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Chapter 4

The geotechnical triangle

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This chapter outlines a coherent approach to the key aspects of geotechnical engineering by making use of a simple aide-memoire termed the *geotechnical triangle.* The distinct and rigorous activities undertaken to obtain (1) the *ground profile*, (2) the *measured behaviour* of the ground and (3) an *appropriate model* are represented as the apexes of an equilateral triangle with empirical procedures and '*well-winnowed experience*' linked to all three at the centre of the triangle. The *ground profile* is placed at the top apex of the triangle because of its crucial importance and *experience* is located at the centre of the triangle because it is an essential aspect of all geotechnical engineering and relates to the other three activities. Each of the above activities has a distinct methodology, each has its own rigour and each is interlinked with the other. Successful ground engineering requires that each activity is properly considered so that a coherent approach is adopted and the triangle is 'kept in balance'. The application of the *geotechnical triangle* is illustrated by re-visiting the well-known case history of the underground car park at the Palace of Westminster in London.

CONTENTS

4.1 Introduction

Geotechnics is a difficult subject and is regarded by many engineers as a kind of black art. The author used to think that this was due to the nature of the ground, which is a two- or even three-phase material. It is true that it is much more complex than the more classical structural materials of steel, concrete and even timber with which most engineers are familiar. As explained in Chapter 14 *Soils as particulate materials*, soil is a particulate material with little or no bonding between the particles. As a consequence:

- The stiffness and strength of a given soil is not fixed but depends on the confining pressure.
- When it is deformed, soil will tend to contract or dilate depending on how dense it is, and this can profoundly influence its properties.
- During shearing, the particles tend to change their orientation, which, in turn, has a big influence on the shearing resistance of the material.
- Most important of all – water pressures acting within the pores of the soil are just as important as the applied boundary stresses.

This complex particulate material has to be modelled as if it were a continuum but it is essential never to forget that in reality it is particulate.

Difficult as soil is as an engineering material, the problems confronted by the engineer in tackling a ground engineering problem are more subtle. Chapter 3 *History of geotechnical engineering* describes the struggles experienced by Terzaghi in establishing geotechnical engineering as a valid engineering discipline. After a careful study of the opinions expressed by Terzaghi and others, and from his own experience, the author came to the view that the main problem confronting the engineer is not so much the complex nature of soil as a material (difficult as that is) but a lack of appreciation of the number of aspects that have to be considered in tackling a ground engineering problem (Burland, 1987).

A close study of Terzaghi's struggles towards establishing the subject reveals that there are three distinct but interlinked aspects that have to be considered in tackling any ground engineering problem:

- the ground profile including groundwater conditions;
- the measured behaviour of the ground;
- the appropriate model for assessing and predicting performance.

All three of these aspects are supported by empirical procedures, judgement based on case histories and what the author has termed 'well-winnowed experience'.

The boundaries between these aspects often become confused. For example, it is frequently not clear whether a particular design approach is based on analysis or is mainly empirical. Moreover, one or more of the aspects is frequently completely neglected. The first three aspects may be depicted as forming the apexes of an equilateral triangle, with empiricism and experience occupying the centre and linked to the apexes as shown in **Figure 4.1**. This representation was originally developed as a teaching aid but it has since become apparent that it also provides a valuable aide-memoire for geotechnical practice.

Associated with each of the above aspects are distinct and rigorous activities and procedures, which are shown in **Figure 4.1** by the broken circles. Each activity is a major discipline in its own right. Successful ground engineering requires that all aspects of the geotechnical triangle should be considered. Excessive reliance on one aspect (e.g. computer modelling or empirical procedures) can be disastrous. The four aspects depicted in the geotechnical triangle and their associated

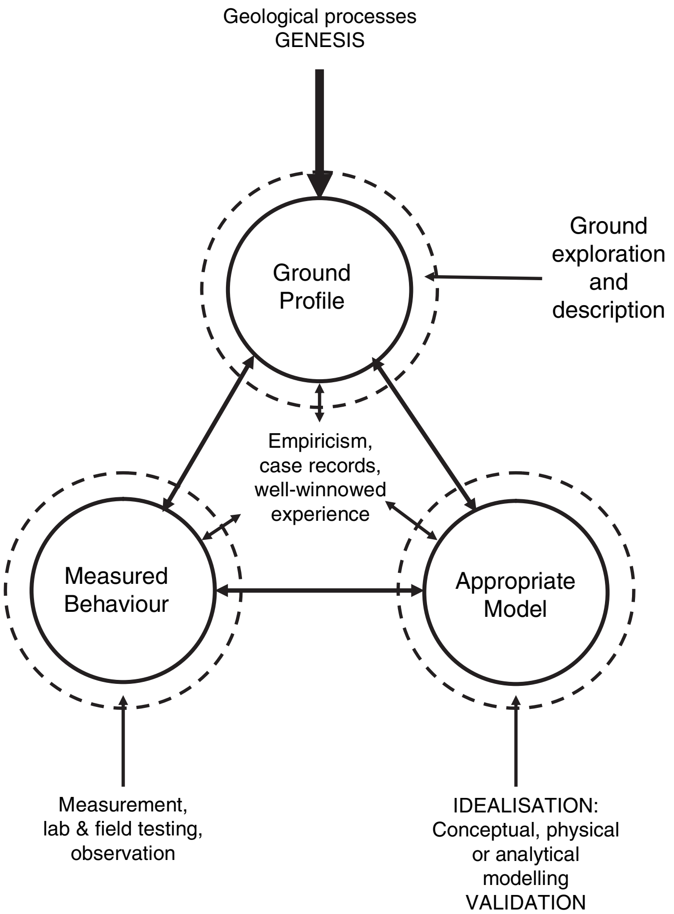

Figure 4.1 The geotechnical triangle. Each activity has its own distinct methodology and its own rigour

activities will now be briefly described. The order in which the activities are carried out will depend on the problem and may involve an iterative approach. For most problems the establishment of the ground profile is an early priority. It is also very important to establish at an early stage what experience is available for the problem being tackled and the ground conditions to be encountered.

4.2 The ground profile

Establishing the ground profile is a key outcome of the ground investigation as described in Chapter 13 *The ground profile and its genesis*. The ground profile is a description of the successive strata in simple engineering terms together with the groundwater conditions and the variations across the site. The importance of handling and describing the soil so as to establish the ground profile cannot be over-emphasised. Also it is vital to understand the geological processes and man-made activities that formed the ground profile, i.e. its genesis. The author believes that nine times out of ten, the key conceptual design decisions for a project can be made on the basis of a good description of the ground profile. Similarly, nine failures out of ten result from a lack of knowledge about the ground profile – often the groundwater conditions. The importance of the ground profile is emphasised by placing it at the top apex of the triangle.

Peck (1962) argued that the methodology of the engineering geologist in establishing the geological model for a site consists in making observations, organising and assembling these, formulating a hypothesis and then critically testing the hypothesis. However, the civil engineer, and in particular the structural engineer, is not usually trained in this methodology, which is at the heart of much geotechnical engineering.

4.3 The measured or observed behaviour of the ground

The activity associated with this aspect involves making measurements of the mechanical behaviour and interpreting the measurements. It includes laboratory and field testing, carrying out field observations of the ground and structural movements (e.g. back analysis of a landslip or of settlement observations) and measurements of groundwater pressures and flow. Rigorous methodologies and advanced instrumentation are often required for this work. The measurements require interpretation, which needs an appropriate analytical framework. A good basic understanding of the mechanical behaviour of soils and rocks is essential to these activities. Section 2 *Fundamental principles* of this manual provides a practical introduction to the fundamentals of soil and rock behaviour.

4.4 Appropriate model

When the author first put forward the original *soil mechanics triangle* in 1987 (now referred to as the geotechnical triangle), the term 'applied mechanics' was used for the bottom right-hand corner of the triangle. However, the term 'appropriate model' is a much better description of this aspect and its associated activities. The procedures involved in geotechnical and structural modelling are described in Chapter 5 *Structural and geotechnical modelling*.

Modelling is the process of:

- identifying what is to be modelled, e.g. the part of the structure, the particular type of behaviour or limit state;
- idealising or simplifying the geometry, material properties and loading;
- assembling these idealisations appropriately into a model, which is then amenable to analysis and, hence, can be used to predict responses.

The modelling process is not complete until the responses have been validated and assessed. The procedure may involve a number of iterations.

It is important to note that 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, or it can be a very sophisticated numerical model. By using the term 'model' we are emphasising the idealisation process and demystifying the analytical process. The geotechnical triangle helps in this. It is also important to appreciate that a variety of models and idealisations will usually be needed for different aspects of a given project or structure.

4.5 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. That is why this aspect is placed at the centre of the triangle and is linked to the other three aspects. Many of our design and construction procedures are the product of what may be 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. The author 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 (see Chapter 3 *History of geotechnical engineering*).

Empirical procedures are often regarded as somehow inferior to analytical procedures. The fact is that both have their essential place in geotechnical engineering and both need to be carried out with care and with understanding of their limitations.

4.6 Summary of the geotechnical triangle

In summary, depicted within the *geotechnical triangle* illustrated in **Figure 4.1** there are four key aspects of geotechnical engineering, each associated with distinct types of activity with different outputs. Each activity has a distinct methodology, each has its own rigour, and 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. The geotechnical triangle provides a useful aide-memoire when tackling any ground engineering problem, whether it is in feasibility, design, construction, forensic investigation or teaching. It is possible to adapt the geotechnical triangle for particular applications. For example, in Chapter 9 *Different types of foundation applications* an adaptation is described for the vital task of verifying design assumptions when construction work has commenced and the influence of construction processes on the ground needs to be assessed.

4.7 Re-visiting the underground car park at the Palace of Westminster

Many of the above aspects can be illustrated by means of the well-known case history of the underground car park at the Palace of Westminster, London.

4.7.1 Background

This case history is described in detail by Burland and Hancock (1977). The site finally chosen for the 18.5-m-deep car park for the Members of Parliament was in New Palace Yard, presenting major engineering challenges due to the proximity of the Big Ben Clock Tower, the Palace of Westminster and the 14th century Westminster Hall, as shown in **Figure 4.2**. The sensitive, load-bearing masonry construction of the buildings and their priceless historic value demanded a structural form and construction procedure for the car park which would result in minimum ground movements, both during construction and in the long term. The structural form chosen consisted of a reinforced-concrete diaphragm wall, strutted at all stages of excavation and construction by the permanent reinforced-concrete floors as shown in **Figure 4.3**. The columns are founded on under-reamed bored piles.

Figure 4.2 The site of the underground car park in New Palace Yard, Westminster

4.7.2 The importance of the ground profile

A preliminary site investigation had been carried out prior to the author's involvement in the project. The results showed that the top 10 m consisted of fill and soft alluvium, overlying medium-dense sand and gravel. London Clay extended from a depth of 10 m to 44 m, at which depth the Woolwich and Reading beds were encountered (now known as the Lambeth Group). A new site investigation was planned, aimed at ascertaining the detailed soil profile, its variation across the site and the groundwater conditions. Altogether 14 boreholes were sunk on the site. The author personally carried out a detailed visual examination on open drive samples from a number of the boreholes by splitting the samples longitudinally with a knife so as to overcome the smearing on the outside of the samples. Visual and tactile descriptions were carried out using a simple scheme described by Burland (1987), which is consistent with BS5930:1999, Code of Practice for Site Investigations. See Chapter 13 *The ground profile and*

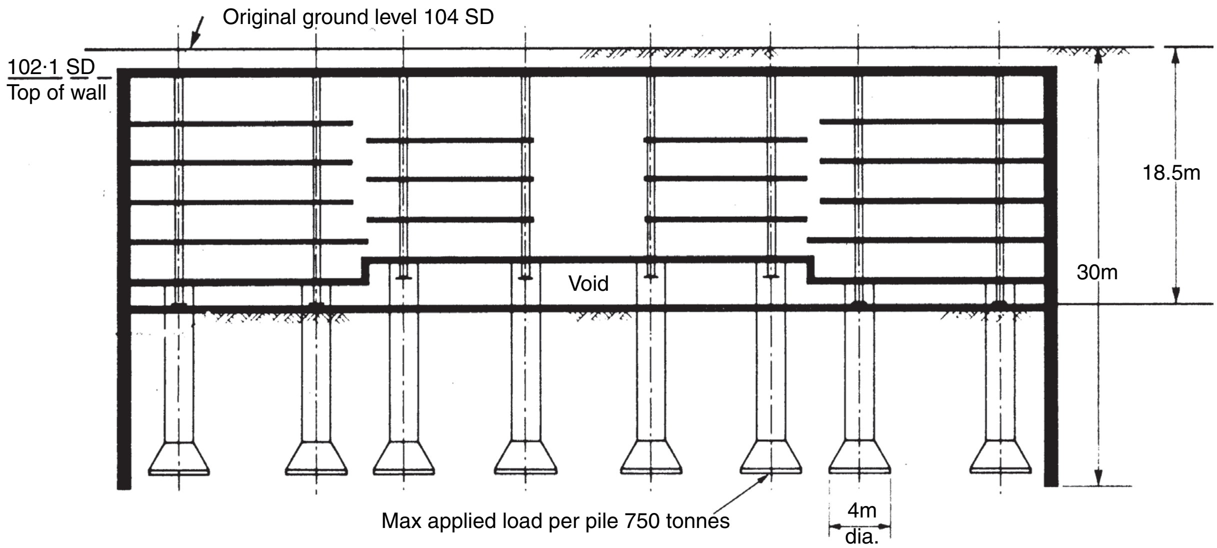

Figure 4.3 Section through underground car park in New Palace Yard

its genesis for more details of the information required in a description of the soil profile.

Good correlation of the various strata was found between the boreholes and the ground profile, as shown in **Figure 4.4**. A visual inspection revealed that immediately beneath the lowest level of the proposed car park, and extending from a depth of 19 m to 30 m, there exists a layer of London Clay containing partings of fine sand and silt up to 10 mm thick and at 50 mm spacing near the top of the layer. The frequency of the partings reduces with depth. This layer is immediately underlain by a 4 m thick layer of very stiff intact clay. Casagrande standpipes installed in most of the soil exploration boreholes showed that the groundwater pressures down to a depth of about 35 m were hydrostatic and in equilibrium with the water table in the overlying alluvium and gravel.

At the time, the finding of the layer containing silt and sand partings came as a surprise. Subsequently it has come to light that it had been encountered during tunnelling elsewhere in London and had caused problems of face instability. Recently, Standing and Burland (2006) encountered the same layer in nearby St James's Park in connection with the Jubilee Line Extension underground railway, where excessive volume losses were encountered during tunnelling. The discovery of this layer containing silt and sand partings had very important implications for the conceptual design of the retaining walls and the foundations. The relatively high horizontal permeability of this layer, coupled with hydrostatic water pressures in the surrounding ground, meant that high water pressures could develop beneath the excavation level, leading to hydraulic uplift and possible base failure. Moreover, seepage from the sand layers could have caused difficulties in the formation of the underreams of the bored piles. The development of high water pressures beneath the bottom of excavations due to the presence of water-bearing permeable strata is a well-known geotechnical hazard. Ward (1957) describes a case in which high water pressures in a stratum of laminated sand caused uplift at the bottom of a trench excavation in stiff clay. The problem was solved by the use of simple gravel-filled relief boreholes.

Various methods were considered for relieving the water pressures immediately beneath the final basement level of the car park, including the use of relief wells. Also detailed flownet calculations were carried out to assess the upward seepage gradients. However, there were considerable doubts about the short- and long-term effectiveness of relief wells. Moreover, the author was very unwilling to rely on a seepage analysis, knowing that even a small undetected permeable region could completely nullify the analysis. A robust solution was adopted, which involved taking the diaphragm retaining walls down into the intact clay layer at a depth of 30 m, thereby cutting off all horizontal seepage along the sand partings.

The choice and depth of the foundations was also profoundly influenced by the soil profile. The indications were that below a depth of 34 m (i.e. below the 4 m thick intact clay layer) there was the possibility of significant erosive seepage during excavation of the piles due to the silty nature of the clay at that depth. At a much shallower depth the significant reductions in effective stress immediately beneath the excavation would give rise to long-term reductions in stiffness and strength. With these considerations in mind, it was decided to use under-reamed bored piles founded on the intact clay layer at a depth of about 30 m, thereby making use of the higher shear strength beneath that level but avoiding difficulties due to seepage. A trial pile was constructed ahead of the main job in order to check on the groundwater and soil conditions and to evaluate the proposed foundation construction procedure. *In situ* inspection of the soil in the trial pile confirmed all the earlier deductions.

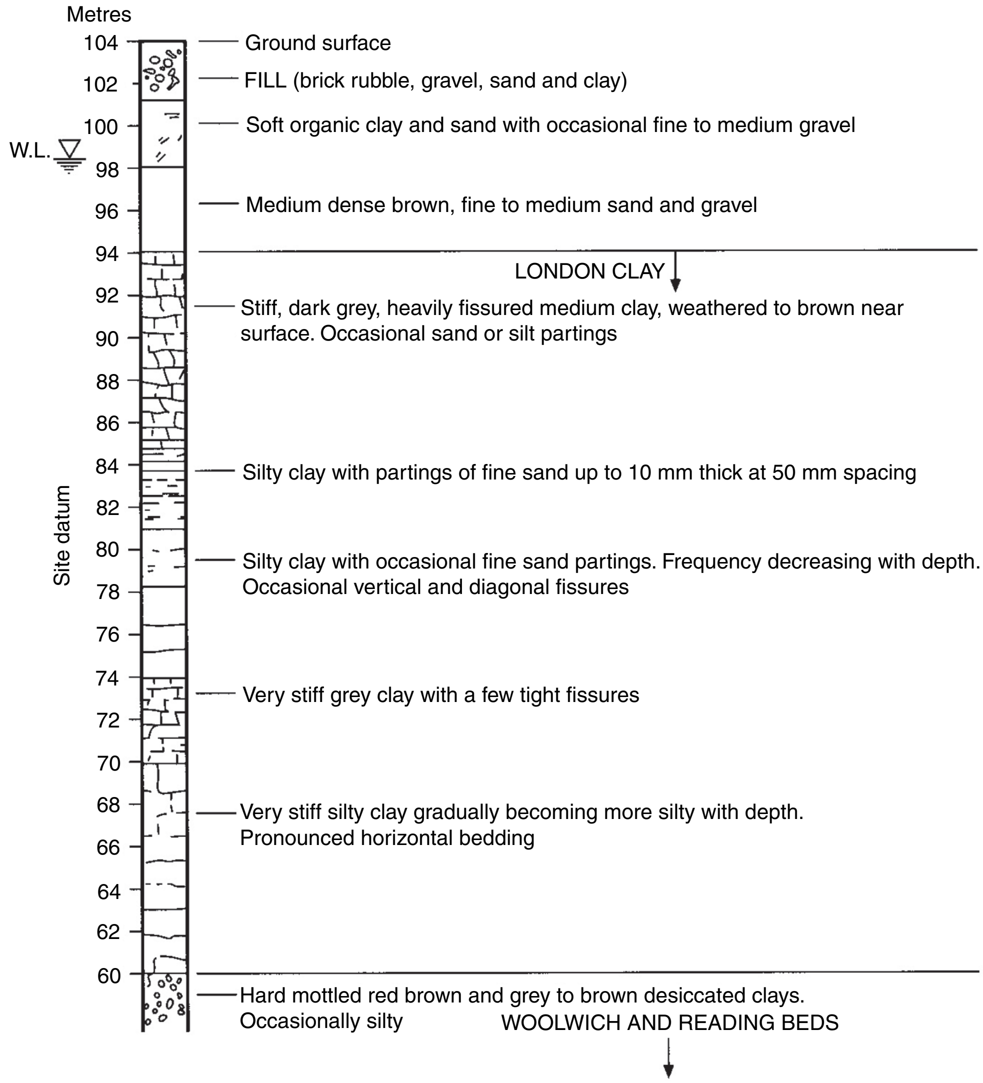

Figure 4.4 The ground profile at the Palace of Westminster

4.7.3 Modelling the ground movements

A major task in the design of the car park was to estimate the effects of the excavation on the surrounding buildings and on the structure itself. Accordingly a detailed finite element analysis was undertaken. The analysis was based on a number of idealisations and it is important to be absolutely clear about these.

Regarding the mechanical properties of the ground, the London Clay was assumed to behave as a linear elastic isotropic porous material having a stiffness that varies with depth. (See Chapter 17 *Strength and deformation behaviour of soils* for a discussion on the strength and deformation behaviour of soils.) This assumption was felt to be reasonable as the best research data available at the time suggested that at small strains, samples of London Clay tested in the laboratory exhibited linear behaviour. The variation of the undrained Young's modulus, E_u with depth used in the analysis is given by the line in **Figure 4.5**.

The stiffness values for the London Clay and Woolwich and Reading beds were based on values obtained by back analysis of measurements of the movements of the retaining walls for the deep basement excavation for Britannic House in the City of London (Cole and Burland, 1972). Thus, the choice of stiffness values was based on previous relevant case histories and observations in the London area – a clear example of the application of 'well-winnowed experience'. The adopted values of E_u for the basement beds of the London Clay and the Woolwich and Reading beds are somewhat lower than those obtained at Britannic House. It was felt necessary to be conservative in view of the lack of knowledge about the Woolwich and Reading beds in the Westminster area. Nevertheless, it is worth noting that the values of E_u used in the analysis were three to five times larger than the values deduced from careful laboratory tests. The author would never have chosen such high values without the benefit of experience from the analysis of previous relevant case histories.

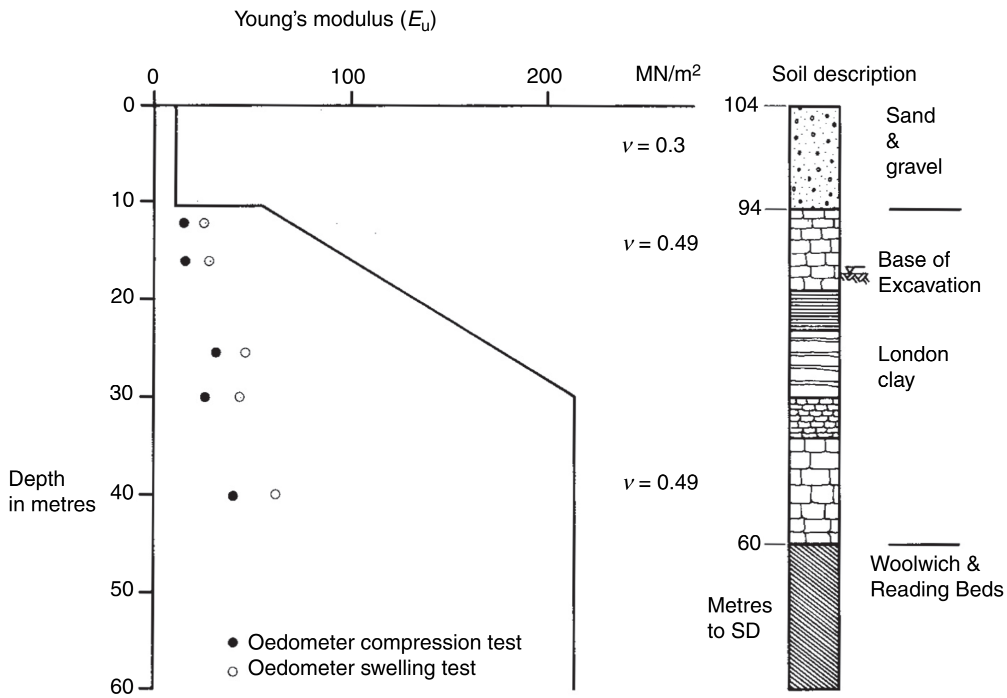

Figure 4.5 Values of undrained Young's modulus used in the finite element analysis

A key aspect of the modelling involved assessing the magnitude of the initial horizontal stresses in the clay, since these had to be progressively released during excavation. Once again the author made use of values deduced by others for various sites in London Clay. An assessment had to be made for the effects of erosion of the surface of the London Clay and the subsequent deposition of the gravel. This illustrates the importance of understanding the genesis of the ground profile – see section 4.2 above.

Even though the problem is highly three-dimensional, a plane strain analysis was adopted as being approximately representative of the centre of the north and south walls, respectively. The finite element mesh extended to the base of the Woolwich and Reading beds (60 m depth) and laterally to a distance of 80 m from the edge of the excavation.

Numerical analysis was carried out in a step-by-step process simulating the excavation and installation of the floor props at each stage, as described by Burland and Hancock (1977). **Figure 4.6** shows the predicted wall displacements at the various stages of excavation, the maximum inward displacement being about 22 mm. The predicted short-term horizontal and vertical movements of the ground surface outside the excavation are given in **Figure 4.7**. These predicted ground surface movements gave a maximum change of gradient of 1/800 and a maximum extension strain of 0.02%. These strains were felt to be unlikely to cause any significant damage to the surrounding buildings. Estimates were also made of the movements of the Clock Tower using an axisymmetric analysis, which was felt to be more appropriate for conditions close to the north-east corner of the car park. The Clock Tower was predicted to rotate away from the excavation by about 1/6000, while its foundations were predicted to move in towards the excavation by about 3 mm. The finite element model was also used to estimate the long-term movements and the swelling of the clay at the base of the excavation. On the basis of these calculations it was decided to use a suspended basement floor with a drained void beneath, rather than a solid slab, so that the clay could swell without interacting with the rest of the structure. It is very important to note that the predicted movements were published prior to work commencing on the project (Ward and Burland, 1973).

The numerical model was also used to estimate the vertical movement of the under-reamed piles during and subsequent to excavation. This information was used to assess the approximate magnitudes of the differential movements across the floor slabs and the associated bending and shear forces within them due to ground movements.

4.7.4 Field monitoring

In view of the depth of excavation, the close proximity of such priceless historic buildings and the sensitivity of the project, a very comprehensive programme of monitoring was undertaken during all phases of excavation and construction. Briefly, the monitoring can be considered under three broad headings: precision surface surveying, ground movements at depth and pore water pressures. Approximately 60 movement points were established by grouting Building Research Station (BRS)

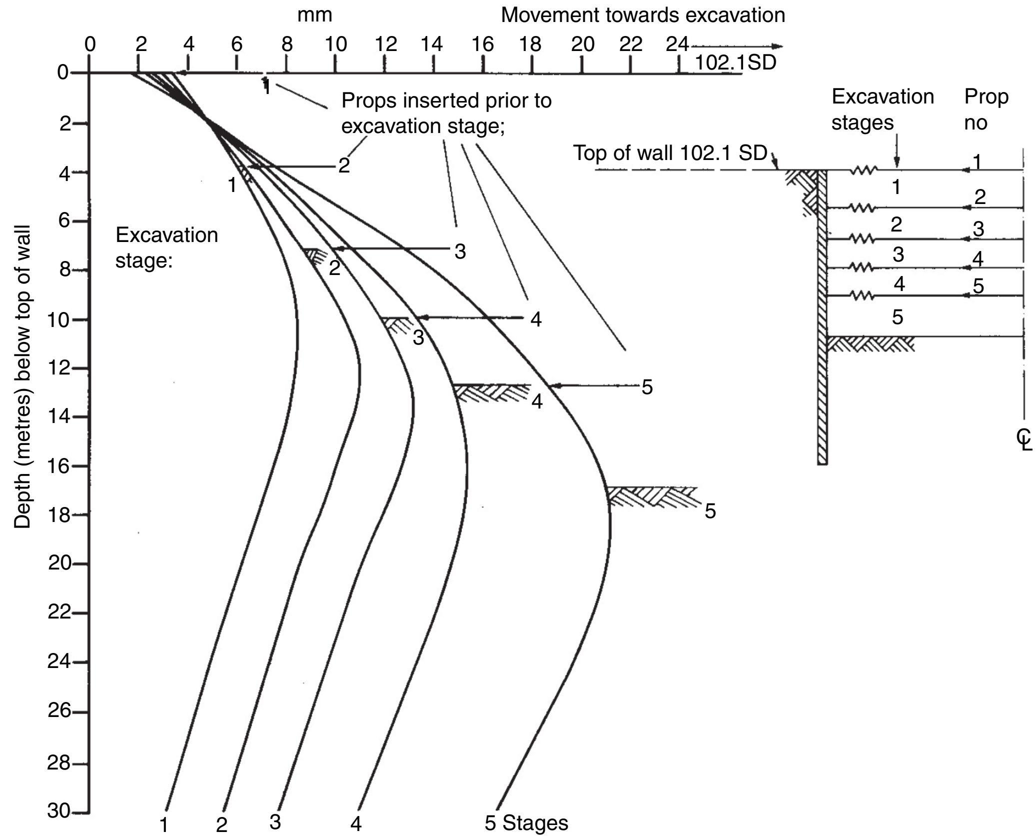

Figure 4.6 Predicted horizontal wall movements during excavation

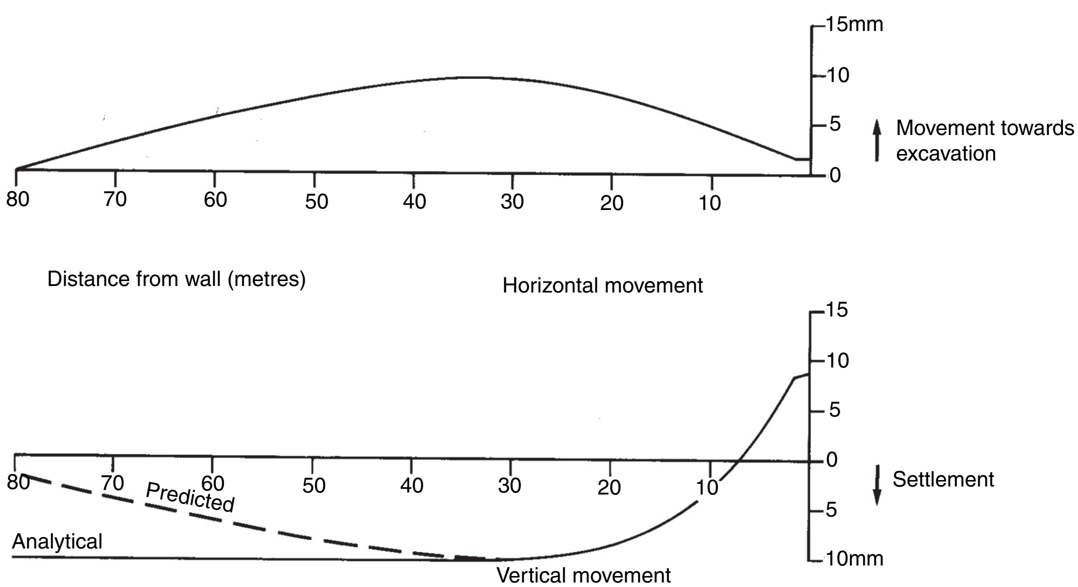

Figure 4.7 Predicted horizontal and vertical ground surface movements outside the excavation

levelling stations into the masonry of the surrounding buildings (Cheney, 1973). Precision settlement surveys were carried out continuously during construction. The frequency of observations was increased close to areas where construction activity was concentrated. Complete geodetic surveys in both plan and elevation were made at intervals of approximately two months over the construction period of about two years. Changes in the verticality of the Clock Tower were monitored daily by means of a Hilger and Watts 'autoplumb'.

The subsurface horizontal deflections of the diaphragm retaining walls were measured by means of inclinometers. Special demountable targets were fitted to the tops of the inclinometer tubes, and their positions were measured in plan and elevation at two-monthly intervals. An important aspect of the below-ground monitoring was to measure the heave at various depths during excavation as a check on the effectiveness of the design measures. Two magnet extensometers (Burland *et al.,* 1972) were installed at the centre of the excavation for this purpose.

A number of standpipes and pneumatic piezometers were installed within the area of the excavation and around its perimeter. They were to be used, in conjunction with the magnet extensometers, to check that hydraulic uplift was not developing. Unfortunately the pneumatic piezometers and many of the standpipes within the excavation were destroyed, but the standpipes outside the excavation all functioned satisfactorily.

4.7.5 Observed behaviour

Figure 4.8 shows the observed deflected shapes of the centre of the south diaphragm wall (inclinometer 8) at the various stages of excavation and support. These may be compared with the predicted behaviour given in **Figure 4.6**, where it is evident that the agreement is very satisfactory. The final predicted shape of the wall is shown as a broken line in **Figure 4.8(a)**. The major difference between the predicted and observed movement is the overestimation of the inward movement beneath the final excavation level. This is a direct result of the deliberate choice of conservative values of the undrained Young's modulus, E_u for the basement beds of the London Clay and the Woolwich and Reading beds.

A large range of deflected shapes were observed for the various wall panels. **Figure 4.8(b)** shows the two extreme cases given by inclinometers 3 and 10. The results demonstrate that, even for relatively uniform ground conditions, widely differing deflected shapes can be anticipated. These differences may be due in part to the precise manner in which the excavation was carried out at various locations. Nevertheless, the differences shown in **Figure 4.8(b)** are a salutary reminder that there are limits to the precision with which predictions can be made.

In **Figure 4.9** the measured total horizontal and vertical surface movements behind the south wall are compared with the predictions given in **Figure 4.7**. The predicted horizontal

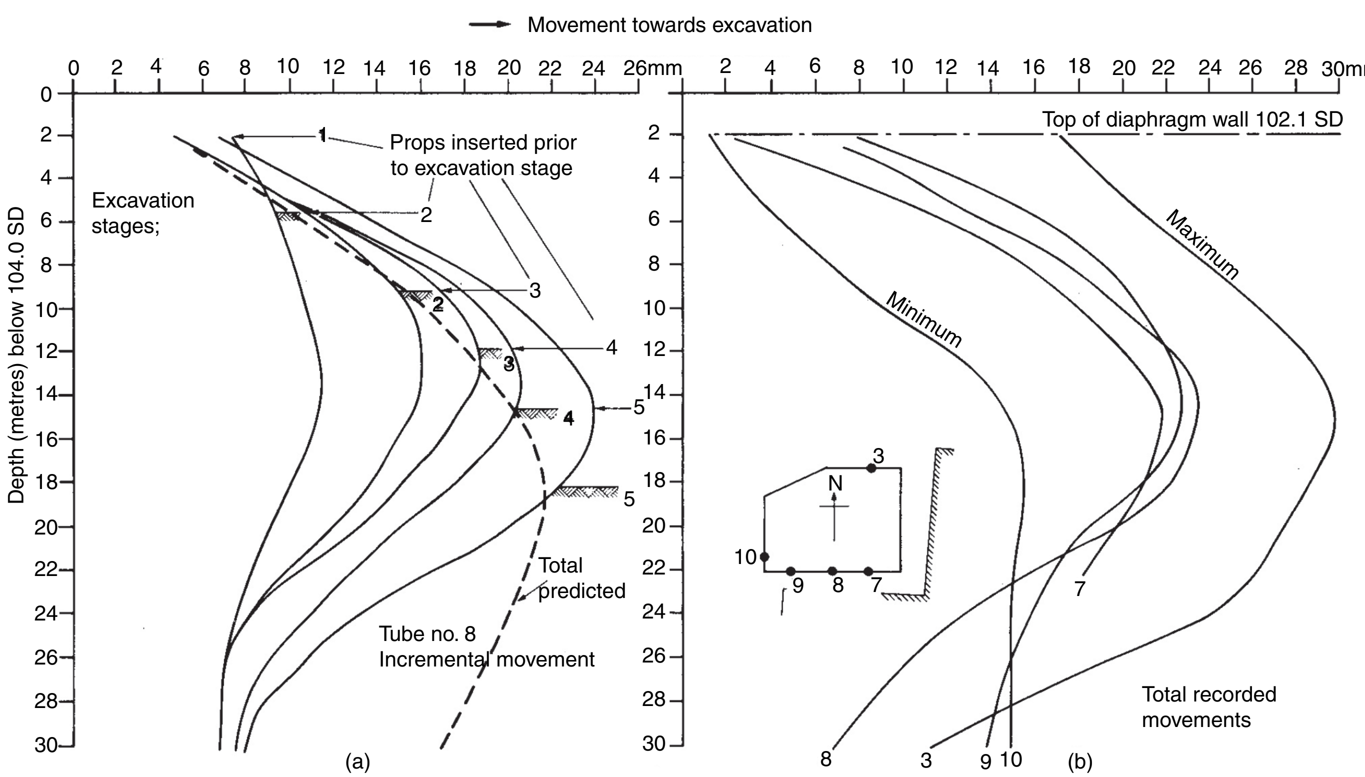

Figure 4.8 Observed movements of the diaphragm walls. (a) Inclinometer tube 8 at various stages of excavation. (b) Range of measured movements at end of excavation

movements are somewhat less than the observed values within 25 m of the wall, but further away the agreement is good. In general the overall form and magnitude of the prediction is reasonable. However, agreement between the observed and predicted vertical movements is not nearly as good. The upward displacement of the wall has been overestimated, while the maximum settlement has been underestimated. The 'settlement trough' is much nearer the wall than predicted. A consequence was that, whereas the Clock Tower was predicted to tilt away from the excavation by about 1/6000, it actually tilted towards the excavation by about 1/7000. The predicted and observed horizontal displacements were much more satisfactory, being 3 mm and 5 mm, respectively, towards the excavation.

In summary: The detailed ground profile together with experience of previous similar constructions led to the key conceptual design decisions – top-down construction to minimise ground movements, diaphragm walls cutting off horizontal seepage through the layer containing silt and sand partings, and founding the under-reamed piles in the intact clay layer. The stiffness parameters used in the finite element analysis were based on a back analysis of other deep excavations in the London area. Numerical modelling was used primarily to assess the movements in the surrounding Palace of Westminster but it was also used in the structural design of the diaphragm walls. The monitoring of the movements and groundwater pressures was carried out as a check that the behaviour was within acceptable limits. The car park was completed without significant damage to the surrounding buildings.

4.7.6 Subsequent refinements of the ground model

The difference between the predicted and measured vertical ground surface displacements just described proved very puzzling. However, shortly after the measurements were published by Burland and Hancock (1977), Simpson *et al.* (1979) showed that, by using a bilinear stress–strain law with a high initial stiffness, the agreement between observations and predictions could be greatly improved – particularly with respect to the vertical movements, as shown by the broken lines in **Figure 4.10**. At the same as this theoretical work was being carried out, laboratory studies began at Imperial College in which axial strains were measured locally on soil samples instead of between the end plattens, as was traditional. These measurements gave highly *nonlinear* stress–strain behaviour, with stiffnesses at small strains which were much larger than those inferred from traditional measurements. It now became clear that the pattern of ground surface movements observed at New Palace Yard, in which the vertical movements are concentrated

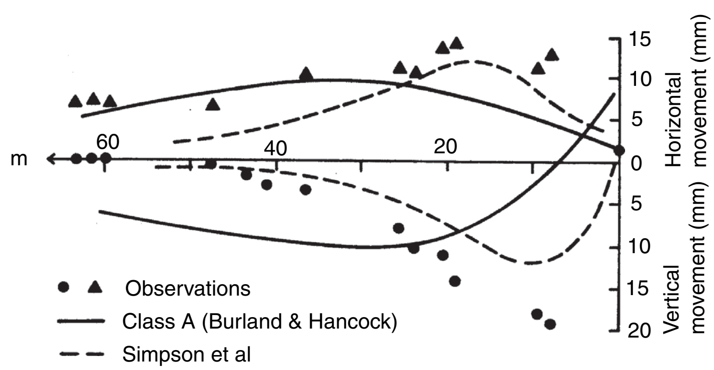

Figure 4.10 Improved predictions of the shape of the settlement trough (shown as a broken line) due to inclusion of small strain *nonlinearity* in the soil model

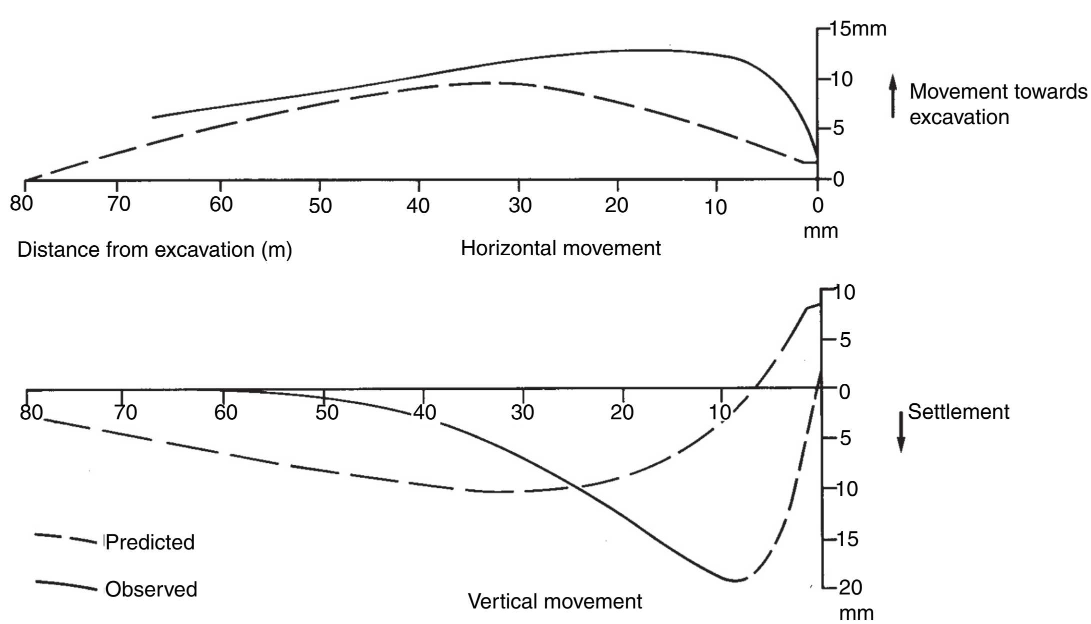

Figure 4.9 Comparison of predicted and measured ground surface movements away from the south wall

close to the edge of the excavation, is due to the *nonlinear* nature of the stress–strain behaviour of the soil.

This process of prior publication of predictions, though uncomfortable at the time, has proved highly beneficial as it caused the author to ponder long and hard as to the explanation for the discrepancies. Without such public disclosure it would have been all too tempting to quietly ignore the discrepancies and move on to other things. The work at New Palace Yard, and the measured response of the Clock Tower, has spawned a whole new important area of study of the behaviour of the ground at small strains – indeed whole international conferences are now devoted to the subject. These studies are proving very important for modelling the key mechanisms governing the interaction effects between ground and structure. Understanding these mechanisms is particularly important in the urban environment, where underground construction is a vital part of infrastructure development.

This case study is a clear demonstration of the importance of publishing well-documented case histories, as they serve to contribute to the profession's collective experience and can be used to calibrate new numerical modelling techniques for many years to come.

4.8 Concluding remarks

This chapter outlines a coherent approach to the key aspects of geotechnical engineering by making use of the *geotechnical triangle* (see **Figure 4.1**). The distinct and rigorous activities of (1) ground investigation, (2) measurement and observation and (3) appropriate modelling are represented as the apexes of the triangle with (4) 'well-winnowed experience' (an equally rigorous activity) linked to all three at the centre of the triangle.

The application of the geotechnical triangle has been illustrated by re-visiting the well-known case history of the underground car park at the Palace of` Westminster, London. A deep excavation was chosen as a case history since this type of problem demands all the traditional skills of the engineer including: reliance on observation and measurement; a deep understanding of both geotechnical and construction materials; the effects of groundwater and seepage; the development of appropriate conceptual and analytical models; and above all, judgment based on a knowledge of case histories and construction methods.

It should be noted that the key conceptual design decisions for the underground car park at Westminster were taken on the basis of a thorough knowledge of the ground profile obtained from the visual and tactile description of the soil samples and measurements of groundwater pressures from standpipes. The choice of stiffness properties for the London Clay was based on the careful and rigorous analysis of other appropriate case histories of deep excavations in the London area, illustrating the importance of case histories and 'well-winnowed experience'. The field measurements made during the excavation of the car park have proved most valuable in gaining an understanding of the influence of small-strain *nonlinear* behaviour of the ground. Even more importantly, these measurements have shown that precise prediction of behaviour is not possible and that successful design requires that inherent uncertainties of response must be taken into account.

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All chapters within Sections 1 *Context* and 2 *Fundamental principles* together provide a complete introduction to the Manual and no individual chapter should be read in isolation from the rest.