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# 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 relieved!

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



Figure 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 4<sup>th</sup> 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 Address 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 6<sup>th</sup> 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 2<sup>nd</sup> 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.

##### 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.

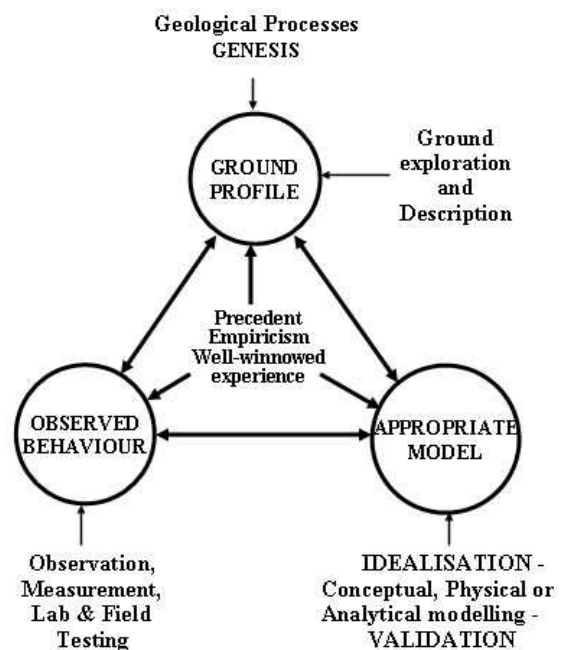


Figure 2. The Geotechnical Triangle

### 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 remain) 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  $\nu'$ .

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  $\nu'$ . It follows that the effects of change in mean normal effective stress  $p'$  and shear stress are uncoupled and the relationship between  $E'$  and  $E_u$  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. Because 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 Boussinesq 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  $K_0$  and the undrained strength ratio  $S_u/\sigma'_v$ . It has been found that, for a normally consolidated soils, the Jaky expression

$$K_0 = 1 - \sin\phi' \quad (1)$$

works reasonably well for a wide range of soils, where  $\phi'$  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

$$K_o = (1 - \sin\phi') \times \text{OCR}^{\sin\phi'} \quad (2)$$

Numerous laboratory and field studies show that for normally consolidated clays the ratio  $S_u/\sigma'_v$  is well defined and lies between about 0.28 and 0.32.  $S_u$  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  $\sigma'_{vy}$ , 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  $S_u/\sigma'_v$  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  $\tau_{sf}$  is related to the average undrained strength over the depth of the pile  $\hat{S}_u$  by the expression

$$\tau_{sf} = \alpha \hat{S}_u \quad (3)$$

where  $\alpha$  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  $\alpha$  was derived, but also precisely how  $\hat{S}_u$  was derived. For example, the value of  $\alpha=0.45$  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 undrained 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  $\alpha=0.45$  is adopted for such tests the estimate of the shaft resistance will be conservative. The use of the same value of  $\alpha$  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 overhead projector. It can be seen that as the mechanism is refined the estimated failure load  $Q$  decreases.

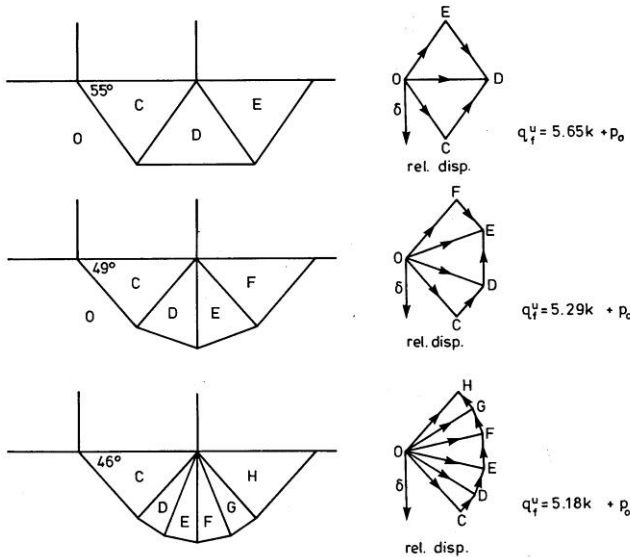
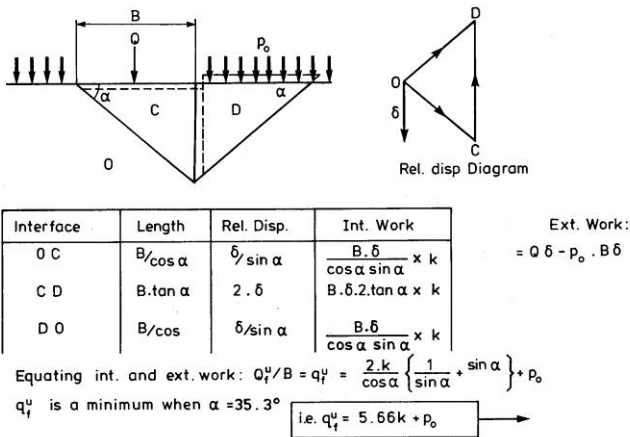


Figure 3. Upper bound undrained bearing capacity calculations

Figure 4 sets out the analysis using the lower bound approach of dividing the material into regions of

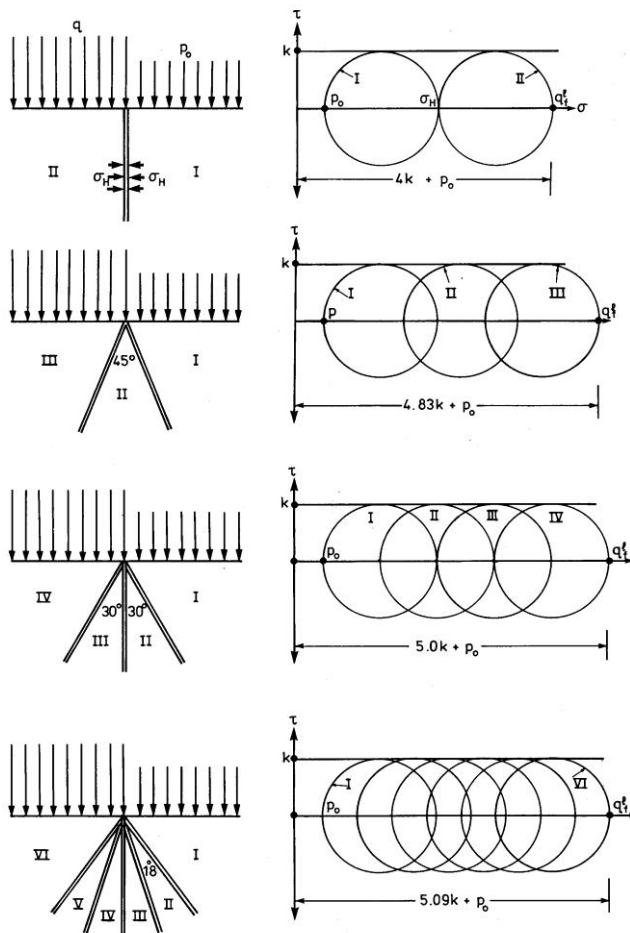


Figure 5

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  $N_k$  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  $N_k=5.14$ . Figure 6 shows the optimum solution using slip circles giving  $N_k=5.52$  which is some 7 percent greater than the exact Prandtl solution. This problem that is well within the grasp of most students.

Figure 4. Lower bound undrained bearing capacity calculations

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

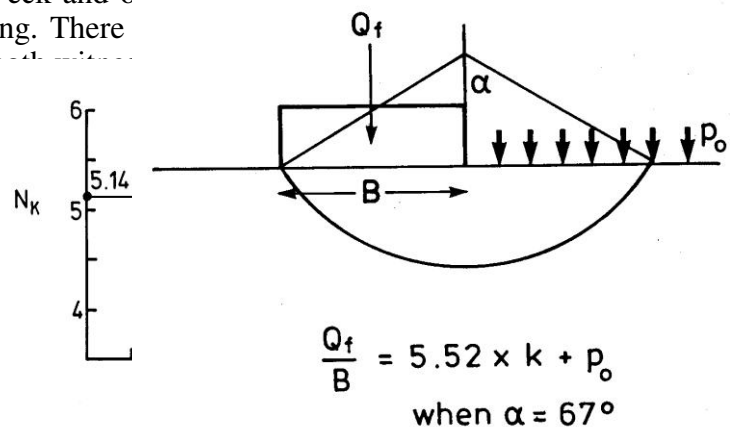


Figure 5. Relationship between  $N_k$  and the number of kinematic blocks or stress regions

munications 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 modelling*

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 to 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

Figure 6. Slip circle solutions to undrained bearing capacity problem

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. 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, meas-

urements 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 modelling 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

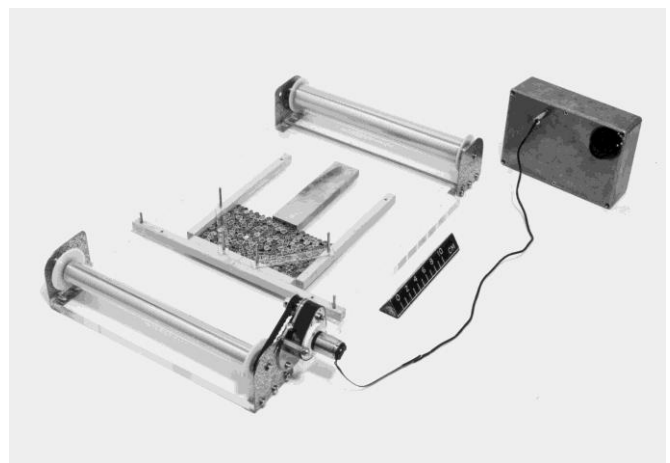
teaching soil mechanics as the paper contains a number of examples.

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-

Figure 7. Base friction model for granular material

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 dra-

matic 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. Thus there are many more arches than is at first apparent. It is usually possible to trace numerous vertical and sub-vertical

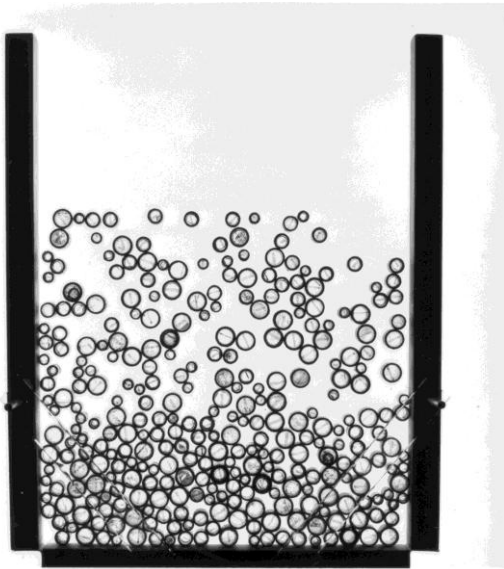


Figure 8. Deposition of granular material columns of particles showing a well defined preferred fabric. Two key conclusions can be drawn from this part of the demonstration. The first is that the deposit is very loose and therefore capable of contracting when sheared. The second is that the vertical 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.

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 forgotten 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 driv-

ing a pile. Watching the movements of the particles around the tip and against the shaft as the pile penetrates is particularly instructive.

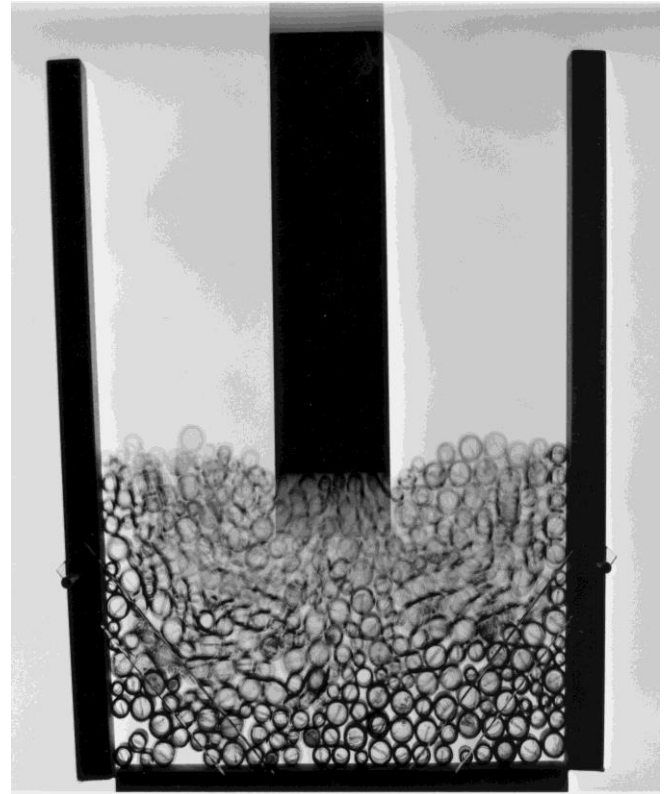


Figure 9. Bearing capacity failure

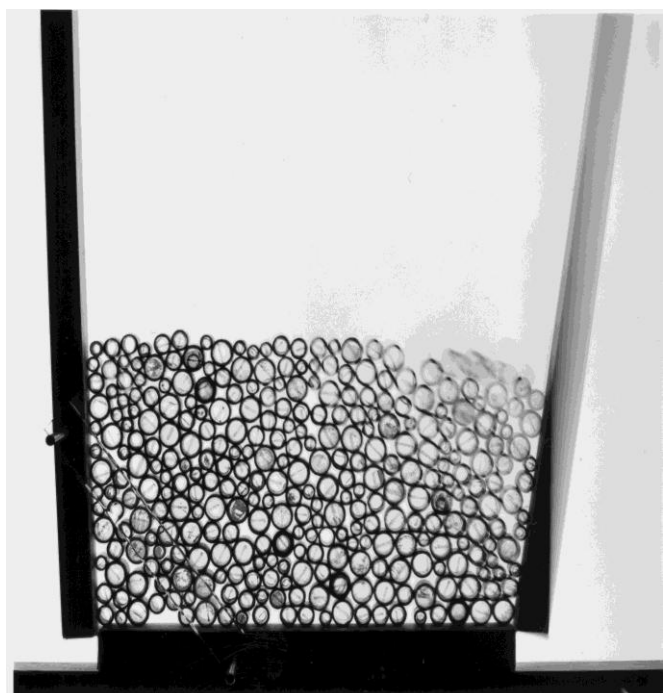


Figure 10. Active earth pressure conditions

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.

Recently 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.

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  $\theta$ . 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  $\mu$  the students are asked to calculate the limiting value of  $\theta$  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  $\theta$  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 address to the 5<sup>th</sup> 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



Figure 11. Passive earth pressure conditions

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 on the ability to explain simply and clearly what it is that the design 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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