher than for the three-legged design. Moreover accidental overload may cause loss of one member and there is then a risk of progressive collapse. In other words the structure is fragile.

If ductile properties are chosen there is little likelihood of catastrophic collapse if one of the three legs is damaged. Moreover, with four legs there is scope for redistribution of load once the carrying capacity of a leg is reached. Even accidental removal or serious damage to one member is unlikely to give rise to progressive collapse.

This simple example is very profound and can be extended to other aspects of structural behaviour and design including buckling and ground-structure interaction. Above all, it illustrates the importance of ductility, robustness and redundancy. It is useful to quote Heyman's conclusions[16] to his study of Hambly's paradox:

‘Hambly's four-legged stool status of course, for the general problem of design of any redundant structure It has long been recognised that, in order of calculate the actual' state of a structure underspecified loading, all three of the basic structural statements must be made - equilibrium, material properties and deformation (compatibility and boundary conditions). However, the calculations do not in fact lead to a description of the actual state Boundary conditions art in general, unknown and unknowable; an imperfection in assembly, or a small settlement of a footing, will lead to a state completely different that calculated. This is not a fault of the calculation whether elastic or not - it is a result of the behaviour of the real structure. There is no correct solution to the equations; but one solution that will lead to the greatest economy in material. This is the solution sought by the simple plastic designer, and it is safe and valid provided that no instability is inherent in the structure.'

The important message seems to be that, in the process of structural modelling, the inherent uncertainties are such that the precise state of the structure cannot usually be calculated. The art of structural engineering is to use the process of modelling to produce a design that is robust enough to safely cope with the uncertainties, at reasonable cost and which is fit for purpose. Difficulties arise in interacting with geotechnical engineers when the inherent uncertainties in the structural analysis are not recognised.

Geotechnical modelling

Soil Mechanics is a difficult subject and is regarded by many structural engineers as a kind of black art. It is helpful to discuss the reasons for some of the difficulties.

One difficulty is that the soil, unlike concrete or steel, is a particulate material with little or no bonding between the particles. It is made up of an infinite variety of shapes and sizes of particles. This material is usually modelled as a continuum but it is important never to forget that its properties are determined by its particulate nature.

Because soil is particulate, the water pressures acting within the soil pores are just as important as the stresses applied to its boundaries. This means that changes in the ground water regime can be crucial in stabilising, or de-stabilising a slope, retaining wall or foundation.

In summary, whereas the strength of structural materials, such as steel and concrete, is primarily cohesive and well defined, soil is primarily frictional so that confining pressure and pore water pressure determine its strength and stiffness.

The soil mechanics triangle

ut it is not just the complexity of the material which causes difficulty. There are at least four distinct but interlinked aspects of any soil mechanics problem:

- the ground profile - what is there and how it got there;
- the mechanical behaviour of soil;
- prediction using appropriate models;
- empirical procedures; judgment based on precedent and ‘well-winnowed experience'.

It is my experience that the major difficulty in soil mechanics lies, not so much in the complexity of the material as such, but in the fact that, all too often, the boundaries between the above four aspects become confused'.

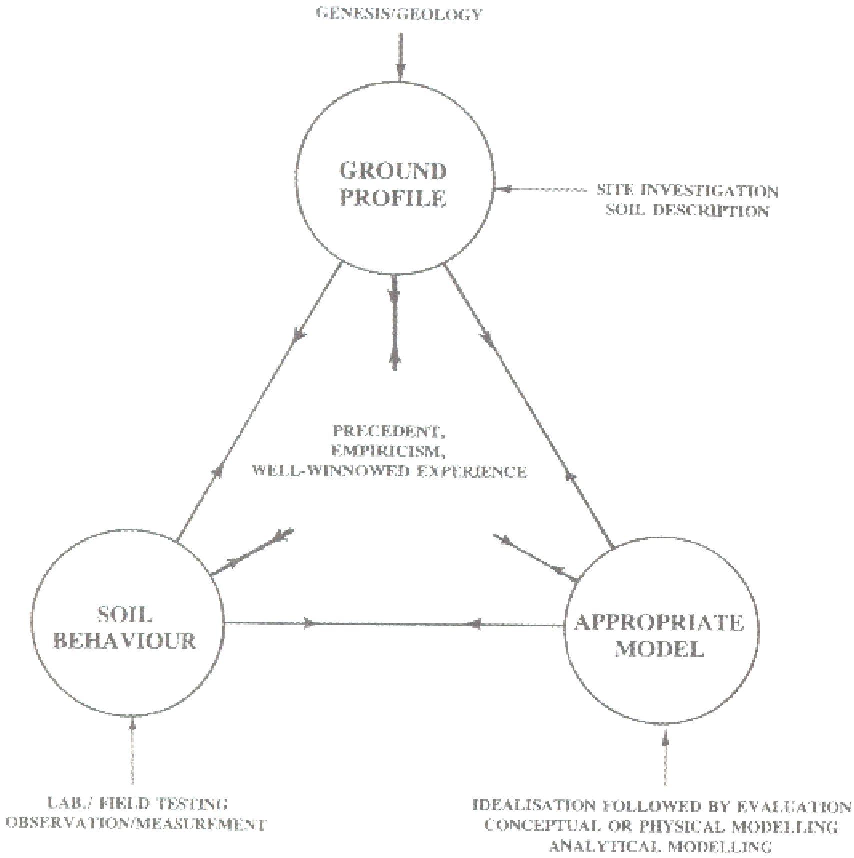


Fig.3.
The soil mechanics triangle

The first three of these may be depicted as forming the apexes of a triangle with empirical procedures occupying the centre as shown in Fig 3. Associated with each of these aspects is a distinct and rigorous activity or discipline. We can consider each of these in turn.

Ground profile: By this I mean the visual description in simple engineering terms of the successive strata making up the ground together with the ground water conditions. The importance of handling and describing the soil so as to establish the ground profile cannot be over-emphasised. It is also important to understand how the ground got there and what might have happened to it during its formation - what is termed its genesis. Establishing the ground profile is a key outcome of carrying out a site investigation – often far more important than measuring the material properties.

Soil behaviour: This is established from laboratory or in situ tests and usually requires very careful and experienced interpretation. The properties may also be inferred from field measurements of behaviour e.g. the back-analysis of a landslip or of settlement observations.

Appropriate modelling: This can be carried out at all sorts of levels. It may be purely conceptual and instinctive; it might be physical modelling or it can involve extremely sophisticated mathematical or numerical work. At whatever level, modelling first involves the process of idealisation (to analyse is to idealise) and should then be followed by review and assessment - it often isn't! Frequently in soil mechanics, as in structural engineering, it is understanding the basic mechanisms of behaviour which is the key rather than the fine quantitative detail. It may be of interest to note that, where as the success of much structural modelling relies on the L*ower Bound Theorem of Plasticity*, geotechnical modelling has traditionally made use of both the *Lower and Upper Bound Theorems of Plasticity* for the study of limiting equilibrium using stress characteristics and slip-line fields. Thus both disciplines are firmly grounded in plasticity. For both disciplines, if the material or structure is brittle in its response extreme caution is required as the *Lower and Upper Bound Theorems* no longer apply.

Empirical procedures: With a material as complex as the ground, empiricism is inevitable and it is (and will always remain) an essential aspect of ground engineering. Many of our design and construction procedures are the product of what I have termed well-winnowed experience".

Each activity in the Soil Mechanics Triangle has its own distinct methodology and rigour. Geotechnical modelling requires that each aspect be considered and that the Soil Mechanics Triangle remains in balance.

Comparisons between structural and geotechnical modelling

It is immediately obvious from the above that the processes of geotechnical modelling usually involves much greater explicit uncertainties and complexities in idealising both the geometry and the material properties than in structural modelling where both of these are usually specified by the engineer.
In introducing the subject of soil-structure interaction to my students, l start by asking them to imagine an Utopean situation of having unlimited computational power in which, given the geometry of the problem, the material properties and the loading, they can analyse any problem. I then ask how much better off they would be than they are at present. As soon as we begin to examine the idealisations that are involved in most ground-structure inter-action problems it soon becomes obvious that we will not be much better off than we are today.

The soil mechanics triangle revisited

Hopefully the above discussion will serve to help structural engineers to understand why the process of modelling geotechnical problems is inherently less certain than it appears to be for most structural problems. Much of the time the structural engineer is working with materials which are specified and manufactured under strict control. Usually the structural form can be idealised in a reasonably straightforward manner. The major uncertainties he in the loading, inevitable imperfections and in the connections. In geotechnical engineering both the geometry (ground profile) and the properties (ground behaviour) of the 'structure' are laid down by nature and not specified. Precise analysis is usually not possible and the key requirement is to understand the dominant mechanisms of behaviour and their likely bounds.
Perhaps the differences between routine structural and geotechnical modelling can bent be illustrated by comparing the approach of the structural engineer working on an existing building to that of the geotechnical engineer because in this situation the structural engineer is no longer able to specify the material and the structural form is often difficult to idealised8. Fig 4 shows an isometric of the West Tower of Ely Cathedral which was strengthened in 1973/74 as described by Heyman[19]. Also shown on Fig 4 is the Soil Mechanics triangle of Figure 3 but with some descriptions changed to represent the key activities undertaken by the structural engineer. For the soil profile at the top of the triangle we can insert the structure of the building and its materials. To establish these requires the most careful examination and investigation.

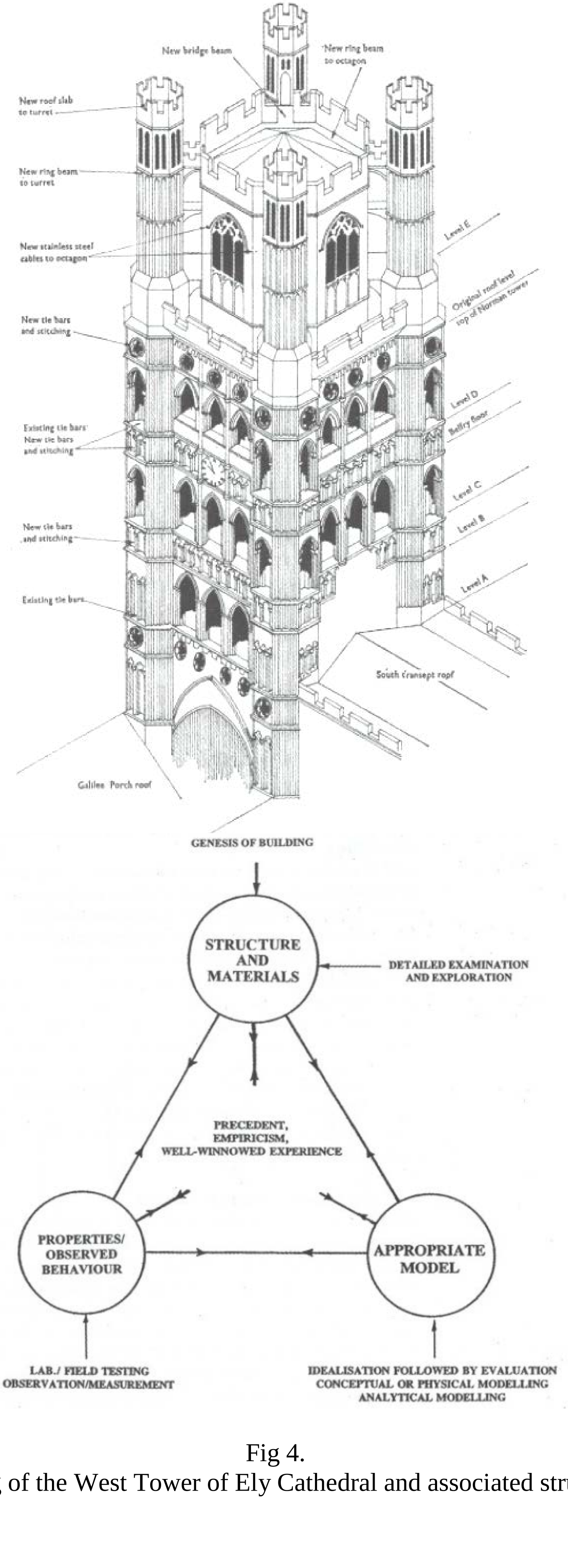


Fig 4.
The strengthening of the West Tower of Ely Cathedral and associated structural activities

As with the ground, small discontinuities and weaknesses can play a major role in determining the overall response. It is also vital to establish the way the building was constructed and the changes that have taken place historically — we might call this the genesis of the building and it is analogous to the geological processes that have formed the ground profile. At the bottom left of the triangle are the properties of the materials and the observed behaviour of the building. This aspect requires observation, field measurement, sampling and testing. At the bottom right of the triangle there is the need to develop appropriate predictive models that take account of the form and structure of the building, its history, its material properties and known behaviour – an almost identical requirement for the ground. There is a whole spectrum of models that and be developed ranging from the intuitive and conceptual right through to highly sophisticated numerical models. The key is to appreciate the inevitable idealisations that have to be made and the limitations that they impose. Finally, as in ground engineering, well-winnowed experience is of supreme importance and well-documented case records are invaluable. It is of interest to note that, in developing his structural understanding of the behaviour of the West Tower of Ely Cathedral, Heyman drew extensively on the Safe Design Theorem and did not attempt to model the ‘actual' stress distributions within the structure.

It is evident from the foregoing that, even if engineers were in possession of unlimited analytical power, the uncertainties in both the soil and the structure are so great that precision in the prediction of behaviour would be unlikely to improve significantly. As in so many fields of engineering, modelling is only one of the many tools required in designing for soil-structure interaction. In most circumstances the real value of modelling will be in assisting the engineer to place bounds on likely overall behaviour, in under-standing the mechanisms of behaviour and in beneficially modifying that behaviour if necessary. In the remainder if this paper case histories are given which illustrate the importance of ductility and in understanding the mechanisms of behaviour.

Using the ductility of piles

Most piles exhibit reasonably ductile load-settlement behaviour when loaded to their maximum capacity i.e. once full capacity has been mobilised the resistance of the pile does not usually reduce significantly with increasing settlement. This is because both shaft resistance and base resistance are mainly controlled by the frictional properties of the ground – a reflection of its particulate nature.

An example of this behaviour is given in the paper by Lee et al.[20]. Fig 5 shows the measured relationships between local shaft resistance and displacement at three depths down an H-pile jacked into Completely Decomposed Granite in Hong Kong. It is evident that little change in shaft resistance takes place after full mobilisation. Such behaviour- is typical of piles of various types installed in a wide range of soils.

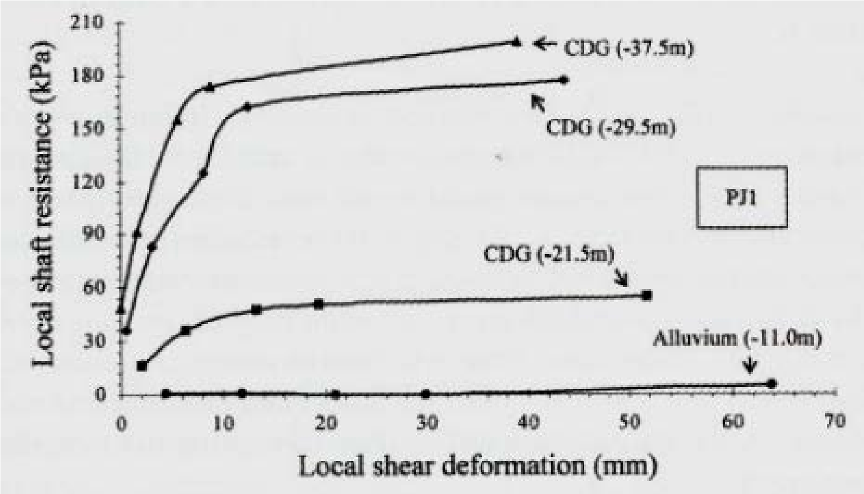


Fig 5.
Relationship between local shaft friction and displacement for ajacked H-pile in CDG[20]

Computer programs for pile group analysis

Powerful computer programs are becoming widely available for the analysis of pile groups. Most assume elastic behaviour of the ground. Such programs can be useful for settlement analysis and for evaluating the bending stresses in the raft itself. The programs also output the calculated magnitudes of the forces at the head of each pile. Because of soil-structure interaction effects, the distribution of load between the piles will usually be non-uniform. For a uniform load applied to a relatively rigid piled raft the piles at the edges of the raft will carry significantly higher loads than those piles near the centre of the group as confirmed by field measurements made by Cooke *et al*.[21]. This is not unexpected as it has been well known since the work of Boussinesq that the contact stress distribution beneath a rigid footing on an elastic material gives very high stresses at the edges[22].
Unfortunately some engineers and regulatory authorities both in the UK and overseas have required that loads calculated in this way in each and every pile must individually satisfy traditional factors of safety or presumed allowable bearing pressures. This has led to grossly conservative pile group design with significant increases in cost. For example, when this approach was adopted by some UK Road Construction Units in the 1980s, the cost of piled bridge foundations at least doubled compared to the cost of traditional pile groups designed on the basis of overall factors of safety:
As a consequence, the approach of applying factors of safety to the carrying capacity of each individual pile was quickly dropped and designers reverted to applying a factor of safety to the bearing capacity of the pile group as a whole – this is nothing more nor less than the application of the Safe Design Theorem. It can be justified because, if a pile exceeds its working load, its stiffness reduces and ductility ensures that it retains its carrying capacity and load redistribution takes place to the adjacent piles. The analogous situation for a rigid footing is that the high edge stresses cause local yield with stress redistribution towards the middle of the footing.
It has never been suggested that local factors of safety should be applied to such edge stresses beneath foundations.
The use of modern methods of pile group analysis has recently begun to enter a more creative phase in which the pile dispositions and lengths are adjusted to reduce raft bending moments

and relative deflections[23,24]. This approach often results in the reduction of the number and depth of piles around the circumference of the piled raft.

Direct use of pile ductility

Numerous instrumented tests on bored pile have shown that the shaft friction is fully mobilised at small settlements but that much larger settlements are required to mobilise the end resistance.
This is shown in Fig 6 for a test on an instrumented underreamed pile in London Clay from the celebrated tests of Whitaker and Cooke[25] in which the load carried by the base was measured. It can be concluded from this behaviour that, for an underreamed pile to operate efficiently, the shaft resistance will often be fully mobilised under working load. Indeed there can be no doubt that thousands of underreamed piles all over the world have operated satisfactorily this way.

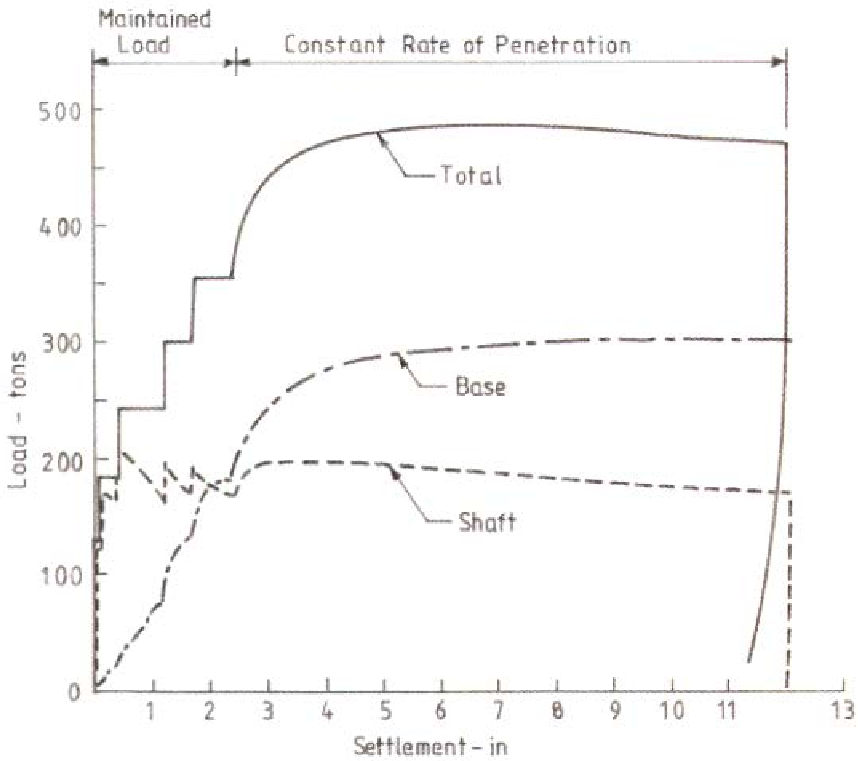


Fig 6.
Results of a load test on an instrumented underreamed bored pile in London Clay showing ductile behaviour of the shaft[25].

I made use of this concept of full mobilisation of shaft resistance for the foundations of the Quecn Elizabeth II Conference Centre, London[26]. The conference area is founded on a 2m thick raft in a relatively shallow excavation and total settlements of the order of 20mm were calculated. Over half the weight of the superstructure is transmitted to the raft by means of a few columns carrying loads of up 26MN. Concern was expressed about the excessive bending and shear stresses in the raft set up by these loads.

One method of dealing with the problem would have been to thicken the raft locally. This would have generated a number of costly and time consuming ‘knock on' effects. Instead a novel method was developed using what have been termed stress reducing piles. A single straight shafted pile was placed directly beneath each heavily loaded column in the knowledge that the settlement of the raft: was sufficient to fully mobilise the shaft resistance of the piles. The effect was to apply a constant upward force beneath each column thereby significantly reducing the loads transferred from the columns into the raft. In view of the novelty of this approach the Building Research Establishment instrumented one of the piles to measure the magnitude of the load transferred into it. The results are shown in Fig 7 where it can be seen that the long-term measured pile loads are in excellent agreement with the calculated shaft resistance and have remained constant for many years.

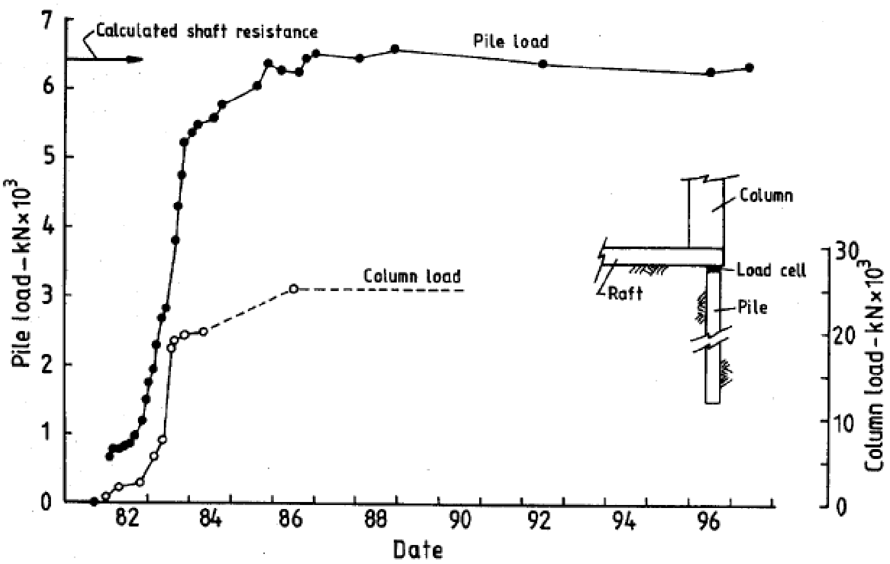


Fig 7.
Queen Elisabeth II Conference Centre, London. Measured performance of a stress-reducing pile designed to operate with the shaft resistance fully mobilised[26].

Ductile piles can also be used to substantially reduce the cost of piled rafts in situations where the piles arc primarily used to reduce settlement and where there is an adequate factor of safety against bearing capacity failure[27]. The essence of the method is to employ only the number of piles that is required to reduce the settlement to an acceptable amount and the term settlement reducing piles was used to describe the system. Since the acceptable settlement is invariably enough to fully mobilise the shaft resistance, this procedure implies that the piles will be operating close to full carrying capacity.

This approach is slowly gaining acceptance[28]. One of the difficulties encountered in gaining acceptance is the perception that the method' skimps on the piles'. To overcome this perception, and to reinforce the message that the piles arc improving the performance of the raft, I have suggested that this use of ductile piles be termed ‘pile enhanced rafts'. This term conveys the message that the raft on its own has adequate bearing capacity and that the function of the piles is simply to enhance the settlement performance of the raft. The approach has particular benefits for foundations carrying lateral loads, such as bridge foundations, since the raft or footing is designed to transmit a proportion of the total vertical load directly to the ground and can therefore be used to carry horizontal loads in friction rather than carrying these loads on piles.

The concept of limiting tensile strain as a measure of potential damage

Burland and Wroth[29] and Burland[30] used the concept of limiting tensile strain in masonry walls as a measure of potential damage. Fig 8 illustrates the approach where a building is represented by a rectangular beam of length L and height H. Simple beam theory is used to calculate the bending and diagonal strains in the beam corresponding to a given value of deflection ratio Δ/L. It has been demonstrated that the onset of visible cracking in masonry buildings corresponds to a reasonably well-defined value of tensile strain (approximately 0.05 to 0.1%) which is not very sensitive to the materials. The concept has been extended such that different limiting values of strain are related to different categories of damage. This simple approach has proved most valuable in the assessment of allowable distortions of buildings subject to settlement and induced subsidence due to tunnelling and excavation[31].

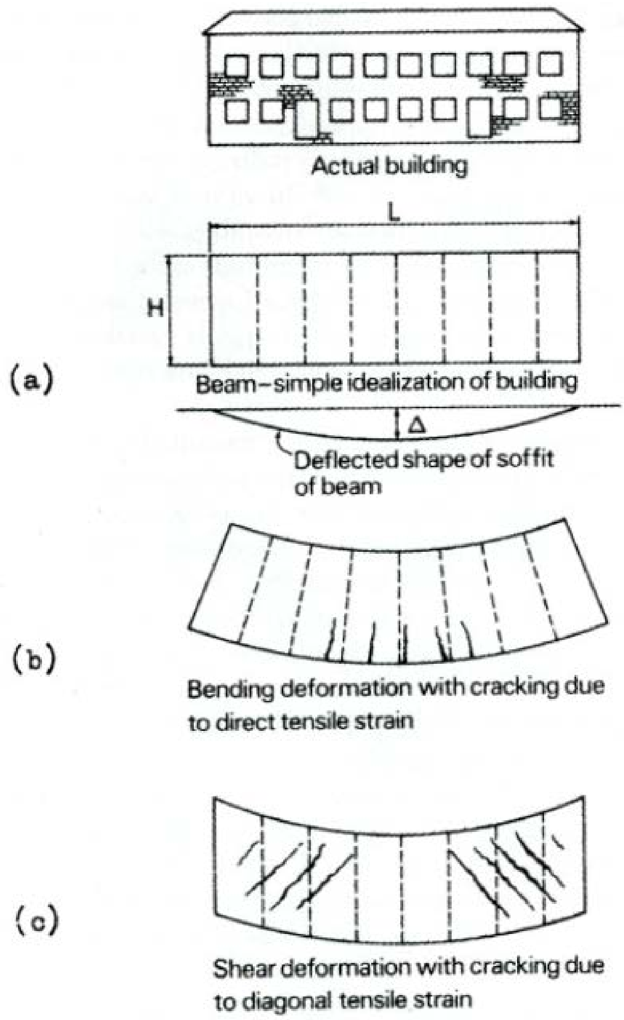


Fig 8.
Cracking of simple beams in bending and in shear[29]

At first sight this approach appears almost naive in its simplicity. The reaction of many structural engineers is to relate Δ/L to- tensile stress. This approach does not work because the stress at which tensile failure occurs depends critically on the composition of the wall and varies over a wide range. Moreover values of Δ/L at which loss of tensile strength occurs are very much smaller than those that produce visible cracking. Finally the approach via tensile strength cannot easily be extended to deflections beyond ‘first crack'.

The approach of relating different levels of damage to limiting values of tensile strain works very well for large masonry buildings because their response to distortion is usually relatively ductile and robust. This ductility results from the restraining effects of the floors and foundation and also the frictional nature of contacts between the masonry elements. Much still has to be learned about the behaviour of masonry structures undergoing distortions aflver the formation of the initial cracks. What is interesting is that the approach to assessing the potential for damage to masonry buildings by means of limiting tensile strain is really an exercise in assessing the behaviour of a structure deforming beyond first yield.

Some examples will now be given of damage due to the brittle response of structures to ground movements.

Cracking of columns

Burland and Davidson gave a detailed case history of damage to some silos due to differential foundation movements. The four silos were founded on 20m diameter rafts, 1.2m thick and resting on soft chalk. Fig 9 shows a typical measured pressure - settlement relationship for one of the silos.

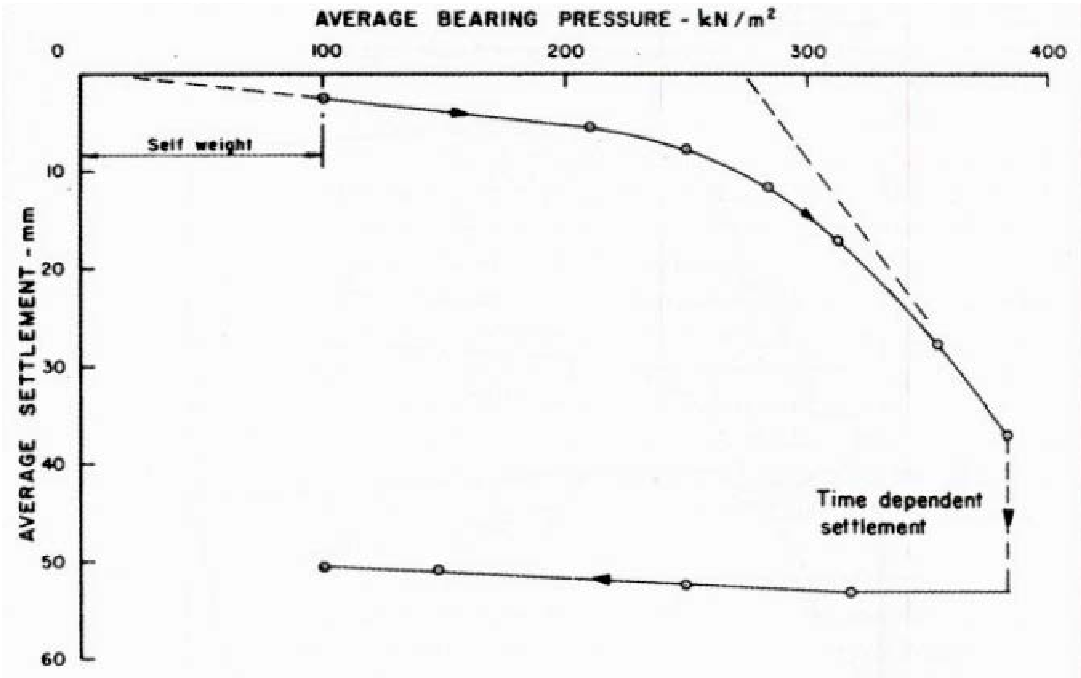


Fig 9.
Relationship between average bearing pressure and average settlement for silo 3

The non-linear behaviour results from the onset of non-elastic behaviour of the chalk. The total settlement is by no means excessive being about 50mm. Fig 10 shows a cross-section through the supporting structure of the silos, together with the measured deflected shapes of the raft foundations.

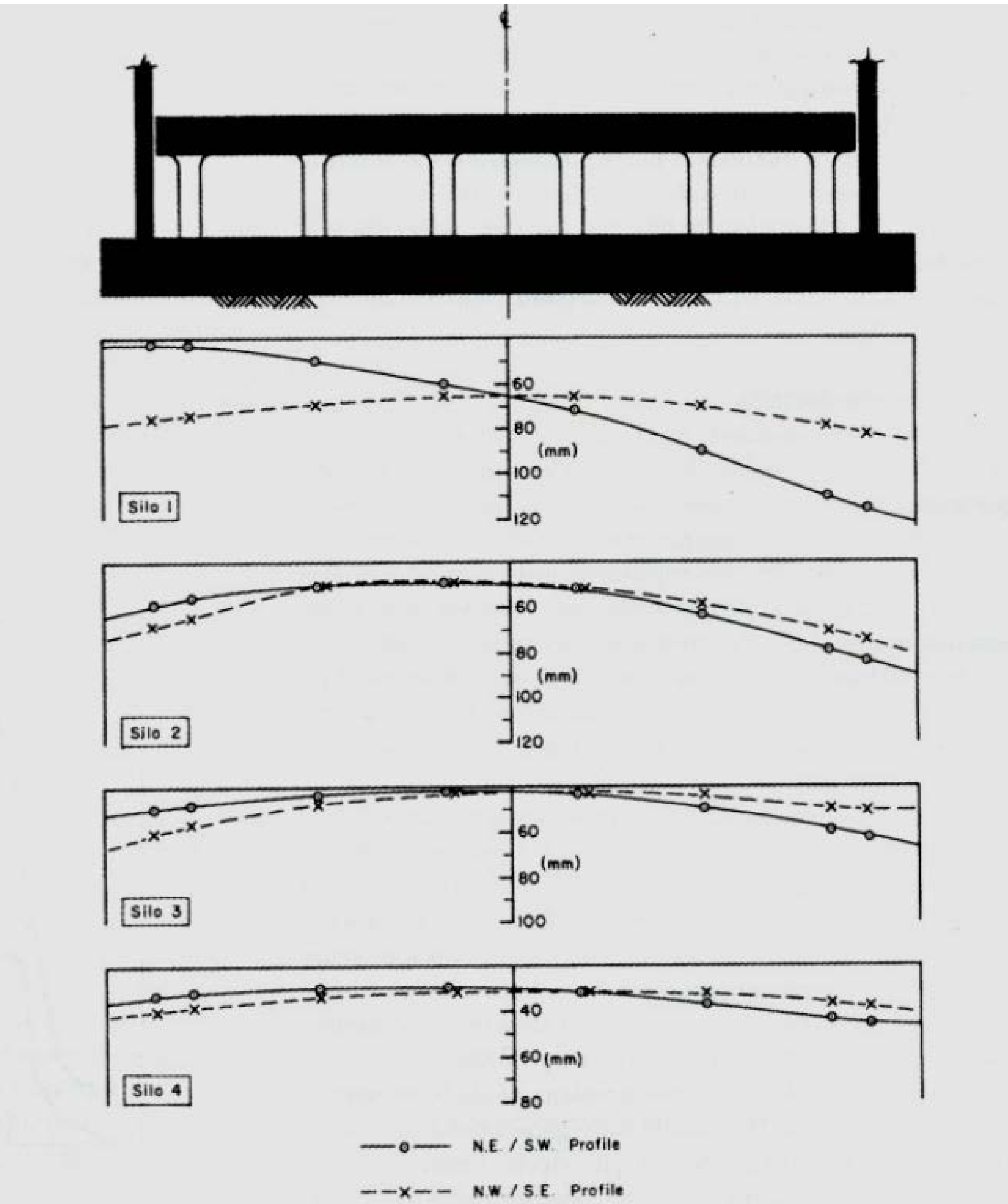


Fig 10.

Deflected shapes of foundation rafts[32]

All the silos showed distinct hogging and silo 1 also underwent some tilting. The investigation showed that fine cracks developed in many of the columns at a deflection ratio $\Delta/L = 0.45 \times 10^{-3}$ and by the time the deflection ratio had increased to 0.6×10^{-3} the cracking was severe enough for the engineers to install temporary props.

The maximum measured deflection ratio was 1.07 x 10.3 and Fig 11 shows a sketch of one of the columns corresponding to this value of Δ/L. Even though these relative deflections are within currently accepted limits the damage was considered severe enough to warrant expensive remedial measures.

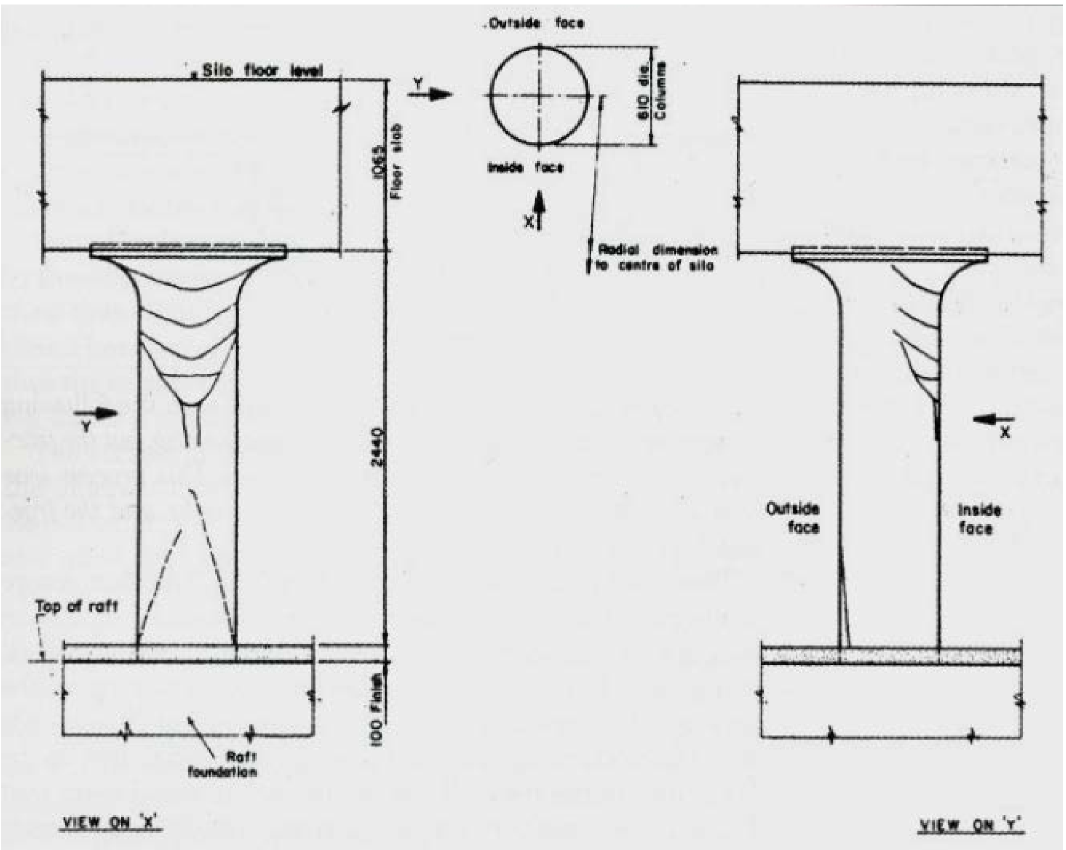


Fig 11.
Typical cracked columns

A simple analysis of the structure reveals that it had a low transverse bending stiffness relative to the supporting ground. On the other hand it can be seen from Fig 11 that the short large diameter reinforced concrete columns made the structure 'brittle' and sensitive to differential settlement. Thus the structure had little inherent stiffness to resist differential settlement and at the same time no 'ductility' to absorb the deformations without damage. This type of design for silos is common throughout the world. Deere and Davisson[33] and Colombo and Ricceri[34] have reported cracking in reinforced concrete columns supporting some silos.
Having recognised the problem a number of solutions arc possible for future design.

These might include:

- limiting settlement (e.g. by using piles),
- increasing the relative stiffness of the structure (e.g. by thickening the raft or introducing shear walls) or
- reducing the sensitivity of the structure to relative displacement (e.g. by using steel columns or incorporating hinges).

This case history emphasises the care that must be exercised when stiff or brittle elements arc introduced into an otherwise flexible structure, particularly if they are load bearing.

More recently Powderham et a1[35] described a case in which ground movements induced by the construction of the Heathrow Express tunnel caused cracking of some reinforced concrete columns in a car park. A risk assessment had shown that the potential damage to the structure was in the category of only ‘very slight'. The measured differential settlements over a span of

12m was 12mm – an angular distortion of only 1/1000. However the outer row of columns were founded on isolated pad footings which appear to have moved laterally with the ground by about 5mm to 10mm and this was sufficient to crack the short stiff columns as shown in Fig 12. Had the footings been tied together by ground beams, as they were elsewhere in the car park, the damage would not have occurred.

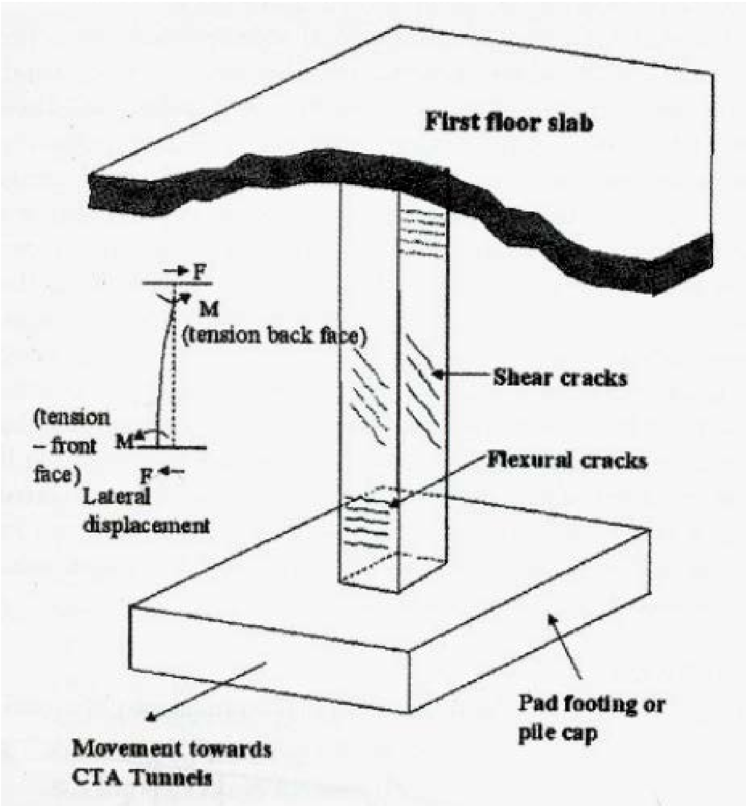


Fig12.
Typical cracking in row of columns due to ground movement towards a tunnel[35]

In summary, for both the silos and the car park, the combination of short stiff columns constructed monolithically with an otherwise relatively flexible structure resulted in high sensitivity to differential foundation movements. Heymian[16] refers to the ‘weak-beam strong-Colulmn' philosophy of designing for multi-storey frames as a means of guarding against lateral buckling. The previous examples show that such a structure may be vulnerable to unforeseen ground movements when the ‘strong columns' are brittle.

An historical enigma

In 1832 James Trubshaw stabilised the 15th century tower of St Chad's church in Wybunbuly, South Cheshire[36] (see Fig 13).

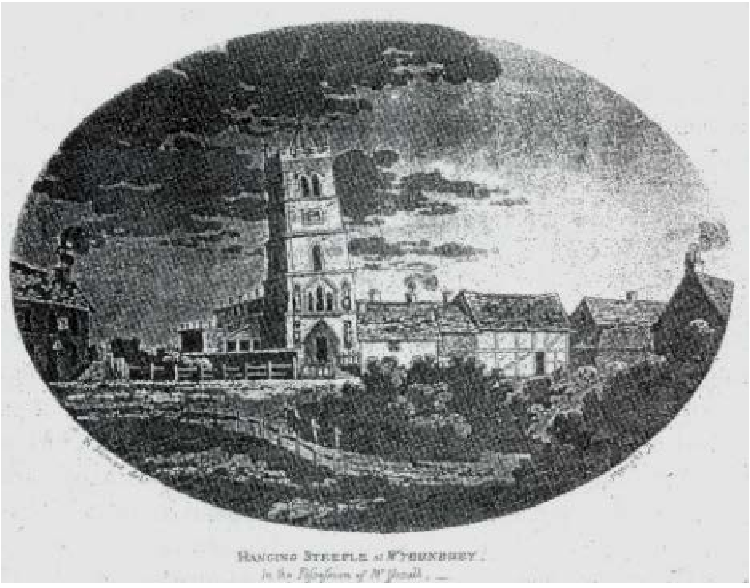


Fig 13.
The Hanging Steeple of Wybunbury

The 29.3m high tower was 1.56m out of plumb towards the north-east caused by subsidence due to brine extraction at depth. Trubshaw dug a trench alongside the foundation on the high (south) side and proceeded to bore a row of horizontal auger-holes through the stiff clay underlying the foundations. He filled these holes with water and left them overnight. The water softened the clay and the south side of tower gradually began to sink. Another row of holes was bored and the procedure was repeated until the tower became plumb. This highly innovative solution appears to be the first fully documented example of the technique of soil extraction which was used so successfully in stabilising the Leaning Tower of Pisa[37].

There have been many churches on this site, but due to the unstable ground in the area each had to be demolished. The 15th century tower is alt that now I remains. Following the demolition of the last church in 1977 efforts concentrated on saving the tower which was again tilting significantly. In 1989 the tower was under pinned by constructing a reinforced concrete slab beneath the existing foundations which were themselves replaced by a reinforced concrete ring to stabilise the masonry Jacks were then inserted between the concrete slab and the reinforced concrete ring and the inclination of the tower was reduced. Like the Pisans, the inhabitants of ‘Wybunbuly were concerned that their tower should be stabilised but not lose its characteristic lean!

The underpinning operations revealed an inverted arch believed to be built by Trubshaw in 1832 as part of his stabilisation works. Sadly this was demolished, thereby removing an interesting and important part of the history of the tower. Fortunately some photographs were taken of the underpinning operations and it has been possible to deduce the approximate location and dimensions of Trubshaw's inverted arch.

Fig 14 shows a north/south section through the lower part of the tower looking west together with a plan of the foundations. A careful study has been carried out of the photographs taken during the underpinning operations and the approximate position and dimensions of the inverted arch have been deduced as shown by means of thick broken lines in Fig 14. The arch was approximately semi-circular, was constructed of hand made bricks and spanned about 4.9m between the north and south walls of the tower. An odd feature is that it was located off-centre, well towards the West and of the foundations. The width of the arch is judged to have been about 1.8m.

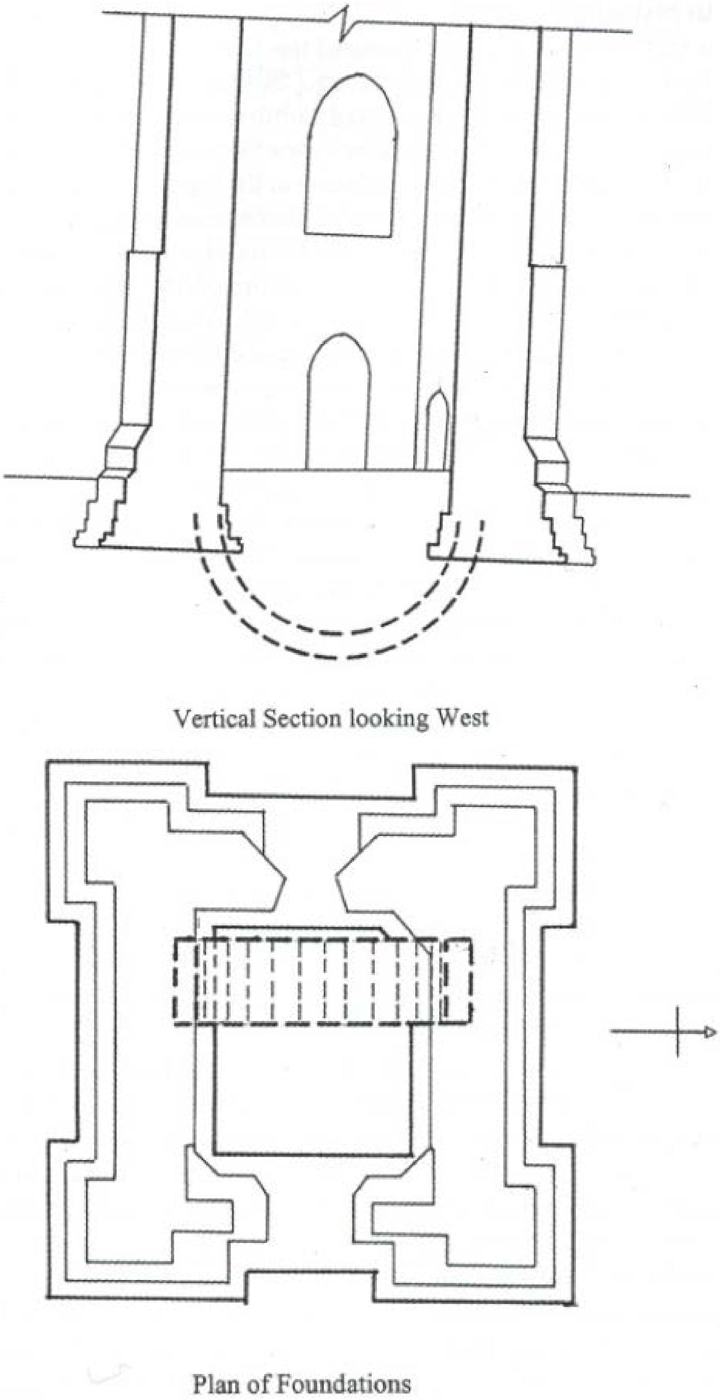


Fig 14.
Vertical section and plan showing the approximate dimensions and location of Trubshaw's inverted arch[36]

The purpose and function of the arch is something of an enigma.

The use of inverted arches as foundations goes back many hundreds of years and are mentioned by Alberti as being used for the Temple of Vespasian. Writing around the beginning of the 17th century, Juanelo Turriano[38] illustrates their use as foundations for aqueducts 'in order not to let the pillars bend to either side, specially where the soil is not very firm'. It seems clear that by the 18th century onwards, inverted arch foundations of the type constructed for the Albian Mill[39] were commonly used to distribute heavy column loads evenly on to the underlying ground. In other words they formed raft or mat foundations.

Trubshaw would have been familiar with their use for this purpose. But the use of an inverted arch to underpin an existing building seems extremely unusual.

There are two particularly puzzling features about the use of an inverted arch in tills is situation. First it might be expected to exert an outward thrust and thereby cause the foundations to spread, which would have been very undesirable. Secondly it was off-centre towards the west, away from the direction of inclination which is north-east.

Regarding the possibility of outward thrust, careful consideration of this particular situation suggests that this is not necessarily the case for a semi-circular arch. As soil extraction took place at the South side, the foundations of the tower would have subsided, transferring load both to the arch at its springing point and also to the ground surface outside the arch. The problem is a most complex one to analyse but model tests using foam rubber demonstrate that, as the foundation subsides the springing point of the arch moves inwards such that the arch closes slightly. Fig 15 illustrates the observed behaviour of the model inverted arch during subsidence at one end. It seems that the near vertical part of the arch not only carries vertical load but also horizontal earth pressures generated by the adjacent foundation loading.

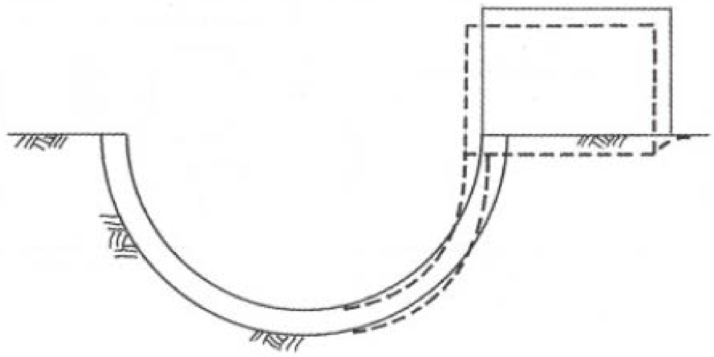


Fig 15.
The observed mode of deformation of model inverted arch when loaded at one end by a rigid foundation[36]

Is it possible that this inward movement was envisaged by Trubshaw? A report from the Architectural Magazine of 1836[40] suggests that it might have been. The report refers to the fact that '*the tower was split inches apart a leng way up the centre'*. Indeed, there is a significant fracture on the west face of the tower running up from the arch over the west door to the window above, as shown in Fig. 16. A photograph taken in 1893 clearly shows the existence of this fracture which is obviously a very old one. The extract from the Architectural Magazine goes on to describe the soil extraction process and ends with the following statement: `...und *the high side not only kept sinking, but the fracture in the centre kept gradually closing up. This process was continued till the steeple became perfectly straight, and the fracture imperceptible*'.

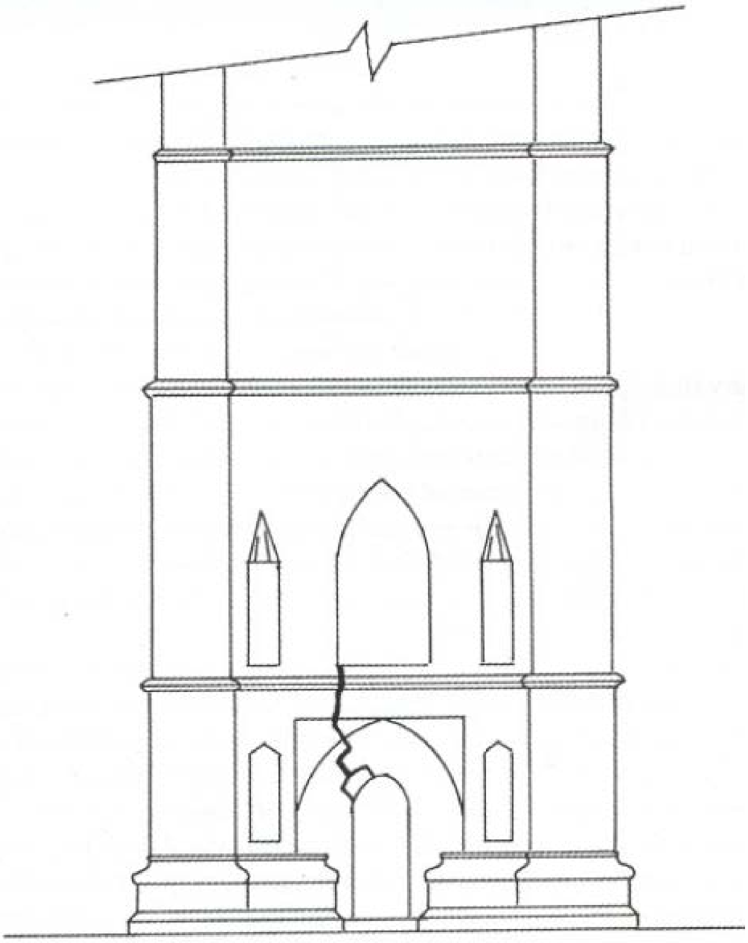


Fig 16.
Western Elevation of St Chad's Tower showing a prominent fissure above the entrance door[36]

We are left with the intriguing possibility that Trubshaw, aware of the existence of this fissure, set about devising a method of closing it by utilising the settlement of the South side during soil extraction. This could be the reason for constructing the north/south inverted arch located off-centre towards the west side of the foundations i.e. the side on which the fissure runs up the lower part of the tower. If this is the case it would seem that Trubshaw was not only a highly innovative engineer, as already demonstrated by his use of soil extraction but he possessed a remarkable feel for the soil-structure interactions.
These may of course be much more mundane explanations. For example, concerned about the treacherous nature of the ground, Trubshaw may have sought to increase the arch of the foundations by infilling between the footings with an inverted arch after the soil extraction had been carried out. Alternatively Trubshaw may have conceived the inverted arch as a mixture of a fulcrum or a roller allowing the tower to rotate in the soil during soil extraction while remaining intact[41]. In both cases the closing of the fissure on the west face might have been an unexpected bonus! These alternative ideas beg the question as to why the inverted arch only extended over the west half of the foundations when the tower had been leaning towards the north-east. Further speculation is probably pointless without more documentary evidence. It is nevertheless of considerable historical interest that an inverted arch was used by Trubshaw to underpin the tower whatever its function was intended to be. It. seems unlikely that such a solution would be adopted nowadays.

Conclusions

This paper explores the differences in the philosophy of modelling and analysis between structural and geotechnical engineers. The idealisations that are involved in both disciplines are compared. It has been demonstrated that the approach that has to be adopted by a structural engineer working on an existing historic building is very similar to that of the geotechnical engineer working with the ground.

Superficially it might seem that the idealisations adopted by the structural engineer in routine practice are more certain than those that have to be adopted by the geotechnical engineer. However, on closer examination it has to be concluded that the calculation of the `actual' state of a structure or building under a known set of loads is very uncertain.

The success of structural design calculations owes much to the inherent ductility of the structural elements so that the `Safe Design Theorem' applies. Geotechnical engineers too owe much to the plastic ductile behaviour of their materials and foundations for the success of their designs. In both cases it is vital to identify brittle behaviour as this invalidates the `Safe Design Theorem' and can lead to progressive collapse.

Structural engineers tend to work and think in terms of forces and stresses. Geotechnical engineers are much more used to working with strain and deformation. This difference becomes particularly apparent for situations in which elements of the building or ground approach their maximum resistance. Structural engineers brought up on concepts of limiting stress fend it difficult to accept behaviour that implies full mobilisation of resistance (which is not the same as `failure'). Reference to Hambly's three- and four-legged stool (Hambly's paradox) greatly aids in the understanding of the above ideas.

The paper contains some case histories which illustrate the importance of ductility and robustness in both structural and geotechnical design and in the interactions between the two. Particular care is needed when a relatively flexible structure of the weak-beam strong-column variety is subjected to ground movements. In such circumstances brittle behaviour of the columns can lead to unsafe conditions.

Of overriding importance is the need to gain a clear under-standing of the mechanisms of behaviour of a soil-structure interaction system. If the analytical model does not capture the key mechanism no amount of sophisticated computation will help solve the problem.

In summary, understanding and designing for ground-structure interaction requires all the traditional skills of the engineer: reliance on observation and measurement; a deep understanding of materials, both ground and structural; the development of appropriate physical and analytical models to reveal the underlying mechanisms of behaviour and; well-winnowed experience based on a discerning knowledge of precedents and case histories.

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Interaction between Geotechnical and Structural Engineers

Synopsis

Prof. Dr. John Burland

A structure, its foundations and the surrounding ground interact with each other. Ground-structure interaction must usually be taken into account in design and this involves important interactions between specialist structural and geotechnical engineers. During his career the speaker has encountered profound philosophical differences in approach between structural and geotechnical engineers often leading to a lack of understanding and difficulties in communication. This lecture explores these differences in approach and the reasons for them. Examples are given of some challenging projects in which successful interaction has taken place across the disciplines.

Professor John Burland

Born in the UK, Professor Burland was educated in South Africa and studied Civil Engineering at the University of the Witwatersrand. He returned to England in 1961 and worked with Ove Arup and Partners for a few years.

After studying for his PhD at Cambridge University, John Burland joined the UK Building Research Station in 1966, became Head of the Geotechnics Division in 1972 and Assistant Director in 1979. In 1980 he was appointed to the Chair of Soil Mechanics at the Imperial College London. He is now Emeritus Professor and Senior Research Investigator at Imperial College.

In addition to being very active in teaching (which he loves) and research, John Burland has been responsible for advising on the design of many large ground engineering projects world-wide including the underground car park at the Palace of Westminster and the foundations of the Queen Elizabeth II Conference Centre in London. He specialises in problems relating to the interaction between the ground and masonry buildings. He was London Underground's expert witness for the Parliamentary Select Committees on the Jubilee Line Extension underground railway and has advised on many geotechnical aspects of that project, including ensuring the stability of the Big Ben Clock Tower. He was a member of the international board of consultants advising on the stabilisation of the Metropolitan Cathedral of Mexico City and was a member of the Italian Prime Minister’s Commission for stabilising the Leaning Tower of Pisa.

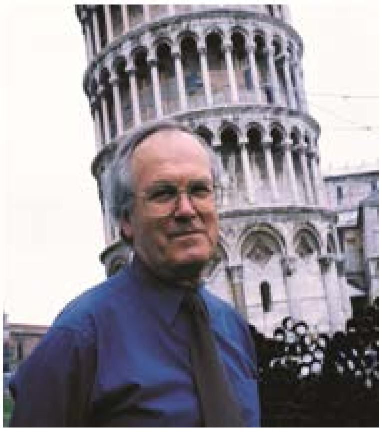
He has received many awards and medals including the Gold Medal for engineering excellence of the World Federation of Engineering Organisations and the Gold Medals of the UK Institution of Structural Engineers and of the UK Institution of Civil Engineers. In 1994 he was awarded the Kevin Nash Gold Medal of the International Society of Soil Mechanics and Geotechnical Engineering ‘In recognition of outstanding services to ISSMGE, to International Goodwill and to International Geotechnical Practice and Education’. In 1996 he was awarded the Harry Seed Memorial Medal of the American Society of Civil Engineers ‘for distinguished contributions as an engineer, scientist and teacher in soil mechanics’. He is a Fellow of both the UK Royal Academy of Engineering and of the Royal Society of London and was appointed Commander of the Most Excellent Order of the British Empire in 2005.

Now the 19th time organized by the ISMGE Hungarian National Committee of the Károly SZÉCHY memorial session co-organization with Technical Committee of the Hungarian Academy of Sciences and Chamber of Engineers Geotechnical Division.
19th Széchy Károly memorial session to be held in the Great Hall of the Hungarian Academy of Sciences(Budapest V. Széchény square 9., II. floor) on 15 February, 2013 (Friday)
The pre-event registration is required. *(web: [http://issmge-hungary.net,](http://issmge-hungary.net) and e-mail: huszak@mail.bme.hu, secretery of the ISSMGE HNC, or web: http://geotechnikaitagozat.hu.)*
That occasion, Professor Joseph MECSI president of the ISSMGE-HNC requested an interview emeritus Professor John Burland (Imperial College, London), who is delivering the opening lecture at the Széchy memorial session.

Interview

Question 1:

What do you think of the relationship between geotechnical engineering and other professions, what are the difficulties and the opportunities for cooperation.?



My lecture explores the relationships between geotechnical and structural engineers. I conclude that there are profound differences in philosophy which must be understood if the two professions are to cooperate successfully. The difficulties stem largely from the fact that the geotechnical engineer is working with natural materials which are both complex in their mechanical behaviour and difficult to explore *insitu* with precision. In contrast the structural engineer specifies the material properties, controls its manufacture and defines the geometry. Geotechnical exploration is very similar to medical diagnosis.

Question 2:

Would you, or would you not, agree that nowadays technical innovations, new technologies give more incentive for the development of geotechnical engineering than fundamental research does?

I largely agree with this. There have been huge developments in geotechnical processes such as tunnelling, grouting, ground treatment, diaphragm walls etc which make possible engineering construction which could not have been achieved previously. However the success of these processes still depend significantly on the properties of the ground and it is essential that these properties are understood and properly researched. I believe that there is still a great need for fundamental multi-disciplinary research.

Question 3:

What is your vision of the future geotechnical designer, what theories and tools will be applied in 15 to 20 years time?

Geotechnical engineering is as much a craft as it is a science and I believe that it will always remain so. A craftsman "knows" his materials by working with them in a way that scientific measurement does not. We are faced with the grave danger that the wide availability of powerful computer models will tempt geotechnical professionals into believing that they can analyse their way through their designs. It is essential that future geotechnical designers are not seduced by the ease of computer modelling. There is a greater need than ever to understand that the inherent variability of the ground and its dependence on the precise method of construction requires that designs must realistically cater for uncertainty. In 15 to 20 years time we will have even more powerful computer models that are readily available. The geotechnical designer must understand the limitations of these numerical models and their proper roles in design. There will be an even greater need for improved methods of monitoring performance and the publication of careful case records. The development of monitoring techniques and SMART sensors will encourage greater reliance on monitoring and observation.

Question 4:

In Europe, the introduction of Eurocodes has brought about changes in favour of uniform practice. How would you judge the general acceptance and efficiency of the new regulations, principles and requirements?

With the introduction of Eurocodes the profession has moved from the use of permissible stresses and overall factors of safety to limit state design with partial factors. My experience, which is limited, is that this has resulted in more complex and time consuming calculations. I have yet to be convinced that it has led to improved economy or safety. My fear is that the use of Eurocodes will cause the geotechnical engineer to concentrate on satisfying procedures which divert attention from focussing on understanding overall mechanisms of behaviour and the influence of test methods and geological factors on the choice of design parameters.

Question 5:

What farewell message would you give for the present young generation of geotechnical engineers?

As a geotechnical engineer you are using the traditional skills of the engineer all the time. The materials are complex since they are laid down by nature and modelling their mechanical properties is as challenging as for any modern artificial material. Determining the design boundary conditions such as ground water flows and the existence of weaknesses requires real detective work and carefully thought through ground investigations. Designing economically and robustly for uncertainties requires an understanding of likely mechanisms of behaviour – this is much more important than precise calculation. Drawing on your own and others experience is a vital aspect of the work, therefore whenever possible observe, measure and read. No job is the same and each has to be tackled in its own way!

It is a wonderfully diverse and challenging profession.

John Burland presentation on the XIX. Széchy Károly

mememorial lecture

Budapest, 15th March 2013

Great Hall of the Hungarian Academy of Sciences
(Budapest V. Széchényi square 9., II. floor)

ORGANIZATORS

The HAS – Hungarian Academy of Sciences, Section of Engineering Sciences,

Hungarian Association of Geotechnics,

Hungarian National Committee of the International Society for Soil Mechanics and Geotechnical Engineering

and

the Geotechnical Section of the Hungarian Chamber of Engineers

Structure-Ground Interaction

- Interaction always takes place between a structure and its foundation ….. whether or not the designers allow for it
- In some situations it can be minimised e.g. very stiff piles
- But this approach can be costly and is often not feasible e.g. deep basements
- A particularly difficult and challenging situation is when ground movement due to nearby tunnelling or excavation impacts on an existing building. In this situation powerful computer models invariably give large areas of "overstress".
- If structure-ground interaction is to be taken into account in design, Structural and Geotechnical Engineers have themselves to interact.

Communication between Structural and Geotechnical Engineers

- The Author has both witnessed and experienced difficulties in communications between Structural and Geotechnical Engineers
- These difficulties are clearly a matter of considerable importance
- This has caused me to explore some of the reasons for these difficulties
- I have come to the conclusion that, at the heart of the problem, there are differences in the approach to modelling the real-world situation
- I will try not to side with either of the disciplines - the objective is to improve the understanding of the way the "average" practitioner tackles design

Contents

- Structural and Geotechnical Modelling
- Some examples of the application of ductility in Foundation Design

Two case histories in which understanding the mechanisms of behaviour provides the key:

- The failure of some silos during discharge – due to soil-structure interaction?
- An intriguing historical example of soil-structure interaction

Modelling

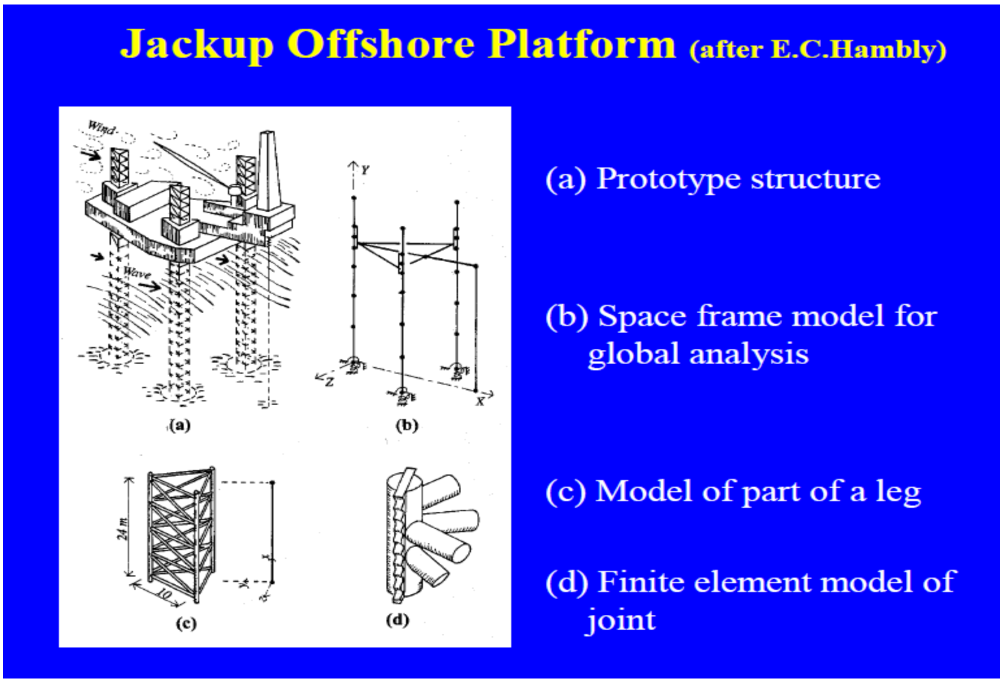
- "The process of **idealising** the full-scale project, including the geometry, material properties and loading …….
- in order to make it amenable to **analysis** and hence assessment for fitness for purpose"
- **Thus the process of modelling is very much more than simply carrying out an analysis**

Edmund Hambly

2. Hambly, E. C.: *Structural analysis by example*, Archimedes, 1994, ISBN 0-9522666-0-1

Structural Modelling
"Structural Analysis by Example" by E.C. Hambly.

- Fifty examples of increasing complexity covering the range of problems and types of analysis encountered by most Structural Engineers in day to day practice.
- It is evident that the **geometry** is usually reasonably easy to idealise.
- Simple **material behaviour** is usually assumed - linearly elastic with a limiting stress specified. In exceptional cases a full elastic-plastic analysis will be carried out.
- The major **idealisations** seem to be in the loading, choice of load factors and choice material factors - but these are usually specified in Codes and Standards.
- See example of jackup offshore platform



Structural Modelling

- Almost all of the examples **focus on the calculation of forces and stresses**.
- If deflections are calculated they are usually in the elastic range
- There is an increasing resort to the use of powerful computer programs …..
- Dare I say …. and to believe the output ?
- **THE FOCUS IS VERY MUCH ON ANALYSIS**

Limitations to Structural Modelling

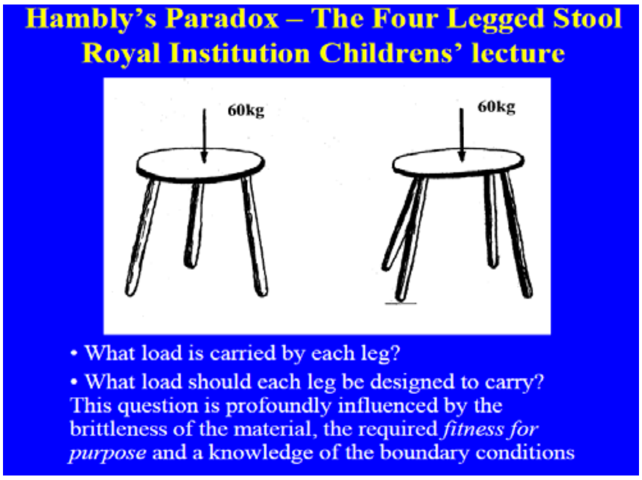
- "Most studies on whole building structures show that the measured forces and stresses bear little semblance to the calculated ones" (Walley, 2001)
- Ministry of Defence Building in Whitehall (Mainstone, 1960)
- Large-scale steel frame structures begun in the 1930"s (Baker et al., 1956).
- I have been involved in many cases of movements induced by subsidence where great concern is expressed. We have found that in many cases the annual thermal movements on buildings exceed the predicted subsidence movements (Burland et al., 2001).

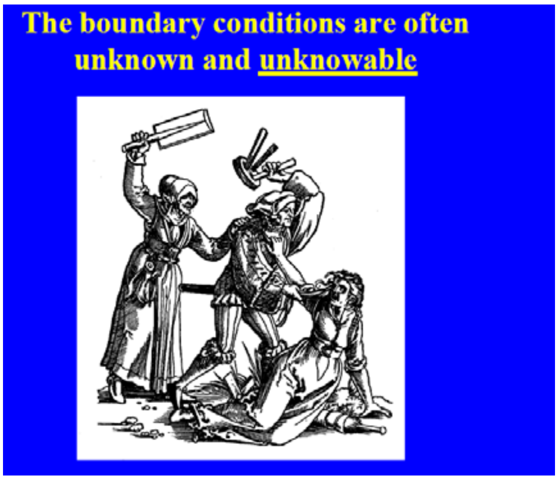
Ductility and Robustness

- Appreciation of these limitations have been known for a long time but are easily forgotten.
- Current routine approaches work because our codes usually ensure that our structures are ductile:
  –Steel members
  –under-reinforced beams
  –"weak-beam strong-column" philosophy
- Recently Beeby (1997, 1999) stressed the importance of designing for **ductility** and **robustness** in r.c. design.
- Modern earthquake engineering is focusing on this as well.

The Safe Design Theorem

- Hambly recognised that current design methods work for ductile structures because of the Safe Design Theorem:
- A structure can carry its design loads safely if:
  - The calculated system of forces is in EQUILIBRIUM
  - Each component has the STRENGTH to transmit its calculated force and the DUCTILITY to retain its strength while deforming
  - The structure has sufficient stiffness to keep deflections small and AVOID BUCKLING before design loads are reached (Note the importance of examining the details of connections and propping points)
- In Summary, if the real structure deforms under load with a different flow of forces from that calculated, it will still be safe as long as the materials are DUCTILE and not BRITTLE, and if there is no risk of local instability.



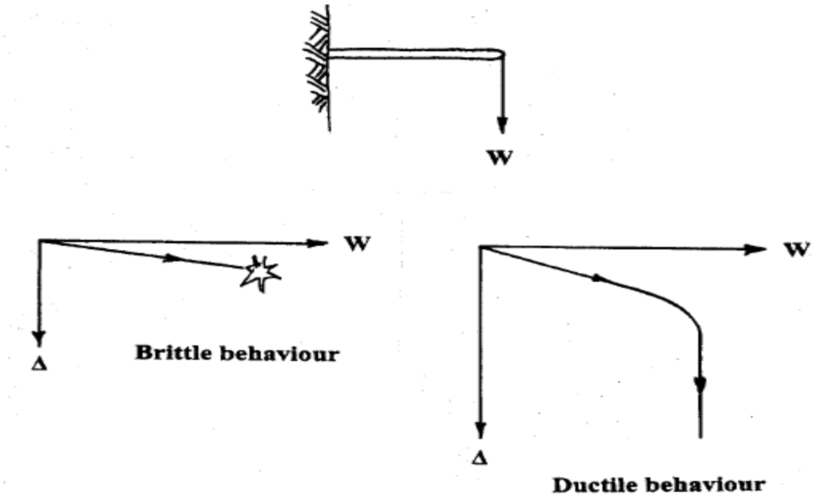


Ductility and Robustness

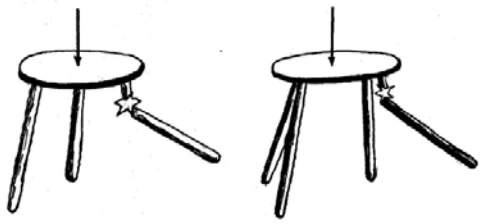
- **Ductility:** "The ability to undergo inelastic deformations without significant loss of strength"

- **Robustness:** "The ability to absorb damage without collapse"

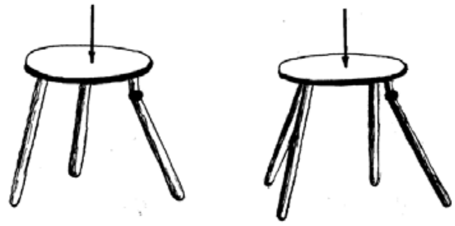
Brittleness and Ductility



Fragile Behaviour



Robust Behaviour



Heyman‟s conclusion on Hambly‟s Paradox:

- Hambly‟s four-legged stool stands for the general problem of design of any redundant structure.
- To calculate the „actual‟ state, all three of the basic structural statements must be made - equilibrium, material properties and deformation.
- **Calculations do not in fact lead to a description of the actual state.**
  - Boundary conditions are often unknown and unknowable
  - An imperfection in assembly, or a small settlement of a footing, will lead to a state completely different from that calculated
- **This is not a fault of the calculations, whether elastic or not, it is a result of the behaviour of the real structure.**
- There is no correct solution, but there is one that will lead to the greatest economy of materials - **provided there is no inherent instability.**

Heyman (1996)

Recent publications in „The Structural Engineer‟ on calculating the state of structures

- Burgoyne (2004): “Are structures being repaired unnecessarily?”
- Mann (2005): Correspondence in Verulam
- Heyman (2005): “Theoretical analysis and real-world design”
- Mann (2006): “The interpretation of computer analysis”
- All these, and many more, stress the difficulty of calculating the state of a structure and our reliance on the safe theorem in our designs and assessments

Geotechnical Modelling

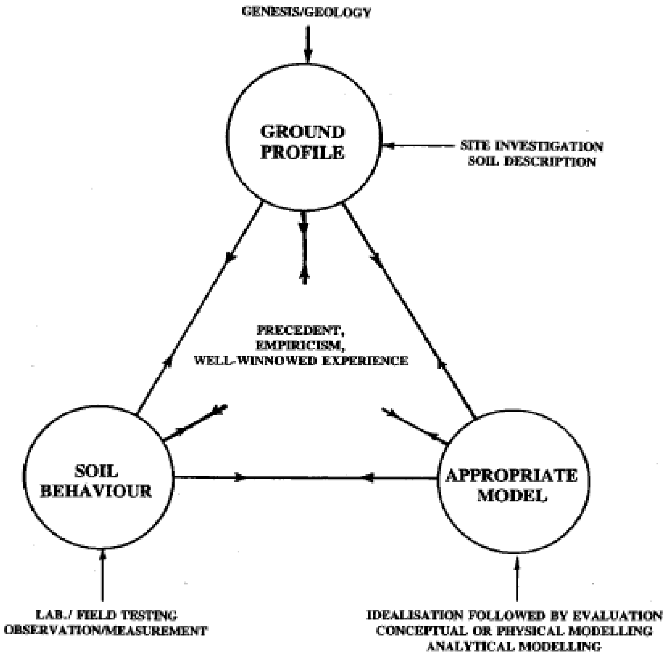
Why is Geotechnical Modelling regarded by many engineers as a difficult subject?

- It is a difficult material:
  - Particulate with little or no bonding between particles
  - Stiffness and strength not fixed - depend on confining pressure
  - Dilates or contracts during shearing
  - Particles can change orientation during shearing
  - Arching action
- Water pressures acting within the pores are just as important as applied boundary stresses.
- We have to model the material as a continuum but we must never forget that it is particulate.
- **But modelling the material is not the only problem**

There are at least four distinct but interlinked activities in geotechnical modelling:

- Finding out what is there and how it got there - ground exploration and geology.
- Determining the material properties of the ground by laboratory or insitu measurement or back-analysis of full-scale behaviour.
- Developing an appropriate model for analysis. (It may range from purely conceptual to very sophisticated but it must capture the essential mechanisms of behaviour)
- Using precedent and well-winnowed experience both in developing and interpreting the model (separating the wheat from the chaff)

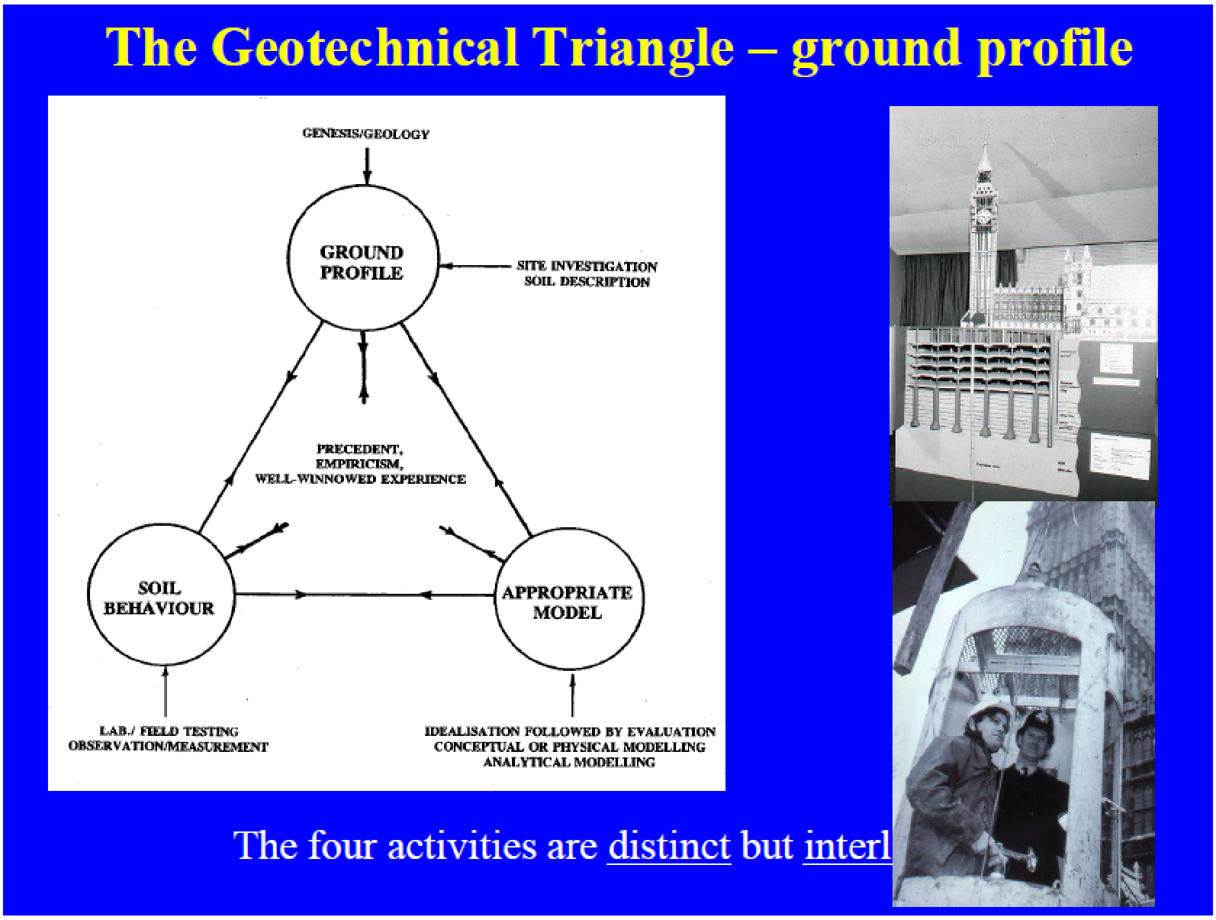
The Geotechnical Triangle Burland (1987)



The four activities are distinct but interlinked

Geotechnical Triangle

Application to the design of the underground car park at the Palace of Westminster

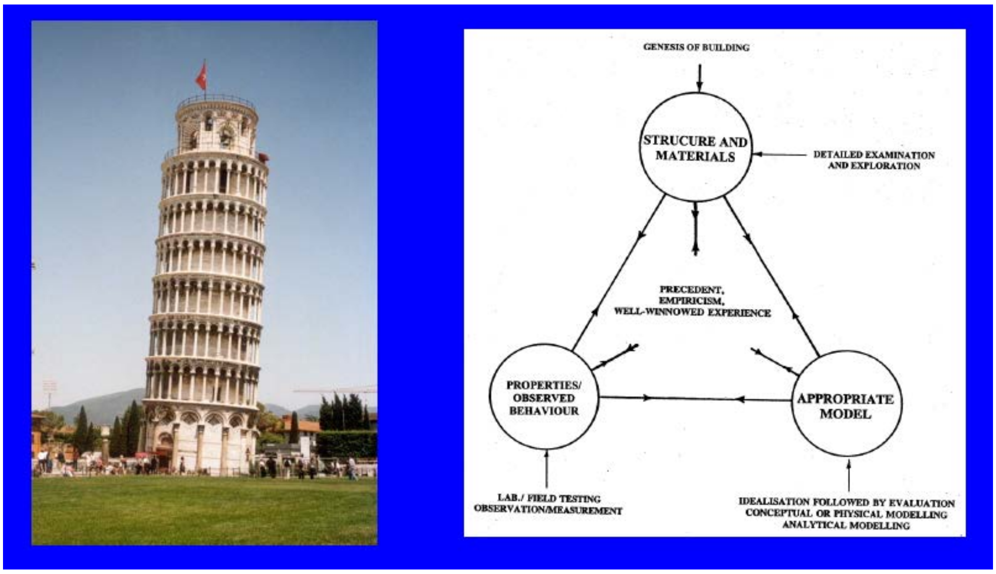


- To analyse is first to idealise.
- Predictions later compared with measurements

Comparison of Structural and Geotechnical Modelling

- For routine modelling the Structural Engineer specifies the material and the geometry. The uncertainties of „actual" material properties and „lack of fit" are often „hidden" in the material and loading factors. There is a huge temptation to believe that a calculation represents the "actual state".
- In geotechnical modelling both the geometry (ground profile) and the properties (ground behaviour) are laid down by nature and are seldom specified. It is more obvious that precise analysis is not possible. The key requirement is to understand the dominant mechanisms of behaviour and the likely bounds.
- In order to understand the activities that a geotechnical engineer goes through in modelling a problem, it is helpful to consider the investigations that a Structural Engineer has to undertake when modelling an existing historic structure - the two pproaches are remarkably similar.

Leaning Tower of Pisa



Summing up on modelling

- Even with unlimited analytical power the uncertainties are so great that our ability to calculate the “actual state” in a building structure and the underlying ground ground is unlikely to improve much, if at all. Our designs work because of inherent ductility and robustness.
- In most cases the real value of modelling is to place bounds on likely overall behaviour and to explore possible mechanisms of behaviour.
- Identifying the basic mechanisms of behaviour must be the key goal of successful modelling.

Some examples of the application of ductility in Foundation Engineering

All foundations have stress concentrations at the edges

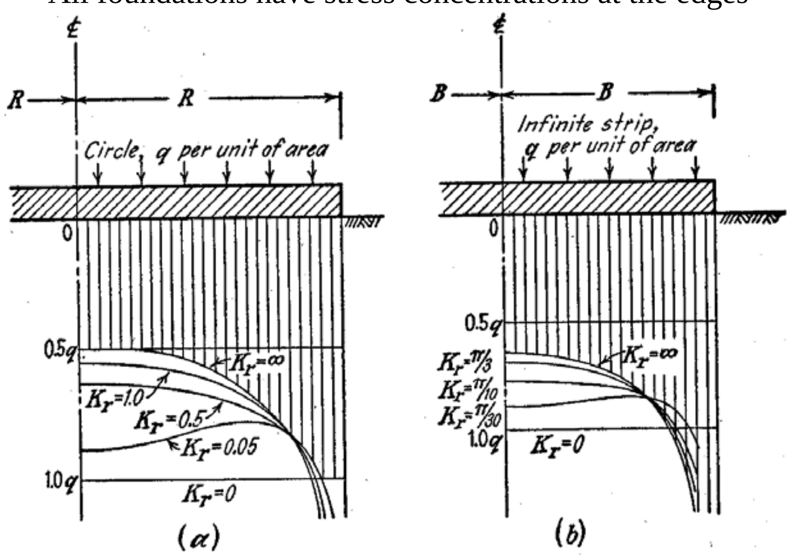
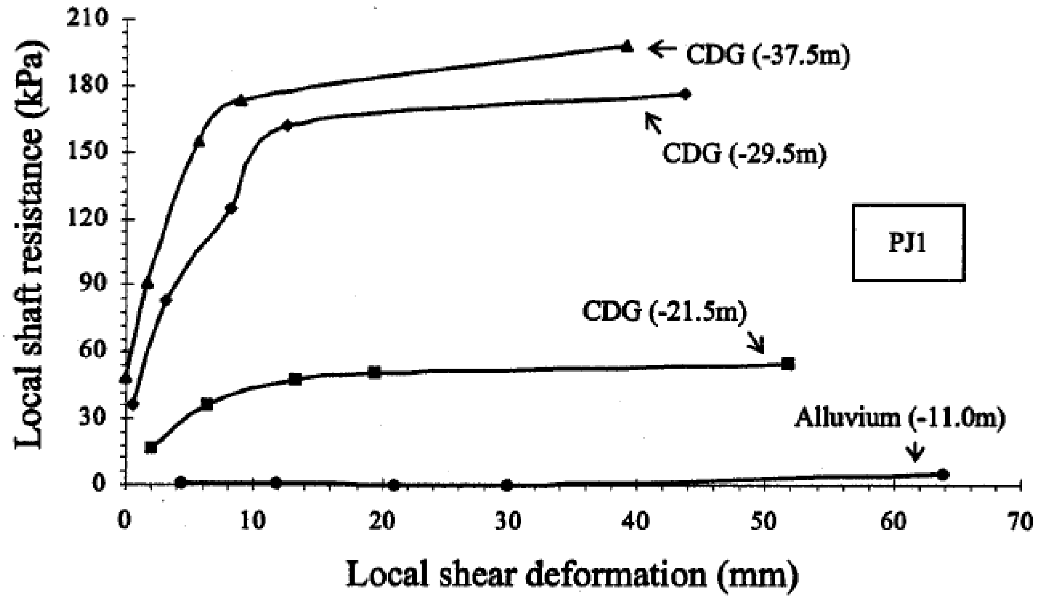


FIG. 125. (a) Contact pressure on base of uniformly loaded, circular plate with different degrees of flexural rigidity; (b) as before, for load applied on a strip. (*After Borowicka 1936 and 1938.*)

The load-settlement behaviour of most piles in soil is DUCTILE

Results of Lee et al. (2004) - jacked H-piles in CDG



Computer programs for Pile Group Analysis

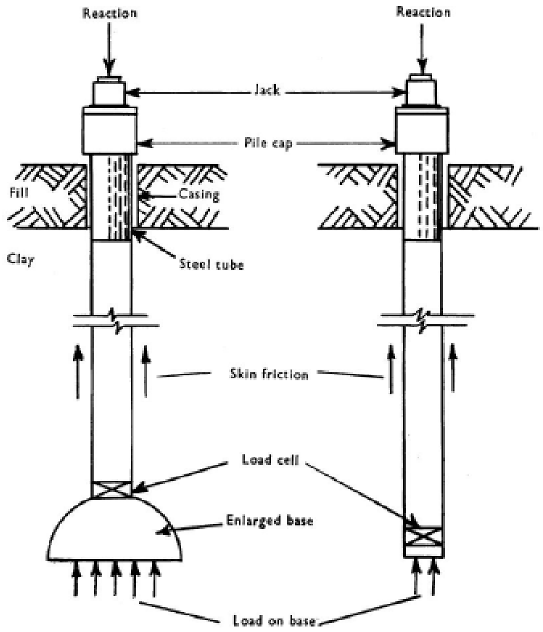
- These are now widely available for pile group analysis - They output the vertical forces in each pile.
- As for footings, the piles at the edges are usually computed to be carrying much higher loads than the centre piles.
- Unfortunately some regulatory authorities, including Hong Kong, have required that each pile should individually satisfy the traditional factor of safety previously reserved for the pile group as a whole.
- This has led to grossly conservative and expensive foundations.
- In the 1980s, when these programs first became available, some UK Road Construction Units adopted the approach of requiring every single pile to satisfy the traditional factor of safety.
- When it was found that the cost of bridge foundations had more than doubled the approach was quickly dropped.
- The traditional approach has been to apply a factor of safety to the pile group as a whole - this is nothing more nor less than the application of the Safe Design Theorem.
- If a single pile approaches its full carrying capacity, its stiffness reduces and load is re-distributed to the adjacent piles. The pile continues to carry its load due to its ductility.
  (In some circumstances ductility of the pile cannot be assumed)
  (Note that local factors of safety are not usually applied to stress concentrations beneath a footing - these are simply permitted to redistribute)

Application of pile ductility in design

•Two examples of the direct use of pile ductility in design:

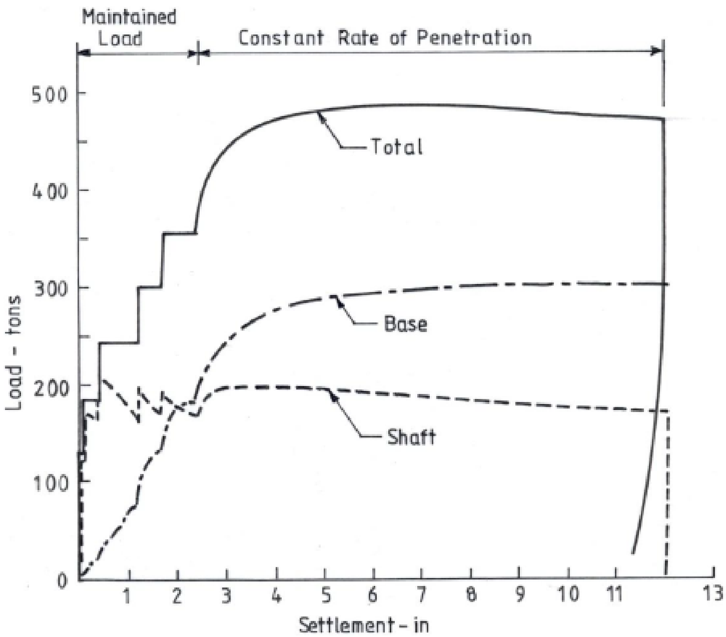
–Undereamed bored piles in stiff clay
–Stress reducing piles

Research by Whitaker and Cooke (1966) on bored piles in stiff clay



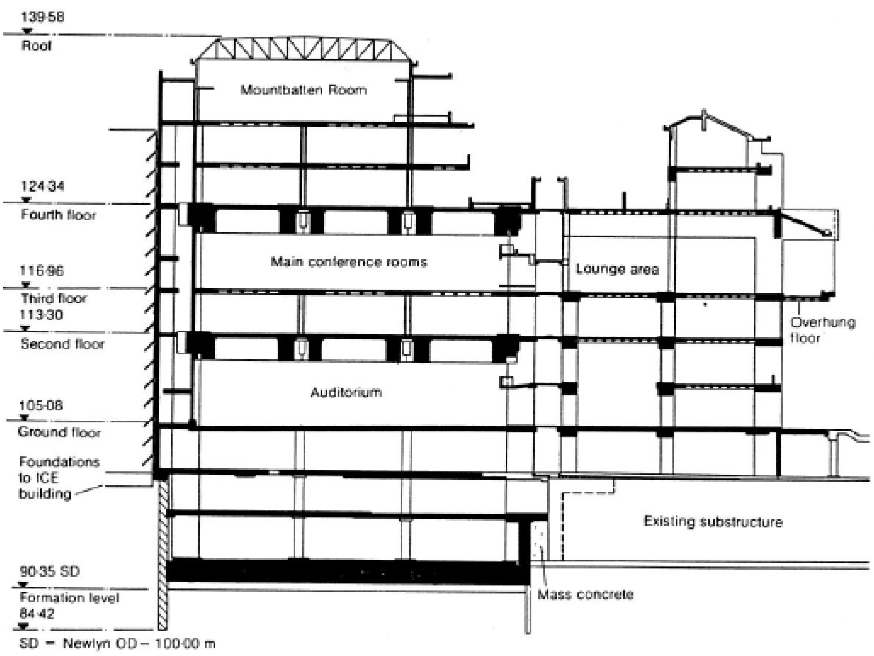
Position of load cells in test piles

Under-reamed bored pile in stiff clay



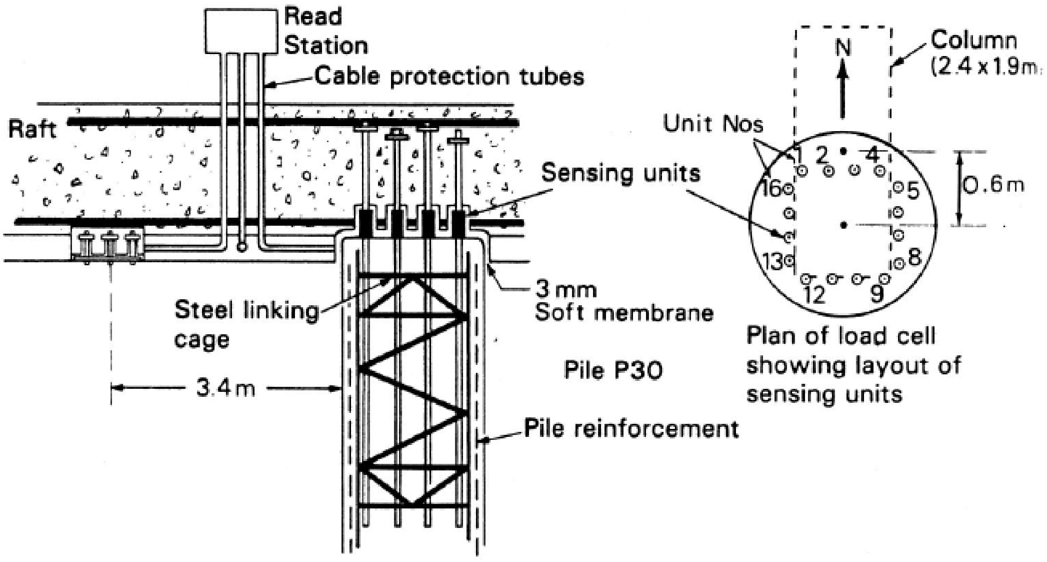
For the base to operate efficiently the shaft will be fully mobilised under working load

Stress reducing piles Burland and Kalra (1986)
Queen Elizabeth II Conference Centre

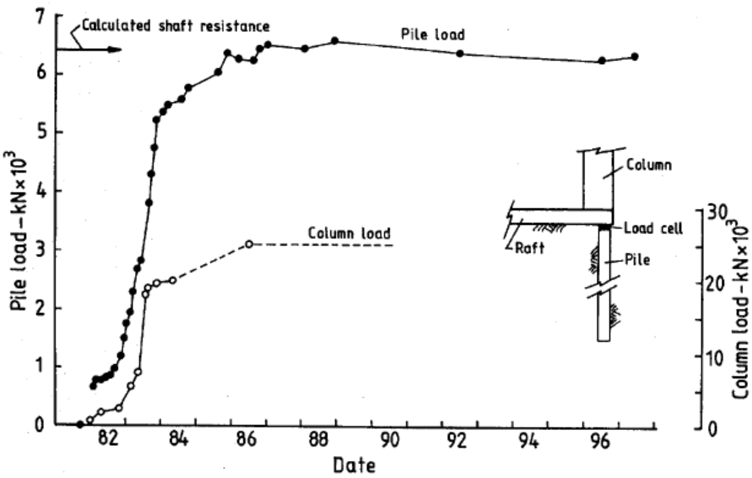


N–S cross-section through building

Queen Elizabeth II Conference Centre



Pile load cell (not to scale)



To avoid thickening the raft locally beneath the heavy columns, straight shafted piles were installed, designed to fully mobilise

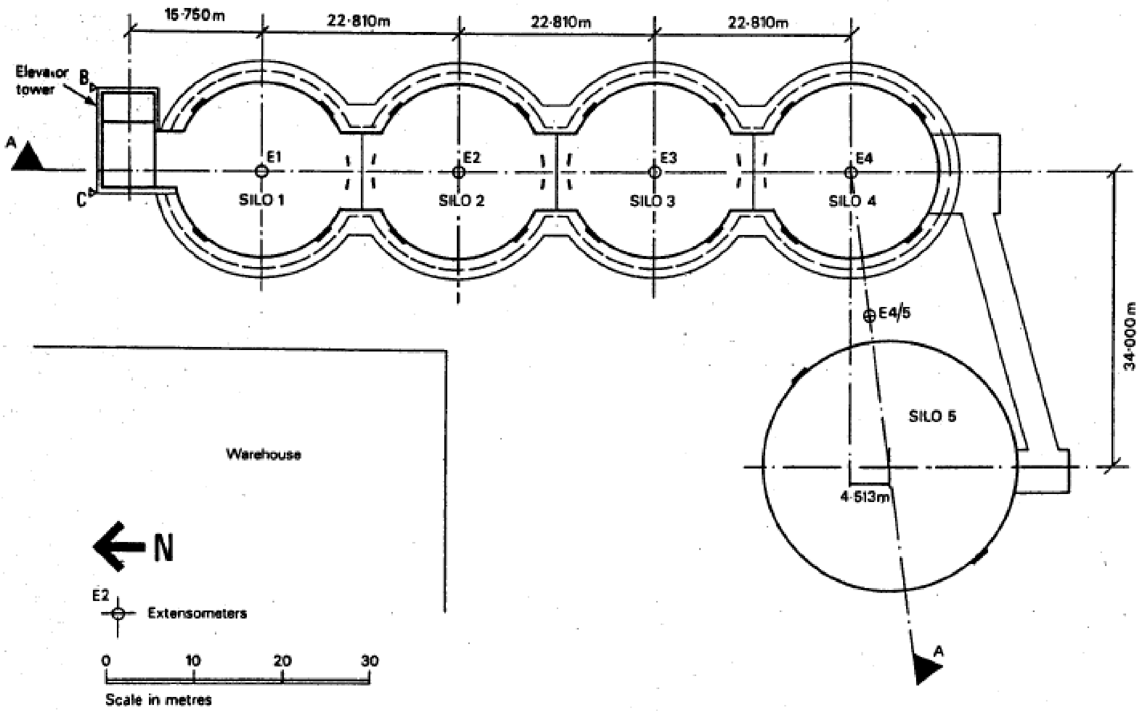
Raft reinforcement being placed

TWO PUZZLING CASE HISTORIES FOR WHICH UNDERSTANDING THE MECHANISMS OF BEHAVIOUR PROVED CRUCIAL

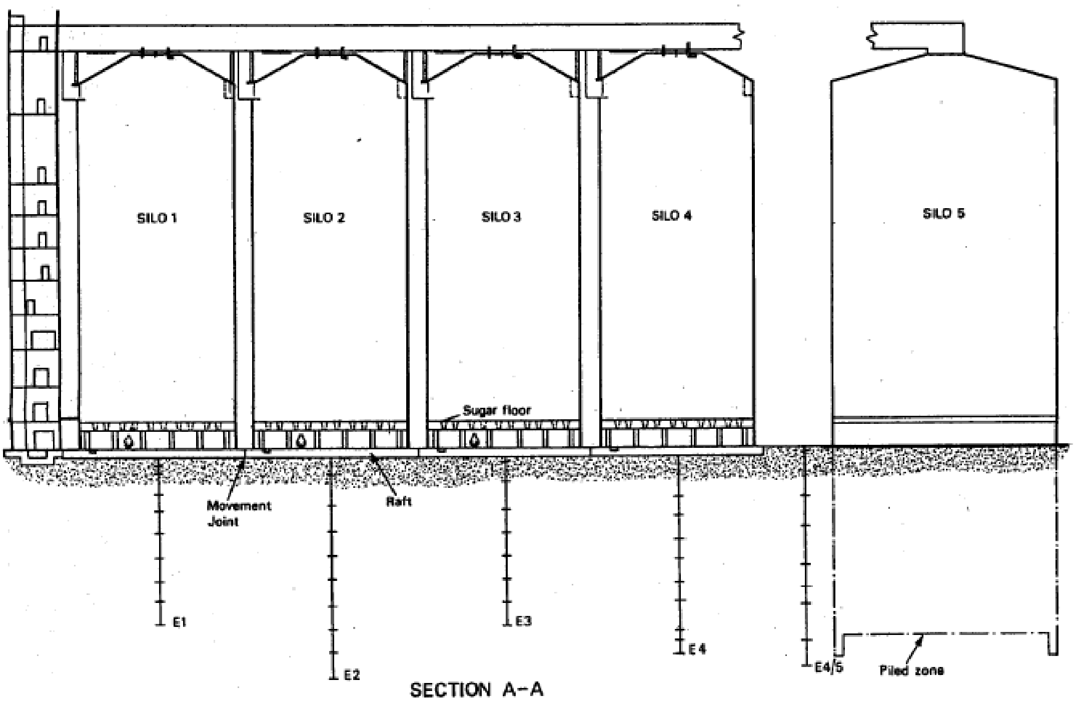
A Case History of the Failure of some silos during discharge (due to soil-structure interaction?)
Silos 1 to 4 built in 1973

Silos 1 to 4 built in 1973

Silo 5 added in 1982



Plan view of Silos



Silo 4 and then Silo 3 failed during discharge, after the first loading of Silo 5

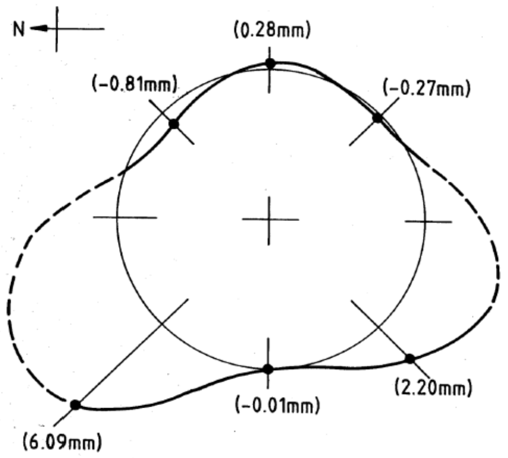
Professor Rowe (1995) attributed the cause of the failure to interaction between the foundations of Silo 5 and Silos 3 & 4
“Causation was traced to the unexpectedly high stiffness of the stored material in reaction even to minimal distortions of the walls imposed from an exterior source”.
However precision levelling measurements made during unloading of the silos suggest that interaction with Silo 5 is not the only possible explanation for the failure.

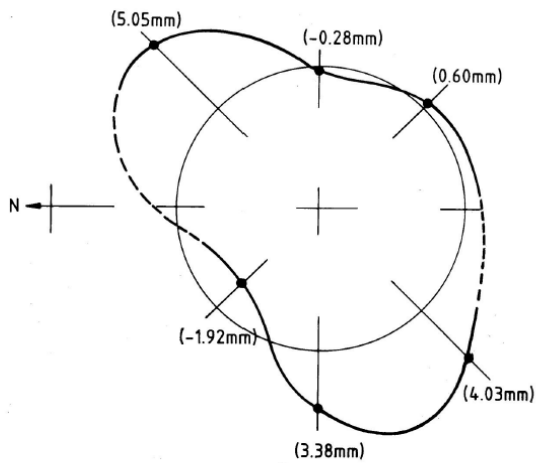
Precision levelling points around the walls and on the columns.
Magnet extensometers.
During first loading of Silo 5 the top of b/h 4/5 settled 3.2mm. Little vertical straining of ground over depth of piles - effectiveness of sleeving.
Silo 4 inclined towards Silo 5 by about 2mm across raft and the centre settled by 3.2mm.
Silo 3 showed no inclination and settled by less than 1mm No measureable out of plane distortions around bases of silos

THE INDUCED MOVEMENTS WERE EXTREMELY SMALL

During the previous operation of Silos 1 to 4 there had been significant interaction between them with induced settlements of up 20mm. But they had performed very satisfactorily A key question is:
“Why should such small movements induced by loading Silo 5 have triggered the failure of Silos 3 and 4 on commencement of unloading when in the past much larger interactions had safely occurred”?
The form of the foundation movements that took place during unloading are crucial in attempting to answer this question

Silo 3: Vertical displacements around base when unloaded from 12,133t to 11,098t





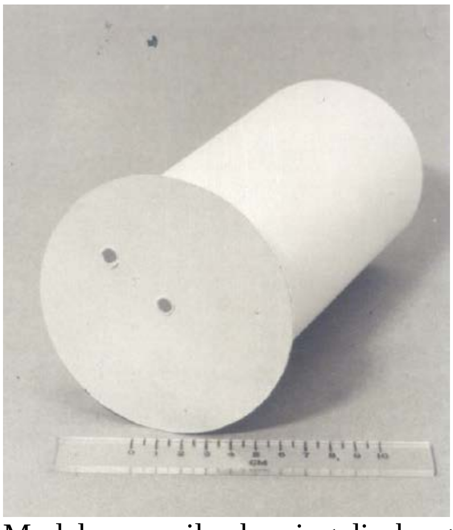
Silo 3: Vertical displacements around base when unloaded from 12,133t to 11,098t

Silo 4: Vertical displacement around base when unloading from 12,133t to 11.098t

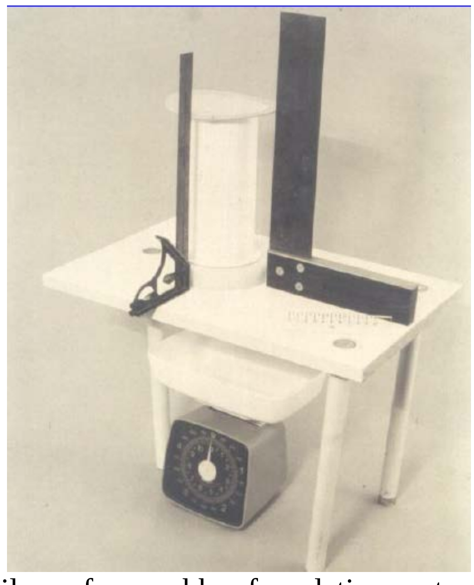
The form of foundation movements were intriguing

- The shapes are different from an expected subsidence trough.
- A vertical cylinder is very stiff when subjected to differential vertical forces around its base. Could such large distortions really have resulted from vertical forces coming up from the underlying ground?
- However the same cylinder is very flexible when subjected to non-uniform internal radial pressures.
- I undertook some simple model tests to explore the effects of eccentric internal vertical flow during discharge

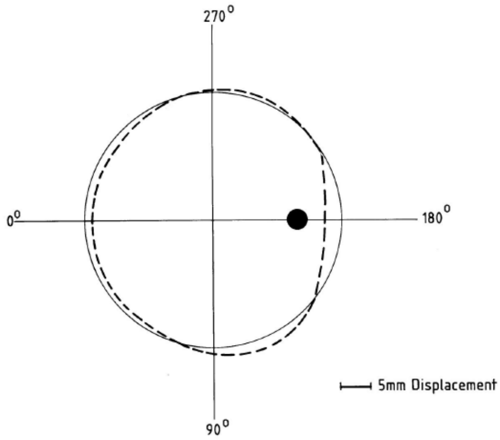
Model paper silo showing discharge holes in cardboard base



Model paper silo showing discharge holes in cardboard base

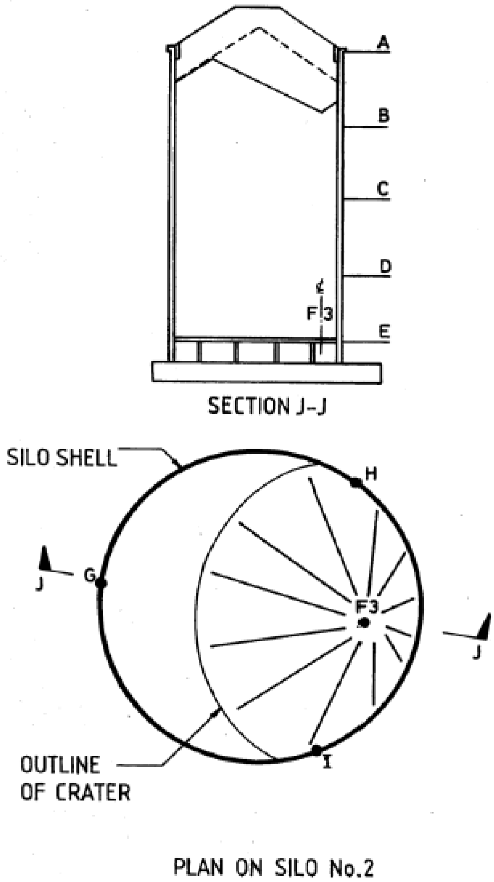


Model silo on foam rubber foundation, note transparent screen on top of silo



Loading model silo – note temporary former

Paper silo: radial displacements at top due to 10 percent eccentric discharge from 2/3 radius



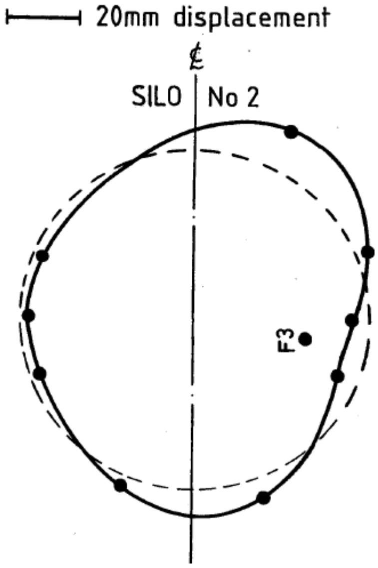
Full-scale eccentric discharge tests at Felsted

(Driver and Dawson, 1988)

Radial displacements measured at various elevations - note elevation C

Content reduced from 12,000t to 10,778t at 2/3r eccentricity

Profile of content after 10% discharge



Felsted full-scale trial.
Measured radial movements
at level C for eccentric discharge
at 2/3 radius (Driver and Dawson, 1988)

Comments

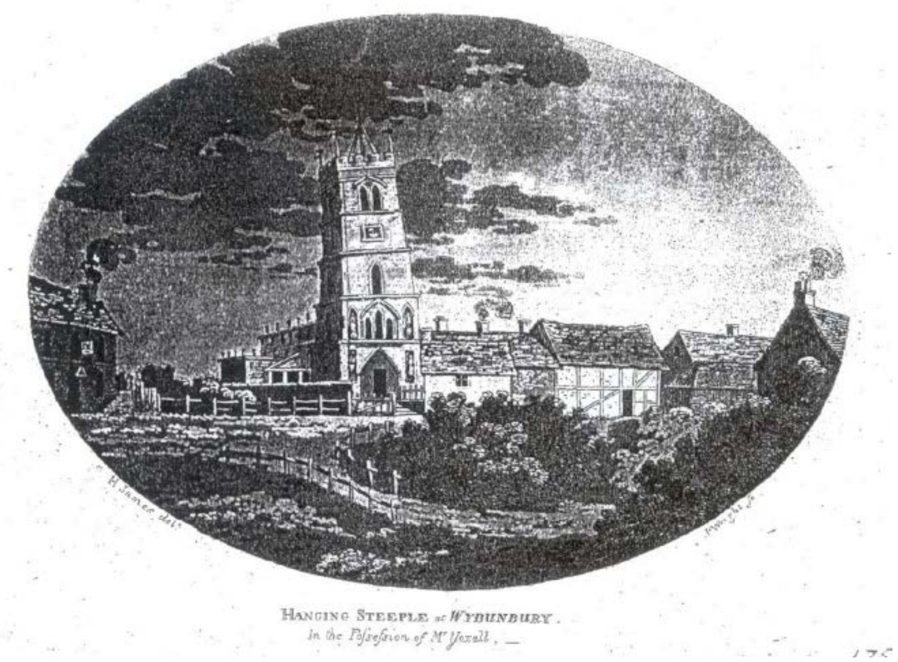
- The circumstantial evidence pointed overwhelmingly to the cause of the failure being due to interaction with the new silo 5
- However the modes of deformation are consistent with eccentric flow
- The owners maintained that they operated the silos within the specified limits of eccentric discharge – there is now circumstantial evidence that this was not the case
- It is well known that numerous factors can give rise to eccentric flow within silos and that it is very dangerous
- Even simple models can be very instructive

AN HISTORICAL ENIGMA

The stabilisation of the 15th century tower of St Chad, in Wybunbury, by James Trubshaw in 1832

15th Century Church of St Chad

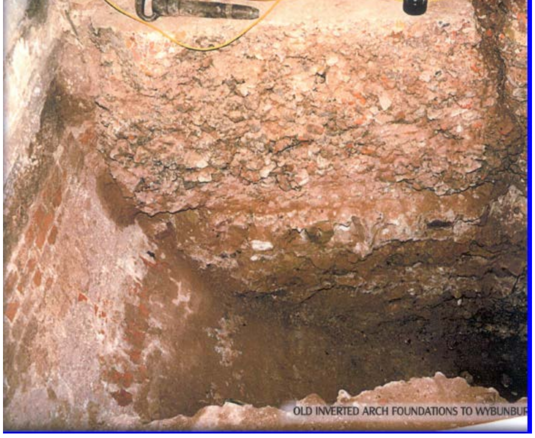
The Hanging Steeple of Wybunbury

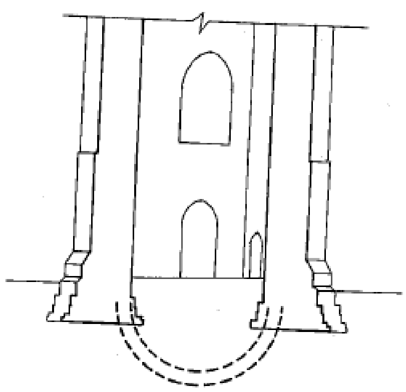


"The spire of a church which had deviated from the perpendicular 5ft 11in., and was split several inches apart a long way up the centre, has lately been set straight by Mr Trubshaw." Architectural Magazine, 1834
"Mr Trubshaw, …... proceeded to bore a row of auger-holes clear through under the foundations of the high side…... These holes he filled with water; and, corking them up with a piece of marl, let them rest for the night. ……….the building gradually began to sink, another row of holes was bored, but, not exactly so far as the first row. …..the high side not only kept sinking, but the fracture in the centre kept gradually closing up. This process was continued till the steeple became perfectly straight, and the fracture imperceptible."

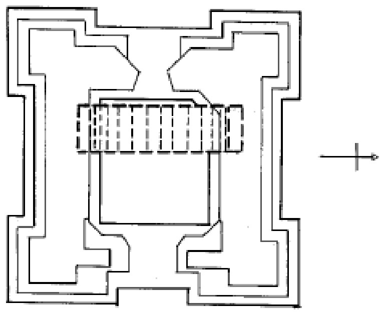
Quote from Anne Bayliss" thesis: Trubshaw stabilised the tower without any "wonderful machinery or secret inventions" Source unknown

IN THE 1980S THE TOWER WAS UNDERPINNED





Vertical Section looking West



Plan of Foundations

Elevation and plan showing Trubshaw‟s semi-circular inverted arch beneath the western side of the foundations

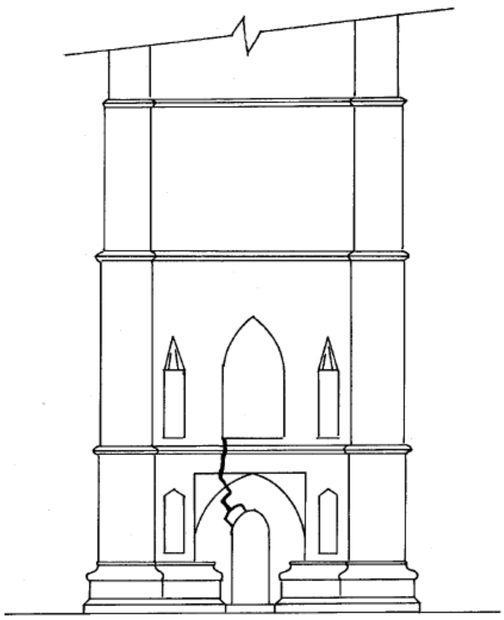
What was the function of this arch?

"…….and the high side not only kept sinking, but the fracture in the centre kept gradually closing up. This process was continued till the steeple became perfectly straight, and the fracture imperceptible.

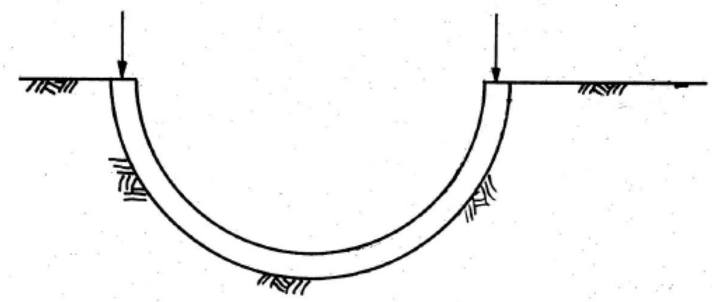
" I had thought that the fracture was between the tower and the church.

But we went back and examined the tower.

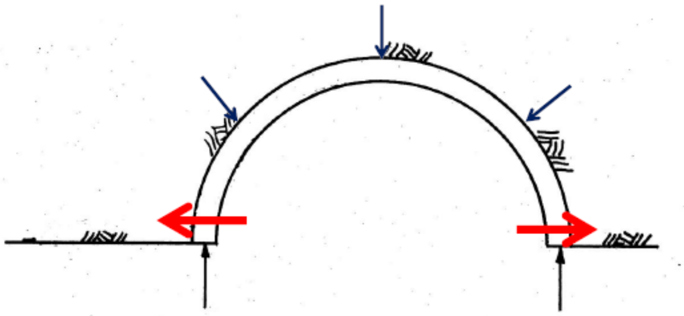
View of west side showing "fracture"

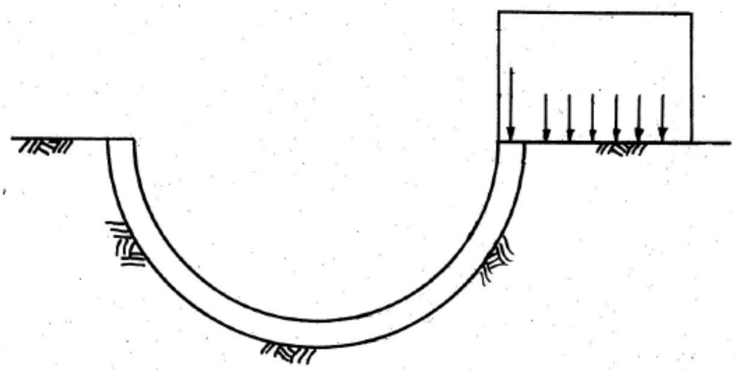


Western elevation of Tower showing: "split several inches apart a long way up the centre" Could the purpose of the inverted arch have been to achieve this closure of the fracture?

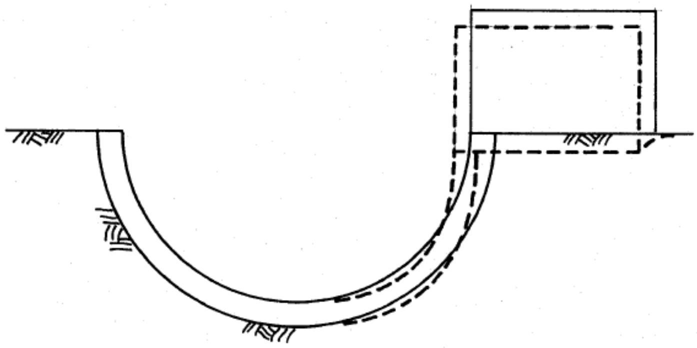


Inverted arch with load applied at springing points





The loading actually applied by Trubshaw



- Model tests using foam rubber demonstrate that, as the foundation subsides, the springing point of the inverted arch moves inwards such that the arch closes slightly.
- This action could have led to closure of the fracture in the western façade.
- **Trubshaw was a most ingenious and intuitive engineer Is it possible that he could have anticipated this behaviour?**

Conclusions

- At first sight the idealisations adopted by Structural Engineers appear less uncertain than those adopted by Geotechnical Engineers.
- However, the success of structural design calculations owes more to the inherent ductility adopted in practice than it does to calculating the actual state of a building - Safe Design Theorem.
- Structural Engineers tend to think in terms of force and stress, Geotechnical Engineers are used to working in terms of strain and deformation.
- Structural Engineers brought up on concepts of limiting stress and "actual state" find it difficult to accept behaviour that implies full mobilisation of resistance of some of the elements.
- Hambly's paradox greatly aids the understanding of these ideas
- A particularly difficult and challenging situation is when ground movement due to nearby tunnelling or excavation impacts on an existing building. Modern powerful computer models invariably give large regions of "overstress" which are very misleading.
- The processes and idealisations involved in geotechnical modelling can perhaps be best understood by considering those processes and idealisation that a Structural Engineer must adopt when working on an ancient historic building - the approaches are very similar.
- Some case histories have been given illustrating the importance of ductility and robustness in designing for structure-foundation interaction.
- I have described two case histories where understanding the mechanisms of behaviour provided the key. Unless the basic mechanisms of behaviour are understood and incorporated no amount of sophisticated numerical modelling will help. Quite simple physical models can be very instructive.

CONCLUDING REMARKS

- Understanding and designing for ground-structure interaction requires all the traditional skills of the engineer:

- *Reliance on observation and measurement;*

- *A deep understanding of materials, both ground and structural;*

- *The development of appropriate conceptual, physical and analytical models to reveal the underlying mechanisms of behaviour;*

- *Well winnowed experience based on a discerning knowledge of precedents and case histories.*

I hope that I have shown that a balanced geotechnical triangle is a good foundation for any structure.

Personal reflections on the teaching of soil mechanics

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ABSTRACT: The Soil Mechanics Triangle was developed by the author in 1987 as a teaching aid but it is now clear that it has wide relevance in practice as well. To reflect its wider application it has been slightly modified and re-titled the Geotechnical Triangle. One of its main attributes is that it clearly sets out the activities and disciplines involved in geotechnical modelling and a comparison is made with structural modelling. Many of the mechanisms of behaviour exhibited by the ground can be illustrated by simple physical models and the use of these is strongly recommended. Not only are they likely to be understood and remembered by students but their use can actually save time. Two of the most striking physical models used by the author are described. Four of the most important characteristics that need to be instilled in the students are discussed: rigour; the ability to simplify; creativity; clarity of expression.

1 INTRODUCTION

In 1987 I had the honour of delivering the Nash Lecture at the Ninth European Conference on Soil Mechanics and Foundation Engineering, Dublin (Burland, 1987). I chose the teaching of soil mechanics for two reasons: firstly Professor Kevin Nash was a dedicated and highly respected teacher with a life-long interest in the education of civil engineers; secondly I had only recently become an academic. This provided me with an opportunity to reflect on what I regarded as my main task - education.

In this present paper I revisit some aspects of the 1987 paper highlighting my own personal views on what I believe to be key issues and also describing how my views have developed.

Right at the outset it is essential that a distinction be made between "education" and "training". Sir Charles Inglis, who was Head of Engineering at Cambridge University, maintained (Inglis, 1941):

> *"… that the soul and spirit of education is that habit of mind which remains when a student has completely forgotten everything he as ever been taught."*
>
> *In these days of rapid technological change this could be replaced by "… when everything a student has been taught has changed".*

Sir Charles did not argue that there should be no element of instruction or training in an engineering education. He recognized that training is an important element of education – but he argued for an appropriate balance between them.

This balance between education and instruction (or training) has to be decided with care on the basis of a number of factors including the objectives of the course, the destination of the majority of the students, their level of attainment and the time available – there can be no "one size fits all". I believe that diversity of curricula and approaches should be encouraged.

I have become aware of three key issues which can, unless we are continually vigilant, devalue the teaching of soil mechanics. The first is that it is very easy to take for granted much that has become "second nature" to an experienced geotechnical engineer or researcher and thereby leave the students baffled. For reasons that I will discuss later, students find soil mechanics a difficult subject. It is identifying and instilling what should become that *habit of mind* that is such a challenge. Secondly, it is only too easy to succumb to the pressure from practitioners and others that a particular topic "is essential to the curriculum".

This is a sure recipe for *"overcrowding, overloading and overteaching*" which leads to the third issue: no matter how hard we try, there never seems to be enough time! Perhaps we can learn from the Professor of Greek at Owen's College, UK who in 1873 stated:

> *"The subject matter of the studies selected is, in fact, of less importance than the discipline imparted. But a selection has to be made which will draw out and strengthen the powers of the mind and afford a broad basis on which to build a subsequent professional career".*

For all of the above reasons I am going to avoid discussing the contents of curricula. I do however believe that a key aim of teaching is to give the student 'sheet anchor points' whose security and limitations have been clearly established whether they be experimental, empirical or theoretical. It goes without saying that a key 'sheet anchor point' in saturated soil mechanics is the principle of effective stress. Time spent on this is a good investment.

I have recently become aware that students appreciate knowing a little about the historical context of a subject and something about the personalities involved. This need not be an historical discourse but rather a few asides which can spice-up the lecture. The following two sections may be helpful in this respect.

2 HISTORICAL CONTEXT

It is not widely appreciated what a parlous state the subject of ground engineering was in, prior to Terzaghi's contributions. Recently, as part of its centenary celebrations, I was given the interesting task of tracing the development of foundation engineering over the last 100 years through the papers published in The Structural Engineer (Burland, 2008). Many of the early papers describe various techniques of foundation construction such as pile types, sheet pile wall sections, coffer dams and caissons. But these papers make little reference to the mechanical properties of the ground and how its response can be assessed. For example Brooke-Bradley (1932-34) states that:

> "*If the bearing power of sub-soil should prove to be inadequate to carry the proposed loads, it must be artificially strengthened".*

Methods of doing this are then described together with the various types of piles available for this purpose. No where does one find how the *"bearing power"* of the ground can be assessed in the first place. It is also stated that *"all settlement should be avoided if possible",* examples are given of damaging settlement but no guidance is given on how it could be estimated.

In the early issues of *The Structural Engineer* some space is given to the design and construction of retaining walls. In 1915 Wentworth-Shields read a paper on "The Stability of Quay Walls on Earth Foundations". He opens with the following memorable statement:

> "*In spite of the large amount of experience which has been gained in the construction of quay walls, it is still one of the most difficult problems in engineering to design a wall on an earth foundation with confidence that it will be stable when completed. . . . Even if the designer of such a wall is assured that it will stand, he cannot with any confidence tell you what factor of safety it possesses".*

In 1928 Moncrieff published a major paper in *The Structural Engineer* on earth pressure theories in relation to engineering practice. He summarises the various approaches to calculating earth pressures from Coulomb (1773) through to Langtry Bell (1915). At that time the angle of friction was generally equated with the angle of repose and Moncrieff refers to the difficulty of determining this angle for clayey soils. He cites a cutting in clay in which the side slopes varied from vertical to 1 vertical in 1½ horizontal while in parts the clay was "running down like porridge".

It is all too clear from these early papers that, in spite of significant, even heroic, engineering achievements in the construction of major foundations, retaining structures, tunnels and dams, there was little understanding of the factors that control the mechanical behaviour of soil in terms of its strength and stiffness. Moreover there is almost no reference to the influence of ground water on strength, stability or earth pressures. It is hardly surprising that there were frequent failures, particularly of slopes and retaining walls. This was the muddle that Terzaghi found when he first began to practice as a civil engineer.

3 TERZAGHI, FATHER OF GEOTECHNICAL ENGINEERING

Because of his work in developing the scientific and theoretical framework of soil mechanics and foundation engineering, Terzaghi is often regarded as essentially a theoretician. In the teaching of Soil Mechanics it is all too easy to leave the student with the impression that the subject is now an exact science and that everything can be calculated, emulating the older discipline of structural engineering. Nothing could be further from the truth (and indeed it is not true for structures either). It is therefore worth reflecting on Terzaghi's struggles to develop the craft and the science of ground engineering for they have relevance in both the teaching and the practice of the discipline.

Goodman (1999) has written a most illuminating and thoroughly researched narrative of Terzaghi's life *"Engineer as Artist"*. He was born in Prague in 1883. He showed an early interest in geography, especially field exploration, and later astronomy which evolved into a passion for mathematics. Later at school he was inspired by the natural sciences and performed brilliantly.

3.1 Terzaghi's education

He went on to read Mechanical Engineering at the Technical University of Graz. For a time he lost his way, engaging in drinking and dueling. He found the lectures were simply a set of prescriptions which he claimed he could read up for himself. Ferdinand Wittenbauer, a wise teacher, challenged Terzaghi to do better and go back to the original sources – in particular Lagrange's Analytical Mechanics. So Wittenbauer led Terzaghi gently on; guiding him, not only into the excitement of scientific creativity but also the very real social and cultural issues of the day. It was Wittenbauer who saved Terzaghi from being expelled after an over exuberant student prank. Wittenbauer pointed out to the authorities that in the history of the University there had been only three expulsions: Tesla, who went on to revolutionise electrical technology; Riegler, who created the steam turbine and a third who developed into a leading church architect. He went on to point out that the University was not good at choosing candidates for expulsion. Terzaghi was reprieved!

Though reading Mechanical Engineering, Terzaghi attended courses in geology. He was keen on climbing and it is related that he made every climbing expedition into a joyous adventure in field geology. During his compulsory year of military service he translated the Manual of Field Geology by Archibold Geckie (Director of the British Geological Survey) into German. In a second edition he actually extended it to a fuller coverage of karst features and the geomorphology of glaciated country, replacing the English examples with Austrian ones.

3.2 The switch to civil engineering

Terzaghi's interest in geology persuaded him that mechanical engineering was not for him. He switched to civil engineering and returned to Graz for an extra year. He went to work for a firm specialising in hydroelectric power generation. Although his main activity was in the design of reinforced concrete, the planning of the structures was of course intimately involved with geology. But frequently he found the guidance of expert geologists unhelpful. He encountered many cases of failure. Significantly these were mainly due to the lack of ability to predict and control groundwater - piping failures were abundant. He also encountered many slope failures, bearing capacity failures and structures undergoing excessive settlements.

3.3 Geology on its own

Recognising the difficulties that civil engineers experienced in dealing with the ground and also the obvious influence of geological factors, he concluded that it was necessary to collect as many case records as possible so as to correlate failures with geological conditions. It is well known that he then spent two intense years (1912 – 1914) in the western

Fig 1. Karl von Terzaghi (by permission of NGI)

United States observing and recording. Two years that ended in disillusion and depression.
The following quote from his Presidential Address to the 4th International Conference on Soil Mechanics and Foundation Engineering sums up his mood at that time (Terzaghi, 1957):

> *"At the end of the two years I took my bulky collection of data back to Europe, but when I started separating the wheat from the chaff I realised with dismay that there was practically no wheat. The net result of two years of hard labour was so disappointing that it was not even worth publishing it".*

So much for geology on its own! So much for precedent and case histories on their own!
To quote Goodman (1999), the problem lay in the fact that:

> *". . . . the names geologists give to different rocks and sediments have developed mainly from a scientific curiosity about the geologic origin of these materials, whereas Terzaghi was aiming towards discerning the differences in their engineering properties.*

3.4 The birth of the science of soil mechanics

Shortly after his appointment to the Royal Ottoman Engineering University in Constantinople in 1916 Terzaghi began to search the literature for insights into the mechanical behaviour of the ground. He became increasingly frustrated. What he witnessed was a steady decline from 1880 in recorded observations and descriptions of behaviour. This was replaced by myriads of theories postulated and published without adequate supporting evidence. This experience must have been uppermost in his mind when, in his Presidential Ad-dress to the First International Conference he stated the following (Terzaghi, 1936):

"In pure science a very sharp distinction is made between hypothesis, theories, and laws. The difference between these three categories resides exclusively in the weight of sustaining evidence. On the other hand, in foundation and earthwork engineering, everything is called a theory after it appears in print, and if the theory finds its way into a text book, many readers are inclined to consider it a law".

Thus Terzaghi was emphasising the enormous importance of assembling and examining factual evidence to support empirical procedures. He is also bringing out the importance of instilling rigour. This is often equated with mathematics but there is at least as much rigour in observing and recording physical phenomena, developing logical argument and setting these out on paper clearly and precisely.

In 1918 Terzaghi began to carry out experiments on forces against retaining walls. He then moved on to piping phenomena and the flow beneath embankment dams. He used Forchheimers flownet construction to analyse his observations and apply them in practice – methods which were themselves adapted from the flow of electricity. We see here the interplay between experiment and analytical modelling.

Over this period Terzaghi came to realise that geology could not become a reliable and helpful tool for engineers unless and until the mechanical behaviour of the ground could be quantified – this required systematic experimentation. On a day in March 1919, and on a single sheet of paper, he wrote down a list of experiments which would have to be performed.

Terzaghi then entered an intense period of experimental work in which he carried out oedometer tests and shear tests on clays and sands, thereby developing his physical understanding of the principle of effective stress, excess pore water pressures and time-rate of consolidation. To make headway with modelling the consolidation phenomenon analytically he turned to the mathematics of heat conduction. Again we see here the interplay between experiment and analytical modelling.

3.5 The impact of soil mechanics on structural and civil engineering

On 6th December 1934 Terzaghi delivered a lecture before The Institution of Structural Engineers in London with the title "The actual factor of safety in foundations", He illustrated his lecture with a large number of case histories of measured distributions of settlement across buildings and their variation with time. He was able to explain the broad features of behaviour using the basic principles of soil mechanics and foundation analysis demonstrating how vital it is to establish the soil profile with depth and across the plan area of the building. Even so, he showed that local variations in soil properties and stratification make it impossible to predict the settlement patterns with any precision. Without actually using the term, he drew attention to the important concept of ground-structure interaction pointing out that the structure of a building should not be treated in isolation from its foundations. He even drew attention to the fact that reinforced concrete beams can yield plastically without impairing the stability or appearance of a frame building provided the cracking is not excessive. It is of interest to note that, in their seminal paper on the allowable settlement of buildings, Skempton and MacDonald (1956) drew extensively on the case histories provided by Terzaghi in this lecture.

Towards the end of his lecture he made the following important assertion:

"Experience alone leads to a mass of incoherent facts. But theory alone is equally worthless in the field of foundation engineering, because there are too many factors whose relative importance can be learned only from experience".

On 2nd May 1939 Terzaghi delivered the forty fifth James Forrest Lecture at the Institution of Civil Engineers, London with the title “Soil Mechanics – A New Chapter in Engineering Science”. The lecture summarised in simple terms the basic elements of the discipline of soil mechanics and its application to a number of engineering problems ranging from earth pressure against retaining walls, the failure of earth dams due to piping through to the phenomenon of consolidation and the settlement of foundations. Early on in the lecture Terzaghi made the memorable statement that:

> *“. . , in engineering practice difficulties with soils are almost exclusively due, not to the soils themselves, but to the water contained in their voids. On a planet without any water there would be no need for soil mechanics”.*

He was a forceful and charismatic figure and this lecture made a very profound impact on the structural and civil engineers in the UK. Many leading geotechnical engineers, including the late Sir Alec Skempton, stress what a pivotal role this lecture played in the development of soil mechanics in the UK. As with his earlier lecture to the Institution of Structural Engineers, Terzaghi emphasised very strongly the importance of retaining a balance between theory and practice in soil mechanics. He stressed most strongly that precision of prediction was not possible due to the inherent variability of the ground and construction processes.

It is clear from the above that Terzaghi is very much more than the Father of the Science of Soil Mechanics. His contribution was to place ground engineering on a rational basis with geology as a key supporting discipline and soil mechanics providing the scientific framework for understanding the mechanical response of the ground. He is indeed the Father of Geotechnical Engineering which embraces engineering geology, soil mechanics and arguably rock mechanics as well.

It is hoped that the previous two sections will provide a helpful summary that puts into context Terzaghi’s struggles to provide a scientific basis for geotechnical engineering. It demonstrates his grounding in geology; the importance of gaining an understanding the mechanical behaviour of the ground and groundwater by means of experiment and testing; the need to develop an analytical framework for predictive purposes and, very importantly, the key role that experience plays and the importance of case histories. Time and time again he insisted that soil mechanics is not a precise science because of inherent variability of the ground and the uncertainty of many factors associated with construction.

4 THE GEOTECHNICAL TRIANGLE

Geotechnics is a difficult subject and is regarded by many students and engineers as a kind of black art. I used to think that this was due to the nature of the ground and the fact that it is a two or even three phase material. It is much more complex than the more classical structural materials of steel, concrete and even timber with which students are familiar.

In 1987, after careful study of the opinions expressed by Terzaghi and others, and from my own experience, I came to the view that the main problem is due to a lack of appreciation of the number of aspects that have to be considered in tackling a ground engineering problem. Since that time my view has been strengthened.

Examining Terzaghi’s struggles towards establishing the subject we see that there are four distinct but interlinked aspects:

- The ground profile including groundwater conditions.
- The measured or observed behaviour of the ground.
- Analytical prediction using appropriate models.
- Empirical procedures, judgment based on precedent and what I have termed “well-winnowed experience”.

The boundaries between these four aspects often become confused and one or more of them is frequently completely neglected. The first three may be depicted as forming the apexes of a triangle with empiricism and experience occupying the centre (Burland, 1987). I called this the Soil Mechanics Triangle as it was developed around the teaching of soil mechanics. Since then I have come to appreciate that it applies equally well to practice and I have therefore re-named it the Geotechnical Triangle – see Figure 2. Associated with each of the above aspects is a distinct and rigorous activity.

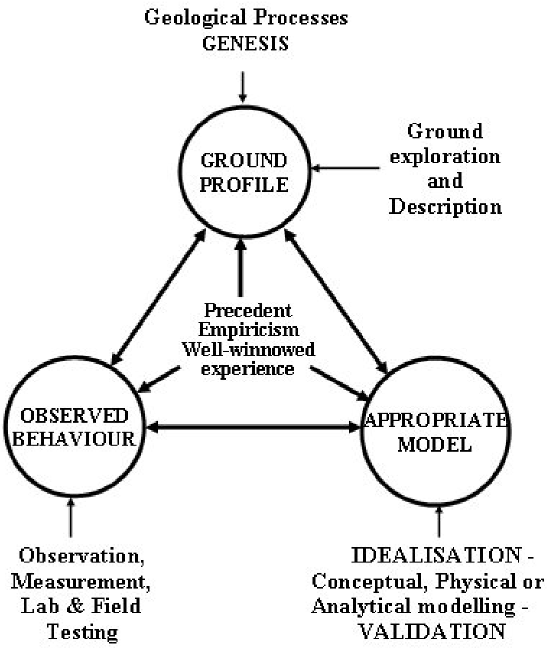


Figure 2. The Geotechnical Triangle

4.1 The ground profile and its genesis:

Establishing the ground profile is the key outcome of the site investigation. By ground profile, I mean the description of the successive strata in simple engineering terms together with the groundwater conditions and the variations across the site. Also it is vital to understand the geological processes and man-made activities that formed the ground profile i.e. its genesis. I am convinced that 9 times out of 10, the major design decisions can be made on the basis of a good ground profile. Similarly, 9 failures out of 10 result from a lack of knowledge about the ground profile – often the ground water conditions.
Peck (1962) argued that the methodology of the geologist consists in making observations, organizing and assembling these, formulating an hypothesis and then critically testing the hypothesis. However the civil engineer, and in particular the structural engineer, is not trained in this methodology which is at the heart of much geotechnical engineering.

4.2 The observed or measured behaviour of the ground

This activity involves observation and measurement. It includes laboratory and field testing, field observations of behaviour including movements and ground water flow. Rigorous methodologies and advanced instrumentation are often required for this work. The measurements require interpretation and to do so requires an appropriate analytical framework. This brings us on to the activity of modelling.

4.3 Appropriate modelling

When I first put forward the Soil Mechanics Triangle in 1987 I use the term 'applied mechanics' for the bottom right hand corner of the triangle. However I now believe that the term 'appropriate modelling' is much more representative of what is going on. The term modelling is being used increasingly and the engineering geologist is very familiar with the process of developing geological models.

- By modelling I mean the process of idealising or simplifying our knowledge of the real world…..
- assembling these idealisations appropriately into a model which is then. . .
- amenable to analysis and hence prediction of response. I often say to students that 'to analyse is first to idealise'.
- The modelling process has not been completed until the response has been validated and assessed.
- The procedure may involve a number of iterations.
- Thus the process of modelling is very much more than simply carrying out an analysis.
- A model can be a very simple conceptual one, it can be a physical 1g model or a centrifuge model, it can be a very sophisticated numerical model.
- By using the term "model" we are emphasising the idealisation process and de-mystifying the analytical process. The Geotechnical Triangle helps in this.

4.4 Empirical procedures and experience

With materials as complex and varied as the ground, empiricism is inevitable and it is (and will always re-main) an essential aspect of geotechnical engineering. Many of our design and construction procedures are the product of what I have termed "well-winnowed experience". That is, experience which results from a rigorous sifting of all the facts that relate to a particular empirical procedure or case history. I chose the term having read Terzaghi's description of his attempts to 'separate the wheat from the chaff' following his two years in the USA collecting case records.

4.5 Summary

In summary we see within the Geotechnical Triangle four key aspects, each associated with distinct types of activity with different outputs. Each activity has a distinct methodology, each has its own rigour, each is interlinked with the other. Terzaghi's approach to ground engineering reveals a coherence and integration which is reflected in a balanced Geotechnical Triangle.

5 GEOTECHNICAL TRIANGLE IN TEACHING

In the 1987 paper I showed how the Geotechnical Triangle could be used to develop a coherent and balanced soil mechanics course. The number of topics covered there are probably greater than would normally be covered in an undergraduate course. However, whatever the type of course that is envisaged, the Triangle offers a valuable frame of reference when considering its content.

In the time since I first put forward the Triangle in 1987, I and others have found it useful as a teaching aid. Students find it particularly difficult to untangle in their minds the differences between results that are based on rigorous analysis, those that are experimental and those that have been developed from empirical rules. It is helpful during a lecture to be able to point out which aspect of the Triangle is being discussed and how it relates to the other aspects. Some examples are given in the following.

5.1 Particulate nature of soil

Very early in the course students learn that soil is essentially particulate. Yet we have to idealise it as a continuum in order to make use of current methods of applied mechanics such as limit equilibrium analysis or deformation analysis. The effective stress principle itself arises out of the particulate nature of soil and it is then incorporated into our continuum analyses. This can be explained by starting off in the bottom left-hand corner of the triangle with the measured behaviour of a particulate material and moving across to the bottom right-hand corner by making a more or less appropriate idealisation. It is important to understand thoroughly the properties of the idealized model and to appreciate its similarities and differences from the actual behaviour of the particulate material it represents. In section 7 of this paper I discuss the use of physical models as an aid to understanding broad mechanisms of behaviour of soils and the principle of effective stress.

5.2 Stress and strain

Concepts of stress and, to a lesser extent, strain relate to idealized continua and are therefore explicitly dealt with in the bottom right-hand corner of the triangle. Mohr's circle of stress occupies a central role in soil mechanics and it is helpful to the student to understand where in the overall framework of the triangle this tool lies. Incidentally, it is important that the differences in sign convention are understood between the equations of stress equilibrium and the Mohr's circle graphical representation.

At post-graduate level I spend a lot of time on the concepts of strain as this is central to developing plasticity theory. However there is unlikely to be the time available at undergraduate level to do the topic full justice. Teaching the concepts of strain are discussed more fully in the 1987 paper.

5.3 Mohr-Coulomb strengths

The Mohr-Coulomb failure criterion is an idealized model of reality and therefore belongs in the bottom right hand corner of the Triangle. But its practical application requires that it has to be adapted to suit various circumstances. Students can benefit from studying experimental results from shear box tests and triaxial tests. For sands, the phenomena of dilatancy and contractancy can be studied together with the curvature of the failure envelope and the dependency of peak strength on initial density. Ideas of post-peak strain softening, critical state strength and residual strength can be developed. We see here the interaction between the experimental corner of the triangle and the modelling corner.

5.4 Ideal porous elastic solid

Analytical and numerical solutions for ideal porous elastic continua play a very important part of geotechnical modelling. I have found from experience that it pays dividends to explore with students the properties of an ideal isotropic porous elastic material. I begin by giving them a physical image of such a material as consisting of a random agglomeration of very fine metal particles spot-welded together at their contact points. The stiffness properties of this skeleton are given by the drained elastic parameters E' and υ'.

Using the simple equations relating increments in principal effective stress to the equivalent strain increments it is possible to derive the expressions for effective bulk modulus K′ and shear modulus G′ in terms of the effective Young's modulus E′ and effective Poisson's ratio υ′. It follows that the effects of change in mean normal effective stress p′ and shear stress are uncoupled and the relationship between E′ and Eu can be evaluated. Very importantly, it is easy to demonstrate that during undrained loading the value of p′ remains constant for this ideal material.

These, and other, properties of the simple ideal material can then be compared with the measured behaviour of real soils. These discussions are important because, without the framework offered by the Triangle, students often get confused between the results from ideal models and measured behaviour.

5.5 The use of elastic theory in settlement analysis

Whilst on the topic of elasticity it is worth repeating the point I made in 1987 in relation to the use of elastic stress distributions for calculating settlement. It is patently obvious to students that soil is seldom elastic, isotropic or homogeneous so how can the approach be taken seriously when the idealizations are so far from reality? For twenty years or more the answer has been clear. Yet most text books still either ignore the problem or shrug it off as one of the approximations that have to be made.

Numerical modelling using 'soil-like' properties such as non-linearity, non-homogeneity and anisotropy has made it possible to assess the accuracy of elastic stress changes beneath loaded areas. These studies have shown that actual vertical stress changes are reasonably close to those given by Boussinesq for the majority of 'soil-like' conditions. Some examples are given in Burland et al (1977) and also in the 1987 paper.
In contrast, the same is not true of the horizontal and shear stress changes which prove to be very sensitive to many parameters.

These results are of profound significance in the teaching of settlement analysis and also in practice. Be-cause it can be demonstrated that the vertical stress changes, due to a known surface pressure, are insensitive to a wide range of properties, we are able to make use of Boussinesq solutions because they are simple and are readily available for many boundary value problems. We no longer need to be embarrassed and uncomfortable about the application of elasticity for this purpose!

There are important limitations to the use of vertical Boussineq stress changes. For the case of a stiff layer overlying a soft layer the vertical stress changes are significantly less than those given by Boussinesq and as a consequence they have a wider lateral spread – the benefit of a stiff road pavement in reducing stresses in the sub-base is immediately obvious. Also Boussinesq cannot be used with such confidence for rigid footings as here the contact pressure distributions are significantly influenced by the detailed material properties.

This topic is useful for illustrating concepts of anisotropy and non-homogeneity. It is also a clear example of providing students and practitioners with a valuable 'sheet anchor point', the security and limitations of which can be clearly demonstrated.

5.6 Empirical results

There are many useful results in soil mechanics that are based essentially on laboratory measurements or field tests. Two typical ones are the coefficient of earth pressure at rest K0 and the undrained strength ratio Su/σ′v. It has been found that, for a normally consolidated soils, the Jaky expression

$$K_0 = 1 - \sin\varphi' \qquad (1)$$

works reasonably well for a wide range of soils, where φ' is the critical state angle of shearing resistance. For overconsolidated soils undergoing one-dimensional swelling this has been extended empirically by Mayne and Kulhawy (1982) to

$$K_o = (1 - \sin\varphi')xOCR\sin\varphi' \qquad (2)$$

Numerous laboratory and field studies show that for normally consolidated clays the ratio S_u/σ'_v is well de-fined and lies between about 0.28 and 0.32. Su is the undrained strength in triaxial compression and $\sigma'v$ is the effective overburden pressure. For bonded soils or lightly overconsolidated soils the effective overburden pressure can be replaced by σ'_{vy}, the vertical yield stress (Burland, 1990). For triaxial extension and plane strain the undrained strength is usually lower than for triaxial compression. The expressions for Su/σ'_v are then different and are not nearly so uniquely defined, being functions of the plasticity of the soil. Provided the empirical basis of these formulae are clearly understood these, and similar, results can be most valuable.

Perhaps my favourite example of the need for clearly understanding the basis of an empirical expression is that for the shaft resistance of a pile. Frequently the average shaft friction τ_{sf} is related to the average un-drained strength over the depth of the pile $\hat{S}u$ by the expression

$$\tau_{sf} = \alpha\, \hat{S}u \qquad (3)$$

where α is determined empirically from pile tests. The use of such an empirical expression requires a clear understanding, not only of the type of pile for which α was derived, but also precisely how $\hat{S}u$ was derived. For example, the value of α=0.45 is frequently used for bored piles in stiff fissured clays based on the work of Skempton (1959). For this work the values of $\hat{S}u$ were derived by taking the average of the scatter of un-drained triaxial compression strength results from 35mm diameter samples over the depth of the piles. It is now known that the use of 100mm diameter samples gives lower average strengths. Hence if α=0.45 is adopted for such tests the estimate of the shaft resistance will be conservative. The use of the same value of α for other methods of measuring $\hat{S}u$ may lead to equally misleading results. It is essential to stress to the students that the basis of any empirical expression must be thoroughly understood. There is a rigour about empiricism!

5.7 The ground profile

In the 1987 paper I devoted much space to the engineering description of the ground including a five page appendix. This reflects the significance I attach to the subject. I do not intend to repeat myself in this paper except to stress that civil engineering students should be taught the key elements of soil description and geology, particularly in relation to the genesis of the shallow deposits formed, for example, during the Quaternary period. It is within these deposits that the majority of students will be working in practice.

I find that interest is stimulated by giving students a presentation of case histories briefly illustrating the key role that a clear description of the ground profile can play in making design decisions or in investigating failures. A classic example is that of the design of the underground car park at the Palace of Westminster in London (Burland & Hancock, 1977) where the finding of silt and sand partings in the London clay dictated the design of the foundations and retaining walls. There are countless examples in the literature where minor structural features, such as thin planes of weakness, pre-existing shear surfaces or permeable layers, have determined the design or given rise to failure. It is imperative that students do not get the impression that all that is needed for design is a site investigation report containing quantified soil parameters that can be inserted into an analytical model.

A major part of the education and training of engineering geologists is related to the development of three-dimensional geological and hydrogeological models. These form a key input into the geotechnical modelling associated with major civil engineering works such as dams and tunnels and is embraced by the framework of the Geotechnical Triangle.

5.8 Limit analysis

In my view the approach to stability analysis using the limit theorems of perfectly plastic materials gives a valuable insight into mechanisms of behaviour and the way that problems can be bounded. Therefore, as well as having practical value, it has very considerable educational merit.

The upper bound theorem states that:

> *"If an estimate of the collapse load is made by analysing a kinematically admissible mechanism of deformation, the estimate will be equal to or greater than the exact solution".*

The lower bound theorem states that:

> *"If any stress distribution can be found which is everywhere in equilibrium internally and balances the external loads and at the same time does not violate the failure condition, then the loads will either be less than or equal to the exact solution".*

In the 1987 paper I gave an example of the progressive refinement of upper and lower bound solutions for the bearing capacity of a surface strip load on a rigid-perfectly plastic material having a cohesion k. These solutions are reproduced in Figures 3 and 4.

Figure 3 illustrates the analysis using progressively more refined kinematic mechanisms. These sliding block mechanisms are well suited to visual aids making use of Perspex blocks on an overheard projector. It can be seen that as the mechanism is refined the estimated failure load Q decreases.

Figure 4 sets out the analysis using the lower bound approach of dividing the material into regions of uniform stress separated by stress discontinuities across which equilibrium must be maintained. Students find this type of analysis more difficult as it requires mastery of the Mohr's circle. Indeed the three region case is an ideal problem for developing skills with Mohr's circles and students should be asked to derive the principal stresses and their orientations in each region. It can be seen from Figure 4 that as the number of regions is increased the estimated failure load Q increases.

Figure 5 shows a graph of the bearing capacity factor Nk versus the number of kinematic blocks or stress regions for the two approaches. It can be seen that the results converge rapidly towards the Prandtl solution of Nk=5.14. Figure 6 shows the optimum solution using slip circles giving Nk=5.52 which is some 7 percent greater than the exact Prandtl solution. This problem that is well within the grasp of most students.

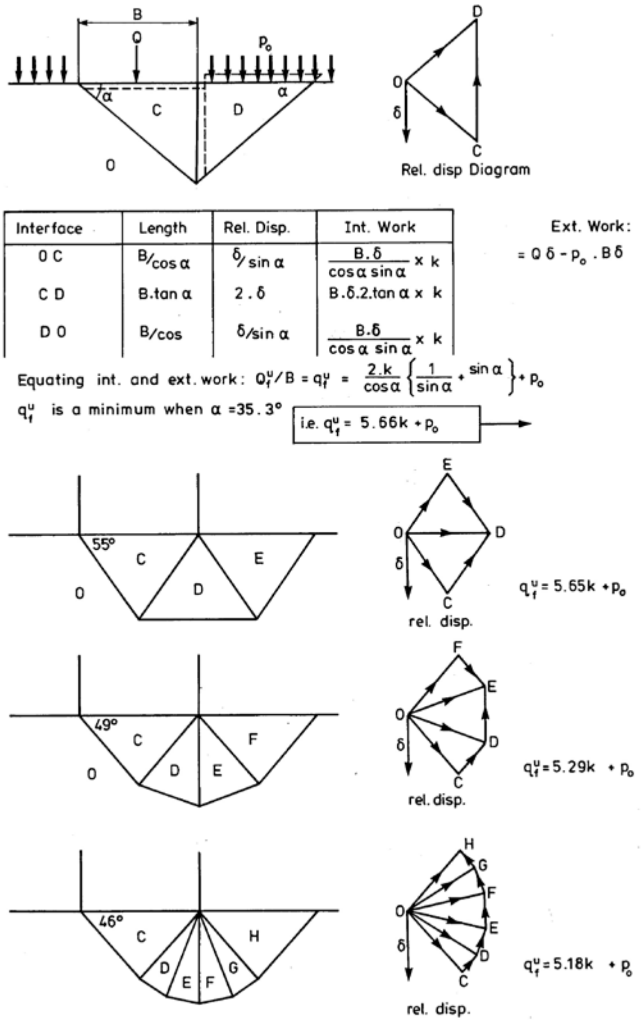


Figure 3. Upper bound undrained bearing capacity calculations

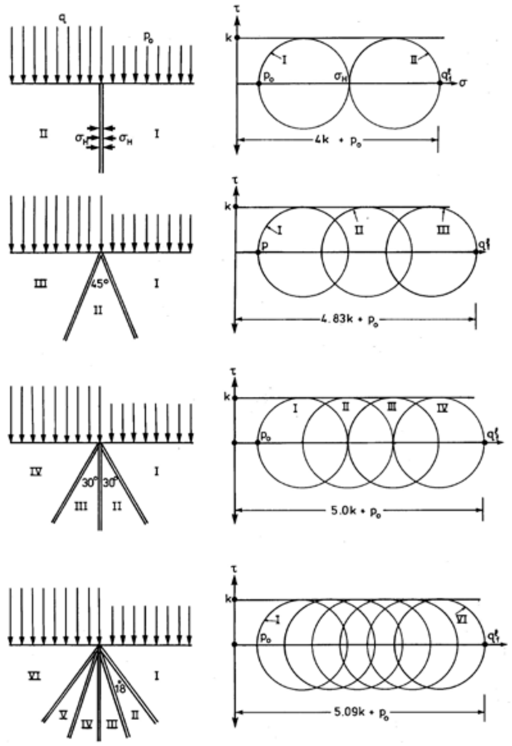
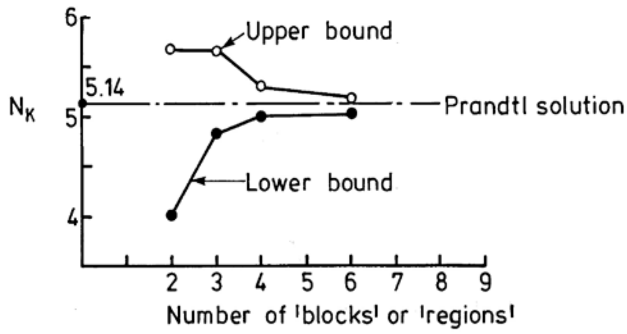


Figure 4. Lower bound undrained bearing capacity calculations



kinematic blocks or stress regions

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A similar approach can be used for an ideal weightless material satisfying the Mohr-Coulomb failure criterion. Strictly the formal limit theorems no longer apply to such a material. Hence the terms ‘kinematically admissible’ and ‘statically admissible’ solutions should be used rather than ‘upper’ and ‘lower bound’ respectively. Once again comparisons can be made with the Prandtl and other solutions.
The approach to stability analysis using kinematic and static approaches provides a valuable overview of the various methods and their accuracy. Through them the student gains a valuable ‘feel’ both for mechanisms of failure, for equilibrium stress fields and for stress characteristics.

6 GEOTECHNICAL TRIANGLE IN PRACTICE

The Geotechnical Triangle was developed by considering the key activities described by Terzaghi, Peck and others in the practice of ground engineering. There have been many occasions when I have both witnessed and experienced difficulties in communications between structural and geotechnical engineers. For many years I have been interested in why this should be so. It is a matter of outstanding importance because poor communication and lack of understanding can lead to poor engineering and even failures. It is significant that the areas of most difficulty seem to be when considering the impacts of ground movements (e.g. due to tunnelling and excavations) on existing buildings. Recently I was invited to give a talk to a combined meeting of the Institutions of Structural and Civil Engineers in London and I took the opportunity to address the issue of interaction between structural and geotechnical engineers (Burland, 2006).

6.1 Structural modeling

I have come to the conclusion that, at the heart of the problem of communication between structural and geotechnical engineers, there is a difference in approach to modelling structural and geotechnical behaviour. This subject is relevant to this paper as the roots of the problem go back to undergraduate teaching. For the structural engineer the geometry of most structures is well defined and reasonably easy to idealise. Rather simple linear elastic material behaviour is usually assumed with a limiting stress imposed. Very rarely is a full plastic analysis carried out. The major idealizations in the modelling process are in the loadings but these are usually specified in Codes of Practice. It is therefore evident that the process of routine structural modelling mainly consists in idealising the structural form, specifying the material properties and carrying out analyses – nowadays usually on the computer. In spite of the pioneering work on plasticity, structural engineers still tend think in terms of limiting stresses and very little about post-yield behaviour.

Present teaching of structural engineering tends to convey the impression that structural modelling is a precise process. Yet most experimental studies on real whole structures show that the measured strains and displacements bear little semblance to the calculated values due to factors such as lack of fit, thermal and shrinkage effects and differential foundation movements.

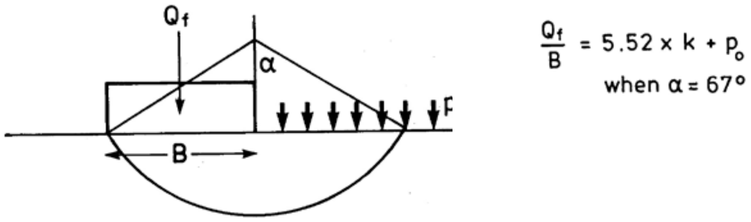

Figure 6. Slip circle solutions to undrained bearing capacity problem

This is well known (e.g. Walley, 2001) but is easily forgotten. Our structures work, not because the stress distributions have been precisely calculated, but because the Codes of Practice ensure that an appropriate level of ductility is incorporated in their design. In this way the lower bound (or safe) theorem of plasticity comes into operation and any forces causing overstress locally are redistributed through the structure. This important topic has been discussed in detail by Heyman (1996 & 2005), Mann (2005) and Burland (2006) but it is not taught at undergraduate level or even at master's level. Hence students are left with the firm belief, reinforced by the now prevalent use of computer packages, that structural calculations represent the 'real life' forces and stresses with a high degree of precision – a

belief that they carry over into practice.
The structural engineer’s approach to modelling can be contrasted with that of the geotechnical engineer as conveyed by the Geotechnical Triangle – see section 3.3. It is obvious that geotechnical modelling involves much greater explicit uncertainties and complexities in idealizing both the geometry and the material properties than in structural engineering. Yet this process of modelling is not easily taught at undergraduate level. Teaching tends to follow the well worn path of structural analysis in which the geometry (including the ground water conditions) and the mechanical properties are specified and the focus is placed on the analytical process.

6.2 The analogy with ancient buildings

A helpful way to explain the geotechnical approach to modelling is to consider the activities that a structural engineer has to undertake when working on (perhaps stabilizing or modifying) an existing building, particularly an historic one. It turns out that these activities map onto the Geotechnical Triangle almost exactly (Burland, 2006).
For the ‘ground profile’ at the top of the Triangle we can insert ‘structure and materials’. It is vital first to find out how the building was constructed and the changes that have taken place historically i.e. the genesis of the building has to be established and this is analogous to understanding the geological processes that formed the ground profile. As with the ground, small discontinuities and weaknesses can play a major role in determining the overall response. These activities require the most careful examination and investigation together with archival searches (termed ‘desk studies’ in ground engineering). Well-winnowed experience and knowledge of appropriate building practices plays a major part in such investigations.
The mechanical properties of the various building materials then have to be studied. This involves careful selection of representative parts of the building, sampling them and laboratory testing. Very often it is helpful to observe the relative movements of parts of the building in order to understand the mechanisms of behaviour. All these activities map on to the bottom left hand corner of the Geotechnical Triangle and involve the activities of testing, measurements and observation. Again, experience plays a vital role in these activities.
Finally there is the need to develop appropriate predictive models of the building that take account of its form and structure, its history of construction, its measured material properties and known behaviour. There is a whole spectrum of models that can be developed ranging from the intuitive and conceptual right through to the highly sophisticated. The key requirement is that the model should capture the important mechanisms of behaviour. This may be better done exploring behaviour with simple models than attempting to go in one step to a very complicated one. The interpretation of the model’s response must take account of the inevitable idealisations that have had to be made and the limitations on precision that they impose.
The activities and approach for the appropriate modelling of an ancient building are almost identical to the day to day approach of the geotechnical practitioner. I have found this analogy most helpful in explaining to structural engineers and to students what geotechnical modelling involves together with its limitations.
From an educational point of view it becomes obvious that very little of our time is spent in exploring the modelling process. Yet it is central to the activities of practising geotechnical engineers. Pantazidou & Steif (2008) describe a most interesting on-going project aimed at introducing students to the processes of model-ling in environmental geotechnics. To date, the outcomes are very promising but the authors recognize the difficulties of introducing the subject into an undergraduate course.

As I mentioned at the beginning of the paper, there is an ever present danger of overloading a course with too much material. Readers can be forgiven for wincing at the thought of introducing more material related to the process of geotechnical modelling. In my opinion it is a topic that can be introduced incrementally as the Geotechnical Triangle is referred to at various stages during the course. In this way the processes can be reinforced to become an important 'habit of mind'.

7 THE USE OF MODELS IN TEACHING

"A picture is worth a thousand words" is a proverb that refers to the idea that complex ideas can be explained with just a single well chosen image. I am firmly of the opinion that an appropriate physical model is not only worth a thousand words but numerous equations as well! Even more importantly, the student will remember a striking model long after the equations have been forgotten. Anyone who has read the 1987 paper will be left with no doubt about my views on the value of physical models in teaching soil mechanics as the paper contains a number of examples.

Just as modelling involves a process of simplification and idealization so too does a demonstration model and this needs to be explained. Its purpose is to demonstrate one or more mechanisms of behaviour. The mechanism might be very simple and capable of straight forward analysis or it might be very complex and not easily amenable to rigorous analysis. I have deliberately emphasised the use of physical models rather than computer models as the students can relate to the physics of the real world more readily than to the output from a black box!

In this final section of the paper I refer to two physical models in particular that I have found both instructive and memorable. One describes very complex behaviour and the other very simple behaviour which can form the basis of a student project.

7.1 Base friction model of granular soil

The mechanical behaviour of soils is largely governed by the fact that they are particulate materials and it is essential that students understand this and that it is reinforced time and again during the course, especially when continuum models are being described. Over many years I have used a base friction model to illustrate many of the important mechanisms of behaviour of granular materials. The apparatus is shown in Figure 7 and consists of a Perspex base across which a standard acetate roller strip is drawn by means of a small variable speed battery- powered electric motor. The model particles consist of short lengths of copper tube of three different diameters. They are contained in a shallow box having wooden sides that are hinged at the base. The apparatus is placed on an overhead projector so that the movements and the development of various mechanisms can be projected onto a screen.

Figure 8 is a photograph of the process of deposition of an initially dispersed suspension of particles. Projected on a screen this deposition process is dramatic and makes a profound impression! When deposition is complete the electric motor (i.e. 'gravity') is switched off. The resulting grain structure can be discussed in some detail. It will be noted that there are a number of largish voids around which the particles arch. Moreover, if a top plate is placed on the surface of the deposit and the whole assemblage is gently moved up and down it immediately becomes apparent that there are a number of loose particles that are not carrying load.

Two key conclusions can be drawn from this part of the demonstration. The first is that the deposit is very loose and therefore capable of contracting when sheared. The second is that the vertical pressures set up during deposition give rise to an anisotropic arrangement of the grains which imply that the deposit will be stiffer (and stronger) in the vertical direction than in the horizontal direction.

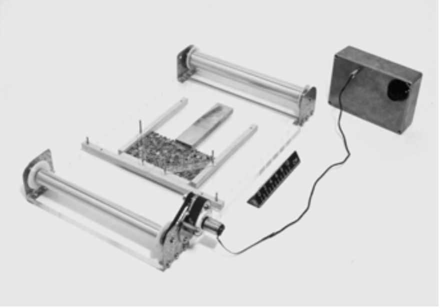

Figure 7. Base friction model for granular material

Thus there are many more arches than is at first apparent. It is usually possible to trace numerous vertical and sub-vertical columns of particles showing a well defined preferred fabric.

Figure 8. Deposition of granular material

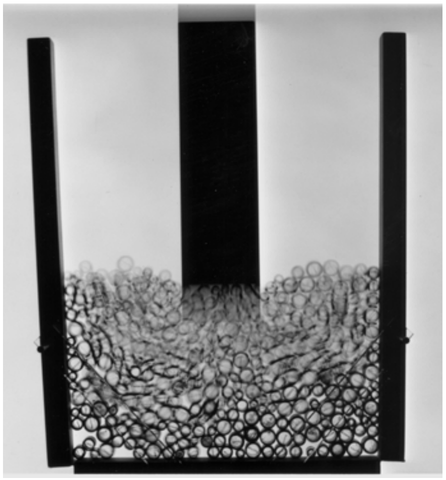

Figure 9. Bearing capacity failure

The apparatus can be turned into a simple shear box with a brass top plate. When the electric motor is again switched on the loose assemblage is subjected to simple shear. The particles are then seen to take on a closer pack and the phenomenon of contractancy is demonstrated. Similarly, after the deposit is compacted by tapping the top plate, the phenomenon of dilatancy is demonstrated. These two phenomena are of fundamental importance in soil mechanics and when demonstrated in this way they are unlikely to be for-gotten by students.
Next the apparatus can be used to demonstrate a number of common soil mechanics problems. The settlement beneath and around a loaded footing can be observed and a bearing capacity failure generated – see Figure 9. A narrow footing can be made to penetrate the deposit illustrating the process of driving a pile. Watching the movements of the particles around the tip and against the shaft as the pile penetrates is particularly instructive.
The development of active and passive regions behind and in front of retaining walls is easily demonstrated by rotating one of the sides of the container about its base as shown in Figures 10 and 11. The active and passive wedges can be seen to develop. I have used the model to illustrate subsidence above tunnels and arching action around them. It is also possible to demonstrate the mechanisms of deep seated ground movement around propped excavations.

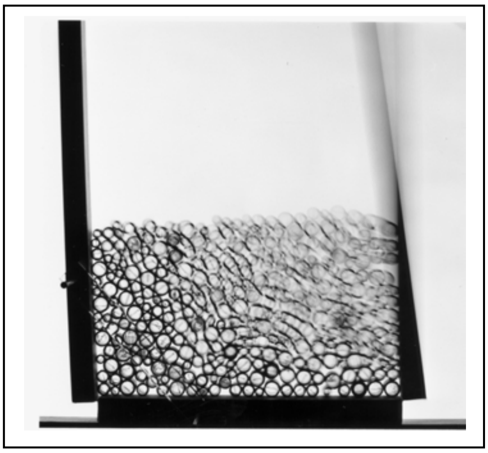

Figure 10. Active earth pressure conditions   Figure 11. Passive earth pressure conditions

The base friction model is a most powerful and striking teaching aid. I find that it can be used very early on, even the first lecture in a course, and then referred to at various times during the course. It could be argued that, far from taking extra time, it actually saves it! Moreover the students do not forget it.

7.2 Effective stress and the sliding beaker

The demonstration involves placing a plastic beaker on a damp slope. It is stable and does not move. A second beaker is then placed next to it and filled with water to the same level as the first, whereupon it slides rapidly down the slope. It is explained to the class that the only difference is that the second beaker has a small pin-hole in its base.

When asked to explain what is going on, the answer is almost invariably that the water is “lubricating” the base of the beaker thereby reducing its coefficient of friction. Interestingly this is precisely the explanation that engineers gave for many slope failures prior to the discovery of the principal of effective stress. It is still widely used in the media. The fact that the slope is damp eliminates a reduction in the coefficient of friction as the explanation.

The students are then given the problem of a parallel sided beaker of known weight filled with water to a known height and standing on a slope of inclination θ.
Beneath the bottom of the beaker is a cavity formed by a small down-stand (ridge) around the circumference of the base. Given the coefficient of friction μ the students are asked to calculate the limiting value of θ giving rise to sliding. They are then asked to repeat the exercise but with a small hole in the base so that the cavity beneath the base is full of water in equilibrium with the water in the beaker. The coefficient of friction is the same as previously.

I find that students struggle with the force diagrams when they are dropped straight into this problem. It is helpful for them first to consider the magnitudes of the horizontal forces necessary to cause slip when the beakers are resting on a horizontal surface. The second part of the question involving evaluating limiting values of inclination θ then becomes more straight forward.

This is a simple but dramatic demonstration of the importance of water pressures acting within a sliding surface. It causes a considerable amount of thought, provides a refresher on the use of force diagrams and is a good introduction to slope stability analysis. The exercise can be used either to introduce the effective stress principle or to reinforce it.

8 CONCLUDING REMARKS

Sir Charles Inglis' definition of education as instilling "that habit of mind which remains" raises the question: what characteristics of that habit of mind should one aim to instill? The following is my list:

8.1 Rigour

As engineers, in the planning and design of projects we carry huge societal responsibilities for public safety, for economy of construction, for raising standards of living and for preserving and restoring the fragile balance of nature. There is no room for sloppy thinking. As Sir Alec Skempton said during his presidential ad-dress to the 5th International Conference in Paris (Skempton, 1961):

> *"Optimism and over-confidence may impress one's clients, but they have no influence on the great forces of nature"*.

8.2 The ability to simplify and to idealise

The engineer has to simplify and to idealise the real world in order to carry out appropriate analysis of the safety and effectiveness of his or her design. "To analyse is first to idealise". This characteristic uses the scientific methods of observation, measurement and modelling to gain the essential understanding that is needed.

8.3 Creativity

At the heart of engineering lies creative and innovative design. As a teacher I believe that the excitement of creativity is something that is better caught than taught. Teaching someone to design is like teaching someone to swim: it cannot be done by theory alone, or copying, or without confidence. It can only be done for real.

In my experience as a teacher, I agree passionately with my colleague and friend, the late Edmund Hambly who was one of the most creative engineers with whom I have ever worked. Hambly taught design at various universities and once stated:

"My experience has reminded me forcefully how much more creative our young engineers can be than they are generally encouraged to be".

This certainly gives food for thought!

8.4 Clarity of expression

"To express oneself clearly is to think clearly". That is why it is so important to get students to set out on paper, and verbally, their understanding of a problem or issue.

Within a few years of graduation, students will be interacting with a wide variety of non-technical people: clients, civil servants, politicians, lawyers and the general public. Success in interacting with these people, and with their own colleagues, will depend the an ability to explain simply and clearly what it is that the de-sign or project is delivering, why it is safe, how the issues have been looked at from the public's point of view etc.

8.5 The Geotechnical Triangle

I trust that I have shown that frequent reference to the Geotechnical Triangle ensures that the Teacher, the Student and the Practitioner develop and retain these four characteristics of "that habit of mind".

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