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RECENT EXPERIENCES OF TUNNELLING AND DEEP EXCAVATIONS IN LONDON

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ABSTRACT

The paper focuses on recent developments in tunnelling and deep excavations in London and it draws on the experiences of the Jubilee Line Extension project which has just been completed. A brief historical review is given of the first tunnels and deep excavations undertaken in London some 150 years ago. Construction methods recently used for bored tunnelling include sprayed concrete linings and closed face pressurised tunnelling machines. Ground movements observed for these various tunnelling operations and for deep excavations are reviewed, and their effects on buildings are discussed. The most extensive protective measure used on the Jubilee Line Extension to control deformations and potential damage to historic buildings has been the relatively new technique of compensation grouting. Examples of its use are presented.

KEYWORDS

Tunnelling, deep excavations, settlements, ground movements, effects on buildings, compensation grouting.

INTRODUCTION

This paper describes some recent experiences of tunnelling and deep excavations in London. These activities have been undertaken in London for about 150 years and considerable progress has been made in developing new construction techniques and in improving understanding of the soil mechanics aspects (in terms of both design and construction). The paper begins with a brief historical review of early construction of tunnels and deep excavations. Construction methods currently used are then described, including sprayed concrete linings and pressurised face tunnelling machines.

Ground movements are inevitably caused by tunnelling and deep excavations in soft ground (soft ground covers all soils requiring support during construction, and applies to all the soils found in the London area). The magnitude of ground movements is a key issue in urban environments such as London where many of the buildings are historic and fragile. The paper describes experience of ground movements caused by tunnelling and deep excavations in London and their effects on buildings. Various protective measures employed to mitigate potential damaging effects are described, with particular emphasis on compensation grouting which has been used extensively for the recent Jubilee Line Extension project in London.

HISTORICAL BACKGROUND

Tunnelling and deep excavations have been undertaken in London since the 1820's. The rapidly increasing population of London at the beginning of the 19th Century following the industrial revolution resulted in congestion on the roads and the need for improved transport connections. The relatively few bridges at that time across the River Thames prompted the eminent Victorian engineer Sir Marc Brunel in 1825 to embark upon the first major sub-aqueous bored tunnel in the world. The tunnel was to cross from Rotherhithe to Wapping in the heart of London's Docklands, where the width of the River Thames is about 300m. The ground conditions are the treacherous Woolwich and Reading Beds (recently re-named the Lambeth Beds), comprising interbedded layers of stiff clays, silts, silty sands and gravels. The Resident Engineer for the Thames Tunnel, as it came to be known, was Sir Marc's son, Isambard

Kingdom Brunel, who later became one of the most eminent of all the Victorian engineers. It was a heroic struggle, which lasted 26 years. Despite employing one of the first tunnelling shields, disaster struck in the form of total face collapse beneath the river on five occasions, resulting in loss of life on two of them. There are records of I.K.Brunel inspecting the aftermath of one of the collapses by means of a diving bell lowered from a boat. Full details of the construction and of the ground conditions encountered (the Brunels kept meticulous records) are given by Skempton and Chrimes (1994).

The first tunnels for the London Underground were constructed in the 1860's as cut-and-cover operations involving deep excavations in the congested streets of London; these caused much disruption. Typical ground conditions in central London are a few metres of fill and Terrace Gravels overlying stiff overconsolidated London Clay; the water table is usually in the gravels, 1-2m above the surface of the London Clay. The construction technique generally involved the driving of timber sheet piles into the London Clay and installing timber bracing between the sheet piles as the excavation proceeded. Excavations were typically to depths of around 10m below ground level.

The earliest bored tunnels for the London Underground were undertaken in about 1880 when new lines were planned with alignments beneath buildings. These tunnels were bored in central London in the stiff London Clay, which proved to be an ideal tunnelling material (in marked contrast to the Woolwich and Reading Beds encountered further to the east by the Brunels during construction of the Thames Tunnel). The London Clay is generally sufficiently strong and impermeable that the excavated tunnel remains stable in the short term while linings are installed (although occasionally local blocks of clay can fall out if an unfavourable set of fissure joints is encountered). The techniques developed in construction of these early tunnels formed the basis for modern tunnelling today: hand-mining was usually undertaken within the protection of a cylindrical steel Greathead shield, and bolted segmental cast iron linings erected, against which the shield was jacked forward. The modern slurry shield, for example, is based on this principle (see Figure 1).

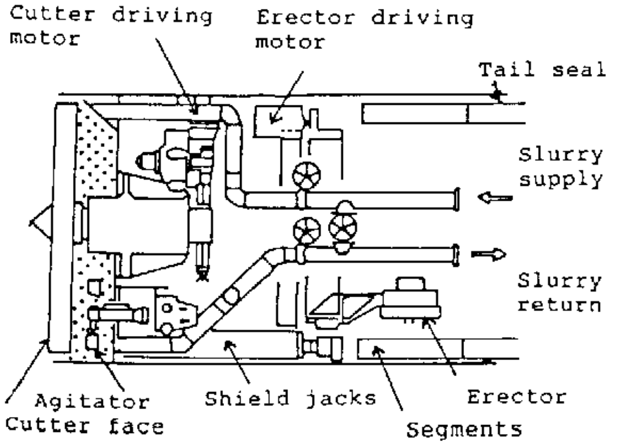

Fig. 1 Slurry shield machine (Fujita, 1989)

In his paper on the construction of the Metropolitan and Metropolitan District Railways (Baker,1885), Sir Benjamin Baker made the following statement in the context of ground movements:

> *"However, with the utmost precautions, tunnelling through a town is a risky operation, and so settlements may occur years after the completion of the works. Water-mains may be broken in the streets and in the houses, stone staircases fall down, and other unpleasant symptoms of small earthquakes alarm the unsuspecting occupants. ....It is hardly necessary to remark that heavy contingencies have to be added to tunnel estimates when, as in the case of the Metropolitan Railway, the Contractors assume the responsibility of damage to adjoining property."*

It is clear that ground settlements caused by tunnelling, and their effects on overlying buildings, were a matter of concern to the engineers constructing these early tunnels. This remains a key issue in modern day tunnelling.

CURRENT CONSTRUCTION METHODS

Tunnels

Hand excavation techniques, using pneumatic clay spades, are commonly used for short lengths of tunnel in London Clay. For escalator shafts and passageways, it is often the case that no shield is employed. This sometimes also applies to station platform tunnels. If the tunnel diameter exceeds about 6m, a pilot tunnel is usually excavated and lined with bolted segments prior to enlargement to the full diameter. Permeation grouting, using silicate grouts, is employed when tunnelling through the water-bearing sandy Terrace Gravels overlying the London Clay. Compressed air is used in ground conditions such as the Woolwich and Reading Beds, comprising interbedded strata of clays, silts and sands, where control of water inflow is essential to maintain stability of the face. For all these types of tunnelling bolted segmental linings are used, and in recent years these are generally made from Spheroidal Graphite Iron (SGI), which is considerably stronger and more ductile than the older cast iron used since the 1880's on many tunnelling projects. The first major use of SGI linings was in the reconstruction of Angel Station in 1989-1991 (Moriarty and Cooper, 1991). A comprehensive review of tunnel lining systems used in London (and elsewhere in the UK) was undertaken by Craig and Muir Wood (1978).

Modern running tunnels for the London Underground are typically about 5m in diameter, and because of their significant length (usually about 1km between stations) these are generally constructed by mechanized shield tunnelling. For such tunnels in London Clay the most common construction technique is excavation by a mechanized shovel in a shield, and lining with expanded precast concrete segments. Progress rates with this technique are typically about 40m per day.

The site investigation and ground conditions for the Jubilee Line Extension Project are described by Linney and Page (1996). In ground conditions other than London Clay, namely the Woolwich and Reading Beds and Thanet Sands, where control of water inflow is essential, tunnels are now constructed with closed face tunnelling machines. Both the principal types of closed face machines, the slurry shield and the earth pressure balance (EPB) shield, have been used on the recent Jubilee Line Extension project. Examples of these types of machine are shown in Figures 1 and 2. Typical progress rates for these machines have been around 12-15m per day.

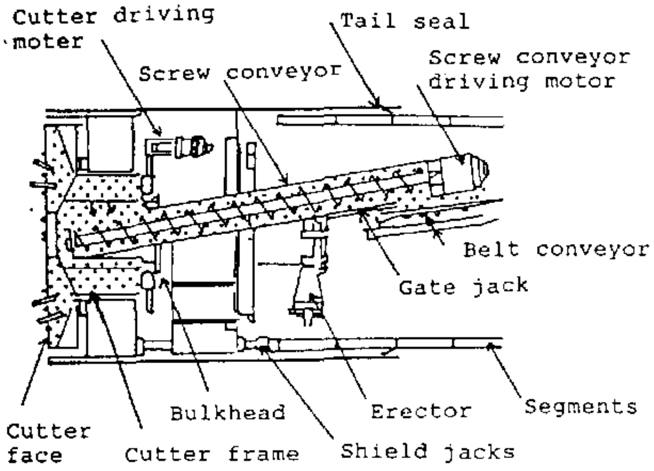

Fig.2 Earth pressure balance machine (Fujita, 1989)

Sprayed concrete linings have been introduced relatively recently for tunnelling in London Clay. The technique, which is sometimes referred to as the New Austrian Tunnelling Method (NATM), has proved particularly successful in the construction of station tunnels and associated passageways for the recent Jubilee Line Extension project. For the larger size tunnels, for example station platform tunnels (typically 9m in diameter), a technique commonly used has been to construct first the running tunnels through the station as pilot tunnels, and then enlarge these to the full size. An example of this technique used for a 12.5m diameter station concourse tunnel is shown in Figure 3.

In general sprayed concrete has only been used for the primary lining and concrete has been cast in situ for the secondary lining. However there have been recent cases in the London area of using sprayed concrete for both the primary and secondary linings, acting as a composite structure (Grose and Eddie, 1996).

Deep Excavations

Generally deep excavations in central London are constructed by means of relatively stiff retaining systems, using diaphragm walls or secant or contiguous bored pile walls. To maximize the control of ground movements deep excavations are usually constructed by providing stiff propping as excavation proceeds. Anchored walls are occasionally used in cases where ground movements are less critical.

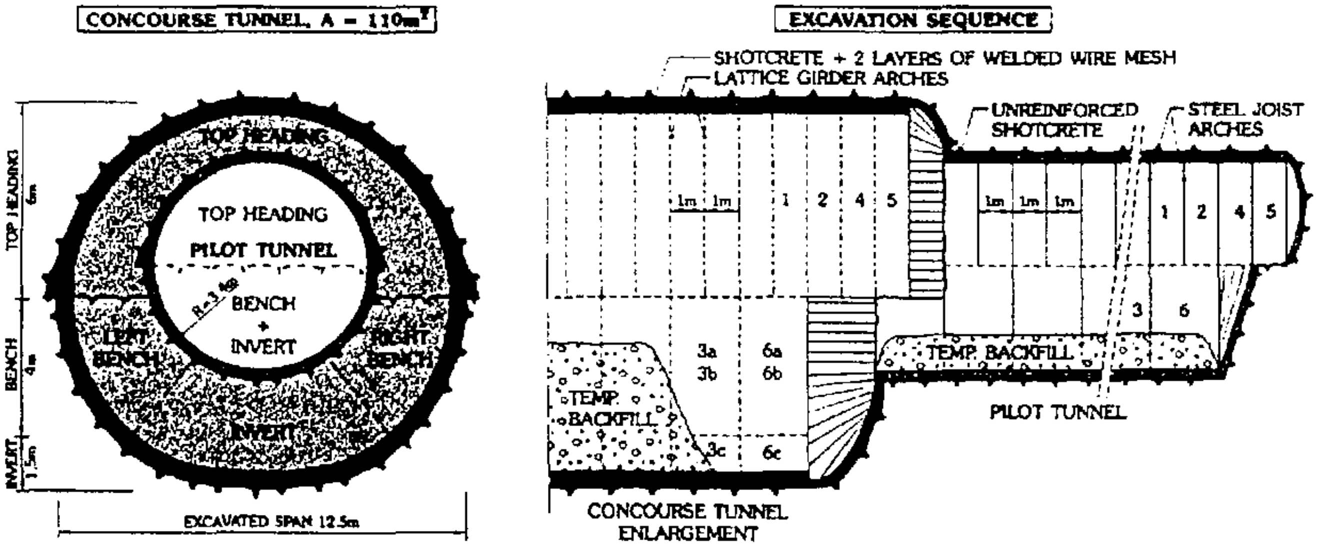

Fig. 3 Sprayed concrete lining (NATM) construction sequence for 12.5m diameter tunnel (Dimmock and Lackner, 1997)

Tunnels

Ground movements are inevitably caused by bored tunnel construction in soft ground, and tunnelling in the London area is no exception. The volume loss, sometimes referred to as ground loss, is a useful and simple means of quantifying the magnitude of ground deformations. It is defined as the total volume of the surface settlement trough per metre length of tunnel (i.e. the cross-sectional area) divided by the cross-sectional area of the tunnel. Observed volume losses are discussed in the following sections.

In London Clay, for which open face tunnelling techniques are used, the volume losses obtained are generally between 1 and 2%, irrespective of whether the tunnel is constructed with a tunnelling shield or by means of sprayed concrete linings (Mair, 1996). An exception to this was the significantly higher ground losses of around 3% obtained at the St James's Park measurement site for the Jubilee Line Extension project (Standing et al, 1996). The reasons for this are not yet fully understood, but there may be significantly different properties of the London Clay at this particular site. The available case histories do not show any noticeable difference in observed volume loss between tunnels constructed with grouted bolted segments and those with expanded segments.

Low volume losses can be observed when pilot tunnels are constructed prior to enlargement to full size, particularly when hand excavation methods are used (Mair, 1993). Figure 4 illustrates how the presence of the pilot tunnel restricts the face deformations of the clay; it acts like a large face dowel. Since the major component of ground movement is normally attributed to face deformations in open face tunnelling in London Clay, the influence of the pilot tunnel can have a significant influence in reducing volume loss. An example is shown in Figure 5. A pilot tunnel of 2.8m diameter was constructed first, followed by enlargement to the full size of 5.5m. The volume loss during the process of enlargement was inferred to be only about 0.5% from measurements by electrolevels installed from an adjacent tunnel (as shown on Figure 5).

Closed face tunnelling using slurry shields or EPB machines in the Woolwich and Reading Beds and in the Thanet Sands for the Jubilee Line Extension project have resulted in volume losses (measured in terms of the surface settlement trough) of between 0.5% and 1%. A key element in control of ground movements with these closed face tunnelling machines is the provision of the appropriate face pressure. Particularly in the case of EPB machines there is often a significant learning curve in achieving this.

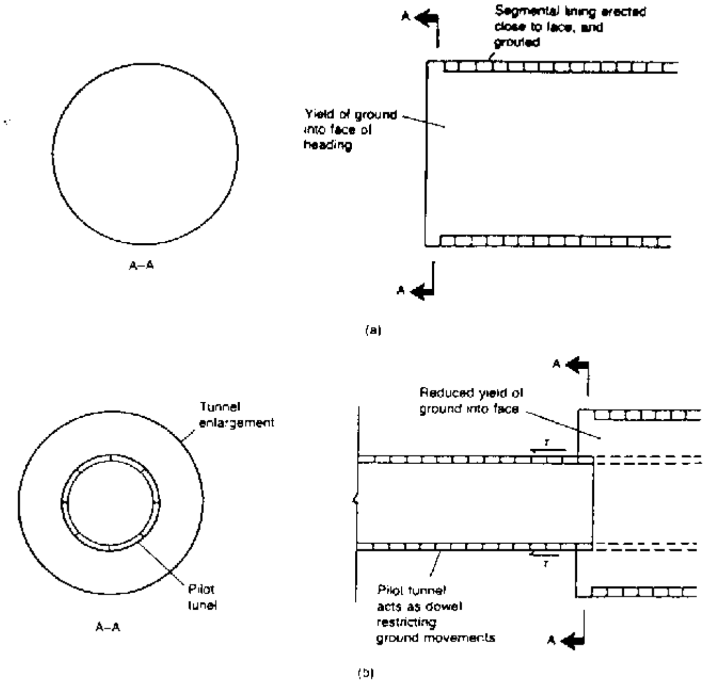

Fig. 4 Effect of pilot tunnel in reducing ground movements (Mair, 1993)

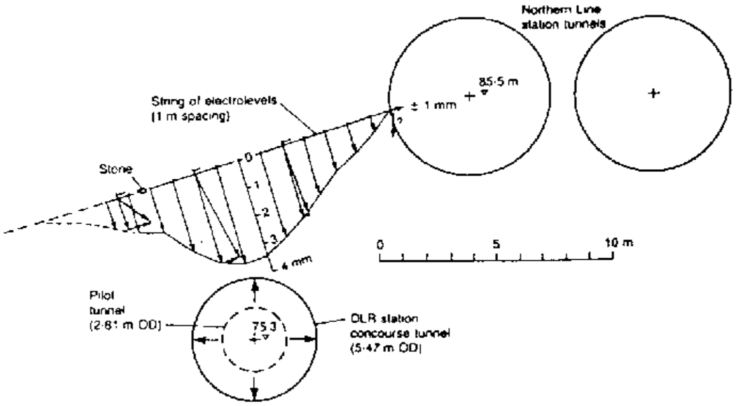

Fig. 5 Sub surface ground movements measured above tunnel during enlargement from pilot tunnel (Mair, 1993)

As noted by Sir Benjamin Baker in 1885, longer term ground movements can be significant. These occur when tunnelling in clays due to time-dependent pore pressure changes (Mair and Taylor, 1997). This also applies to London Clay, although there are generally very few field measurements made over long time periods after completion of tunnels. Figure 6 illustrates immediate and post-construction surface settlement profiles observed above an 8.7m diameter trial tunnel constructed with sprayed concrete linings at a depth of 21m in London Clay (Bowers et al, 1996). The post-construction settlements were measured 3 years after completion of the tunnel, just before the installation of the secondary concrete lining. It is significant that there is a relatively uniform settlement increase across the whole settlement profile in the 3 year period, and there are only very small increases in distortion or deflection ratio. Similarly, Bowers et al present data of short and longer term horizontal strains at the ground surface. Both the short and longer term strains are similar and the data show that there is very little change in horizontal strain in the 3 year period.

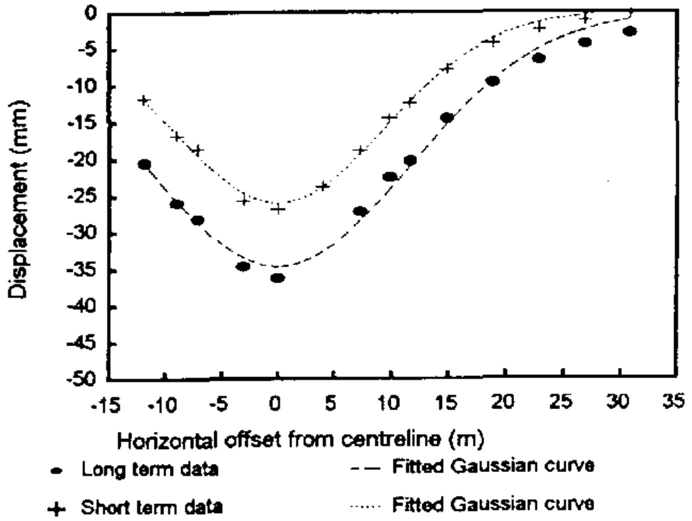

Fig. 6 Immediate and post-construction surface settlements above sprayed concrete tunnel in London Clay (Bowers et al, 1996)

Figure 7 shows post-construction settlement measurements made above a 4.75m diameter tunnel in St James's Park constructed in London Clay at a depth of 20.5m as part of the Jubilee Line Extension project (Nyren, 1998). Similar to the behaviour shown in Figure 6, a relatively uniform settlement increase across the whole settlement profile is observed. These observations are consistent with the general observation in the London area that, despite continuing settlement above tunnels after they are constructed, there is little evidence of new damage to buildings occurring following completion of the tunnels. The implication of Sir Benjamin Baker that damage to water mains and stone staircases occurs years after the completion of the works is not consistent with present day experience.

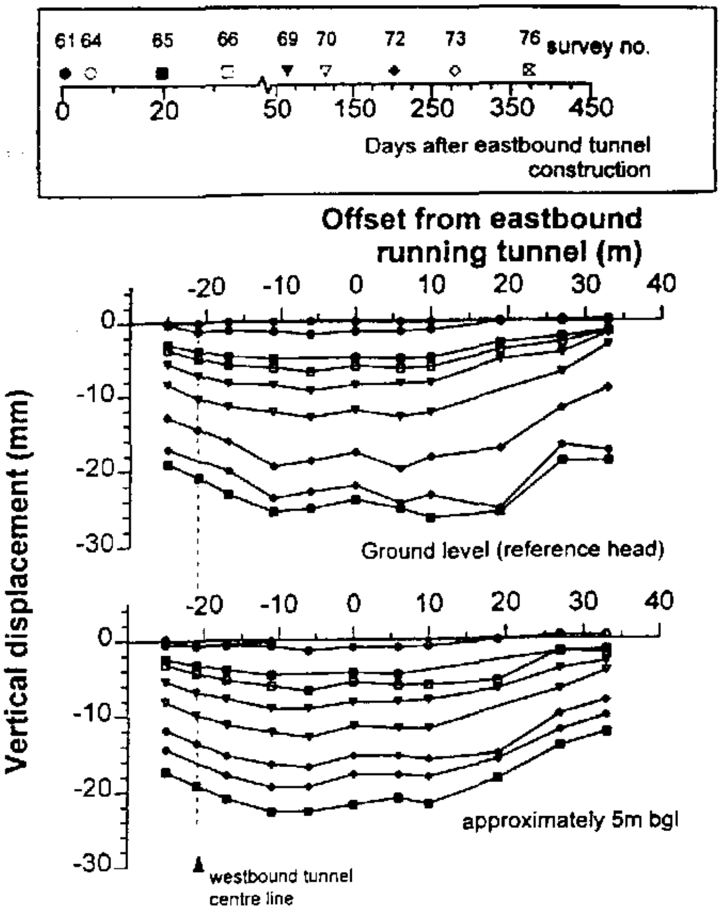

Fig. 7 Post-construction surface and near-surface settlements above segmentally lined tunnel in London Clay (Nyren, 1998)

Deep Excavations

Even with stiff retaining wall and propping systems, deflection of the wall is inevitable as the excavation proceeds, as found in all deep excavations in soils (e.g. Clough and O'Rourke, 1990). Similar behaviour is observed in deep excavations in London Clay. Figure 8 shows observed wall movements reported by Burland and Hancock (1977) for an 18m deep excavation in London Clay constructed by the 'top down' technique, whereby the permanent reinforced concrete floor slabs are cast as the excavation proceeds. Despite the stiff propping provided to the diaphragm wall by this type of construction, significant movement of the wall still occurs and this results in deformations of the adjacent ground. Figure 9, taken from St John et al (1992), shows maximum horizontal movements

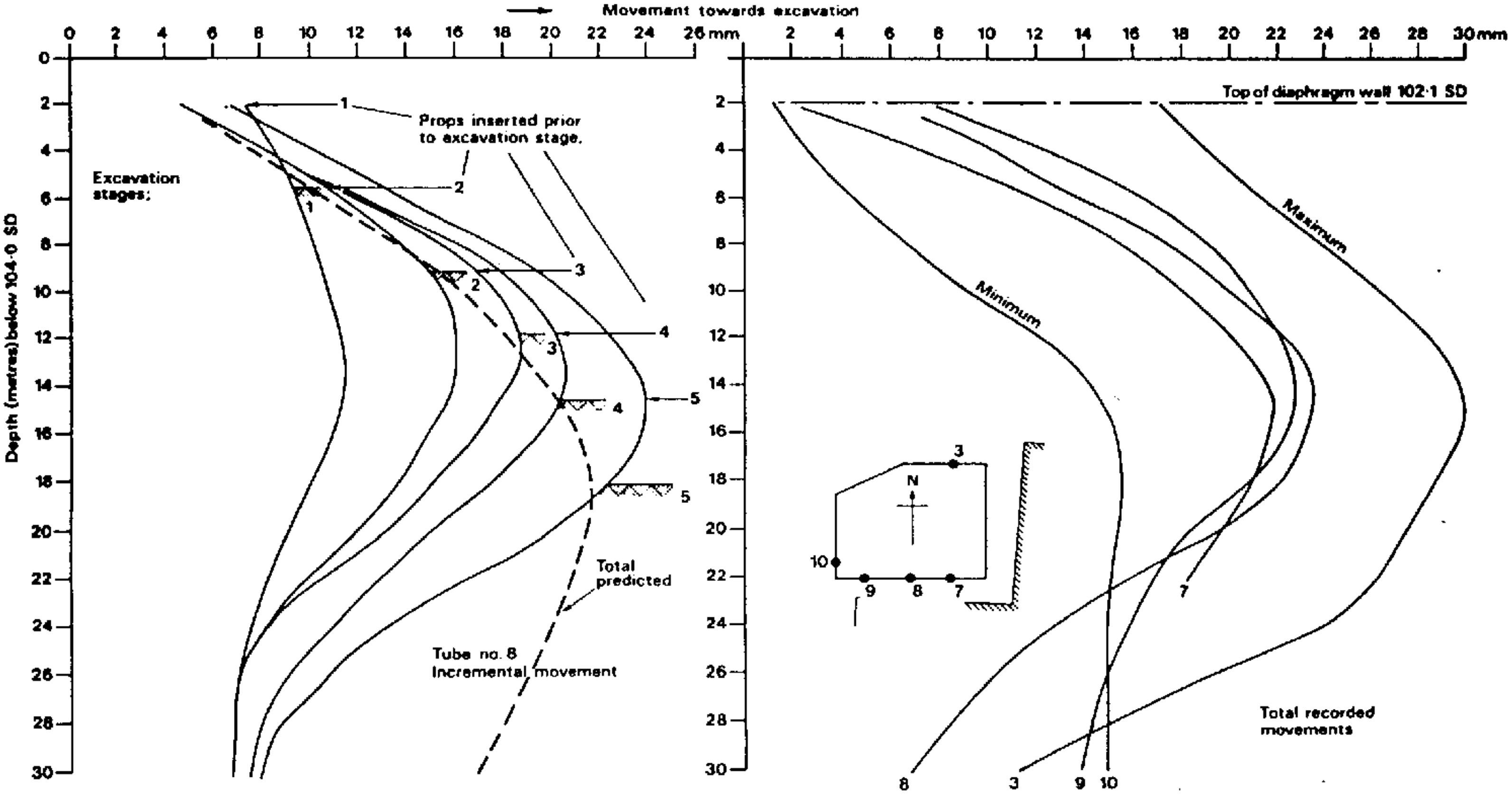

Fig. 8 Wall movements for 18m deep excavation in London Clay (Burland and Hancock, 1977)

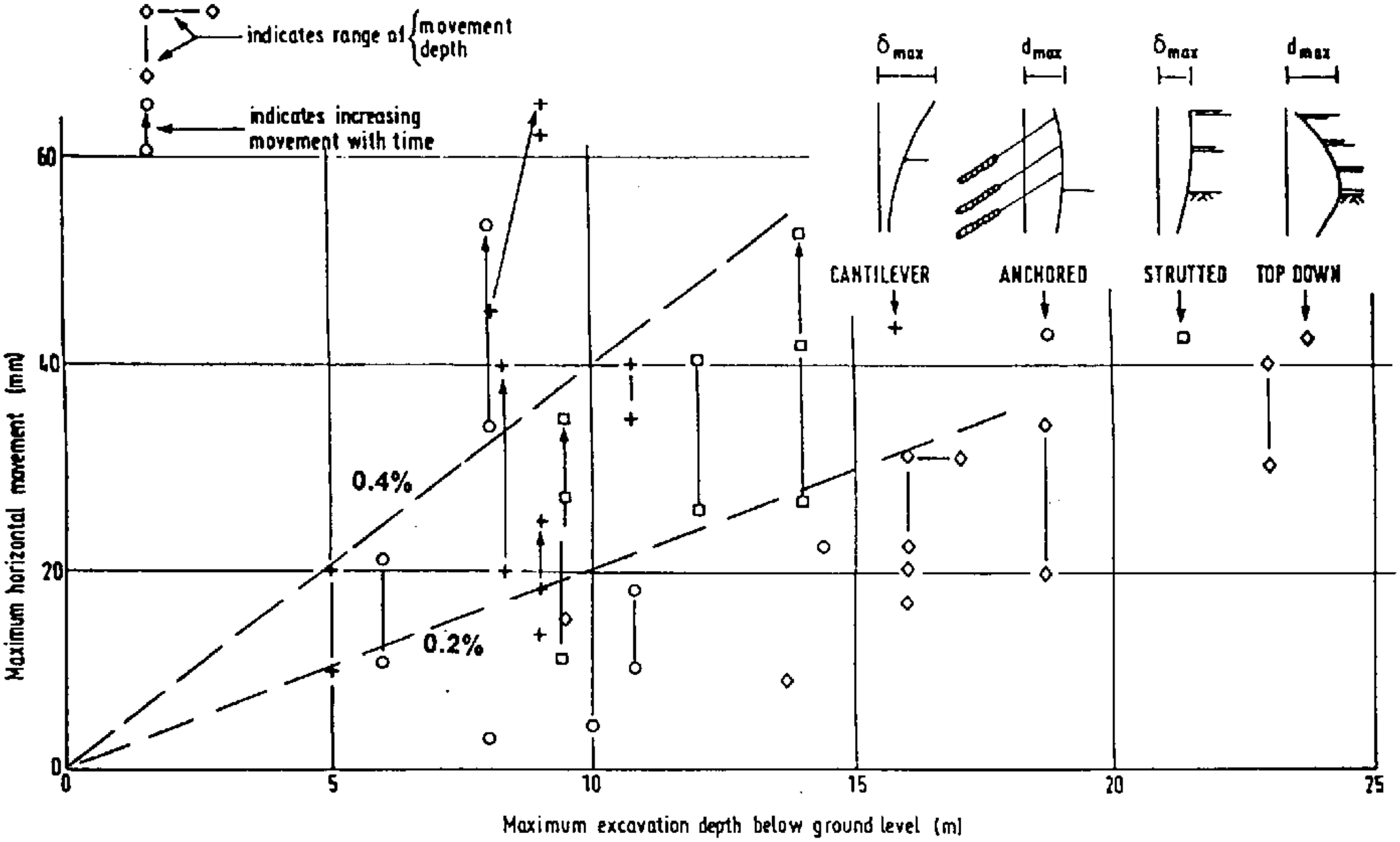

Fig. 9 Maximum horizontal wall movements for different depths and types of excavations in London Clay (St John et al, 1992)

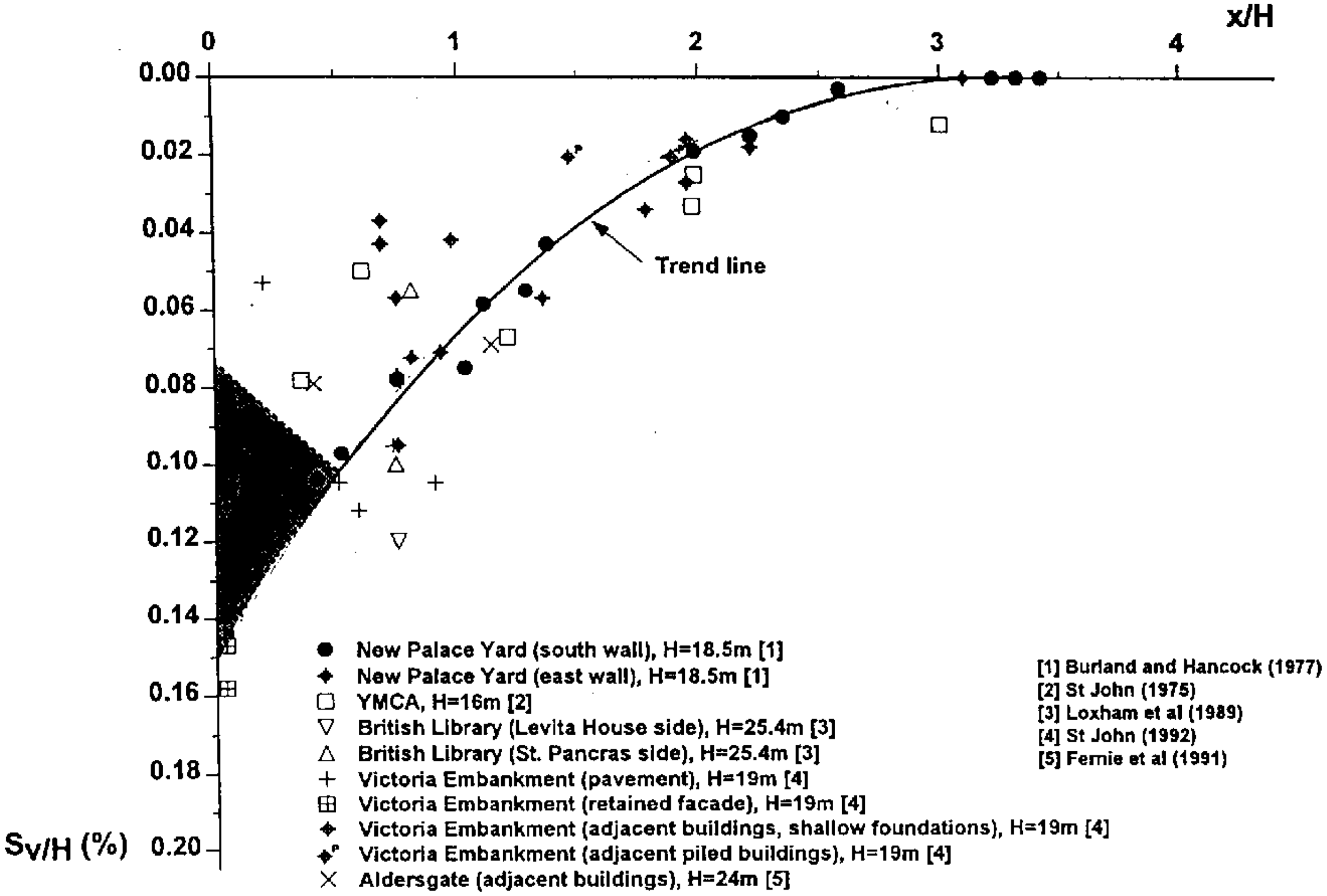

Fig. 10 Surface settlements adjacent to deep excavations (top down construction) in London Clay

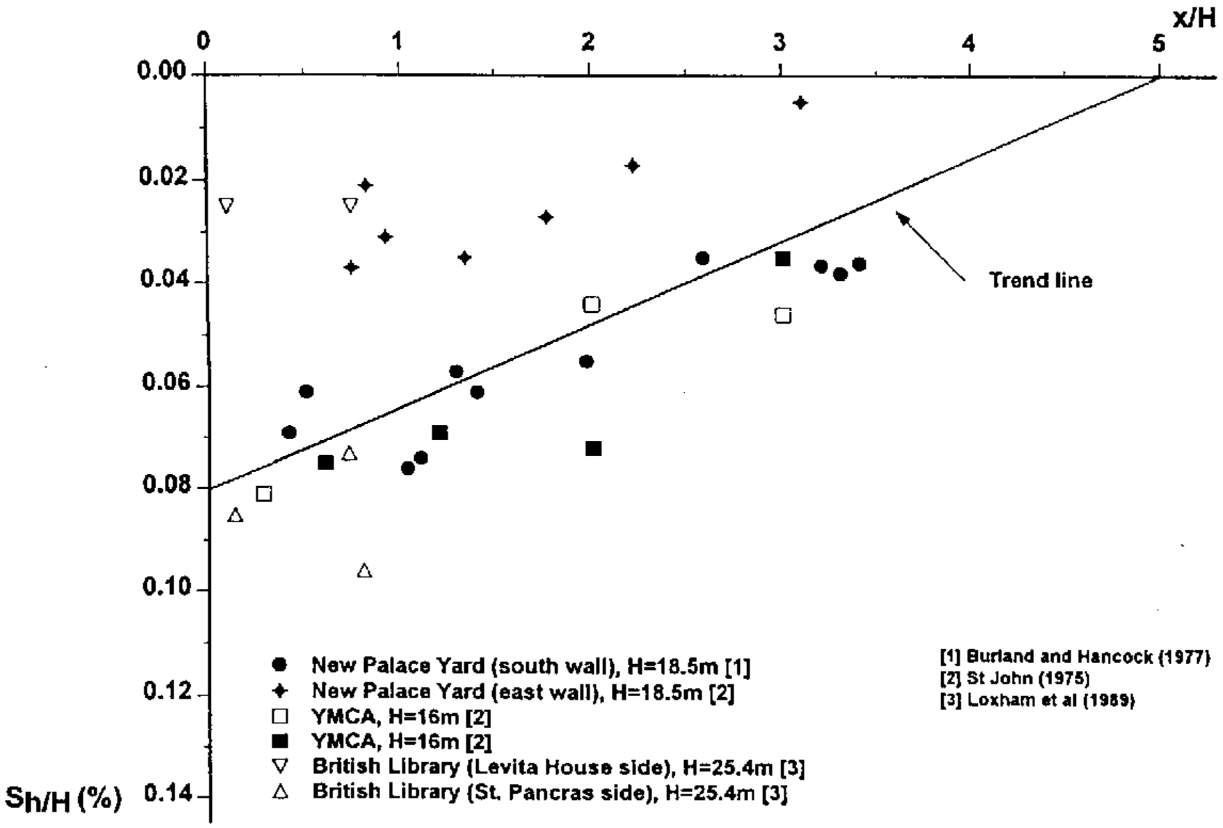

Fig. 11 Horizontal surface movements adjacent to deep excavations (top down construction) in London Clay

observed for embedded walls in London Clay supported by a variety of techniques, namely simple cantilevers (no support other than from the ground), anchored, strutted and top-down. The measurements are shown plotted against the maximum excavation depth (H). With the exception of the cantilever walls, the maximum wall movement varies from about 0.2%H in the case of the stiffest support system (top-down construction) to about 0.4%H in the case of anchored walls.

Surface settlement observations for top-down deep excavations in London Clay are shown in Figure 10, plotted in normalised form. Generally the maximum surface settlement does not exceed 0.15%H and measurable settlement extends back to a distance of about 3H. Close to the wall supporting the excavation the settlements may often be less than the maximum value, because the ground tends to 'hang up' on the wall, as indicated by the upper broken line in Figure 10. For this reason there is often uncertainty about data in the shaded area shown on Figure 10. Figure 11 shows horizontal movements of the ground surface, which are much less frequently measured than settlements, also plotted in normalised form. The maximum horizontal movement does not exceed about 0.08%H. Measurable horizontal movements extend for a distance of 5H, which is more than observed for many case histories (Clough and O'Rourke, 1990). This probably reflects the effect of relieving the relatively high in-situ horizontal stress in the overconsolidated London Clay (K_0 is typically around 2 at higher levels, reducing to about 1.5 at depth).

EFFECTS ON BUILDINGS

The effects of ground movements on buildings due to tunnelling and deep excavations for the Jubilee Line Extension in London have been the subject of a major research project, described by Burland et al (1996). Current methods of assessment of potential damage to masonry buildings are based on work by Burland and Wroth (1974), Burland et al (1977) and Boscardin and Cording (1989). The methodology following this approach and used in the design of the Jubilee Line Extension project is summarised by Mair et al (1996).

A key assumption frequently made in the assessment of potential ground movement effects is that the building is flexible and conforms to the 'greenfield site' settlement trough. In reality soil-structure interaction effects are particularly important in many cases and ground movement patterns based on the 'greenfield site' assumption will be modified by the stiffness of the building and its foundations. The beneficial effects of building stiffness can be very significant, as demonstrated for example by measurements of the effects of a tunnel on the Mansion House in London, which is a historic and fragile building erected about 250 years ago. Figure 12 shows the actual building settlement profile to be significantly wider than the predicted 'green field' profile, with correspondingly much lower deflection ratios and distortions. Although an old and fragile building (and hence a subject of considerable concern), it is evident that the Mansion House possesses appreciable stiffness.

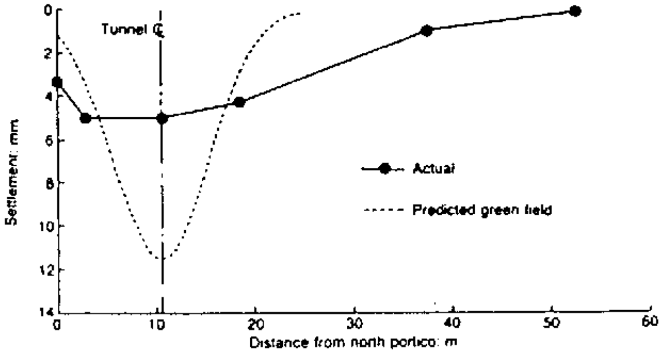

Fig. 12 Influence of building stiffness on settlement profile caused by tunnelling (after Frischmann et al, 1994)

Figure 13 shows similar evidence of the Treasury building (of masonry construction, built around 1900) exhibiting significant stiffness in comparison to the observed adjacent 'green field' site settlements (Standing et al, 1998; Nyren, 1998). As the tunnel approached the wall of the building (e.g. -47m and -11m on Figure 13) and subsequently passed beneath it (8m and 34.5m on Figure 13), the building tilted in a relatively rigid manner and exhibited much less curvature than the adjacent 'green field' site in St James's Park. Other buildings, sometimes of more modern construction, have been found to be much less stiff in their response. Recent work by Potts and Addenbrooke (1997) has introduced the concept of relative bending stiffness, which expresses the relative stiffness between the building and the underlying ground, and this is an important contribution to methods of prediction and understanding of how buildings actually behave in response to tunnelling. This subject is discussed in more detail by Mair and Taylor (1997).

PROTECTIVE MEASURES

Introduction

Protective measures against potentially damaging ground movements used on tunnelling schemes in London have included the following techniques:

- Permeation grouting of gravels immediately beneath a building to create a 'raft' of grouted ground
- Positive jacking by installing jacks in saw-cuts in the foundations
- Tie rods to strengthen fragile masonry buildings
- Pilot tunnels to reduce volume loss and thereby reduce ground movement effects
- Use of soil reinforcement installed from pilot tunnels to restrict ground movements during subsequent enlargement
- Compensation grouting

Of these techniques some examples of compensation grouting are presented in the following section.

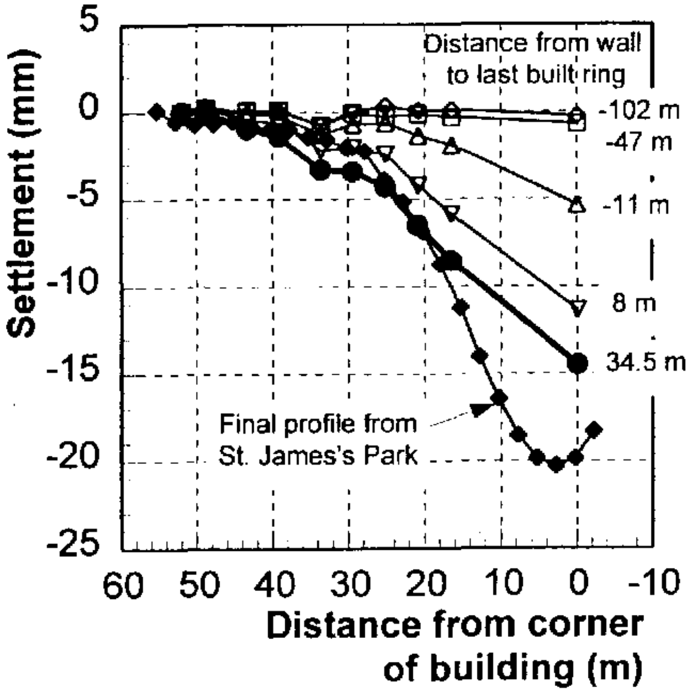

Fig. 13 Settlement of Treasury building and adjacent 'green field' site (after Standing et al, 1998; Nyren, 1998)

Compensation Grouting

Compensation grouting is a relatively new technique for controlling building settlements during tunnel construction. There has been extensive experience of the technique on recent tunnelling projects in London, particularly on the Jubilee Line Extension project. The principles of the method and a review of its applications on other projects are presented by Mair and Hight (1994). Grout is injected between the tunnel and the building foundations to compensate for ground loss and stress relief associated with the tunnel excavation. Grout is injected simultaneously with tunnelling in response to detailed monitoring observations, the aim being to limit building settlements and distortions to specified values. The method was successfully used in the USA in Baltimore to protect about 40 masonry buildings (Baker et al,1983) and in Minneapolis to protect a masonry arch culvert (Cording et al, 1989) using compaction grouting above the tunnels in dense sands.

Injection of a fluid grout with a high solids content into gravels, thereby allowing the grout to bleed rapidly (sometimes referred to as "intrusion grouting"), was successfully used to protect a fragile masonry building and a pair of old masonry tunnels in London during construction of a new escalator tunnel (Mair et al, 1994; Harris et al, 1994). As shown in Figure 14 the 8m diameter tunnel passes within a few metres beneath the Victory Arch (the entrance structure to Waterloo Station) and the Waterloo and City Line railway tunnels, which were built in 1885 and are founded in gravels 3m below the water table. Grouting was undertaken through tubes a manchettes installed from the basement of the Victory Arch and, as shown in Figure 14, from the Waterloo and City Line tunnels. The compensation grouting limited settlements of the structures due to tunnelling to 10-15mm, and no damage occurred. In the absence of protective measures, the likely settlement would have been 50-100mm and would have caused significant damage together with the risk of flooding of the Waterloo and City Line tunnels.

Fracture grouting with a fluid grout is usually adopted for compensation grouting in clay soils and this technique has been successfully used in London Clay for the Jubilee Line Extension (JLE) project. Figure 15 shows a cross section through the new JLE platform and concourse tunnels, which have been constructed using sprayed concrete primary linings directly beneath Waterloo Station (one of the busiest mainline railway stations in London). Tubes a manchettes (TAM's) for compensation grouting were installed about 8m above the two 9.1m diameter platform tunnels and the 11.8m diameter concourse tunnel prior to their construction. A plan view of the grouting shafts and layout of the TAM's is shown in Figure 16, together with an outline of the low level tunnels. The settlements of the foundations of the mainline railway station have been well controlled by the compensation grouting. Construction of the two platform tunnels alone resulted in settlements being limited to generally less than 10mm, compared with up to 60mm expected in the absence of compensation grouting (Harris et al, 1996). The entire JLE station has now been completed, including all the upper level tunnels and passageways, and settlements have generally been limited to 70mm at the end of construction compared with 200-300mm expected in the absence of compensation grouting. Of most importance has been the control of differential settlements, which has resulted in no more than occasional minor damage to the overlying buildings.

The total volume of grout injected into the clay is generally well in excess of the volume loss associated with tunnel construction. Based on a likely volume loss of about 1.5%, Harris et al (1996) showed that the implied "efficiency" (defined as the ratio of volume of ground loss to the volume of grout injected) to be about 0.3. Further research is needed to explain this relatively low efficiency.

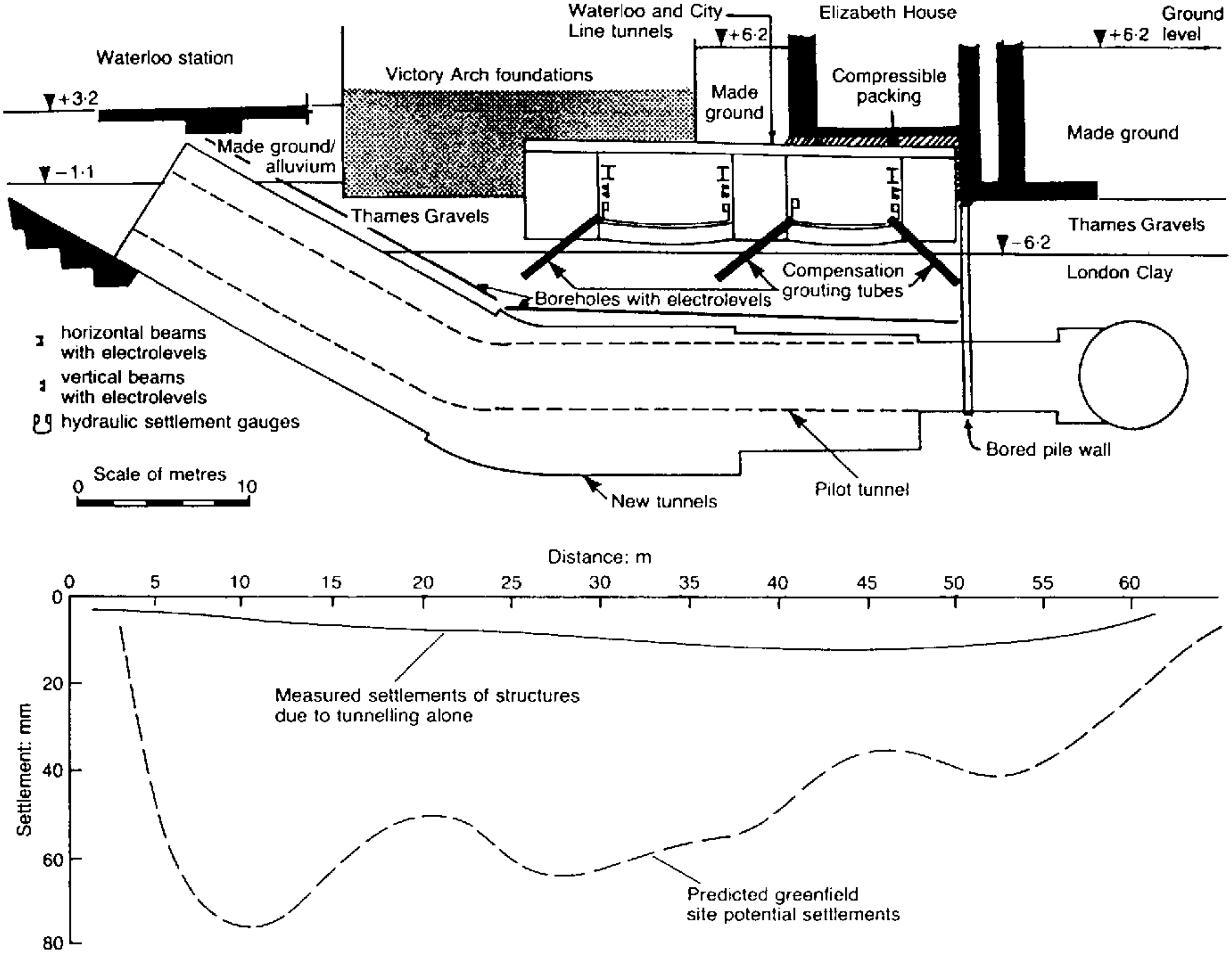

Fig. 14 Settlement control by compensation grouting during tunnelling (Harris et al, 1994; Mair et al, 1994)

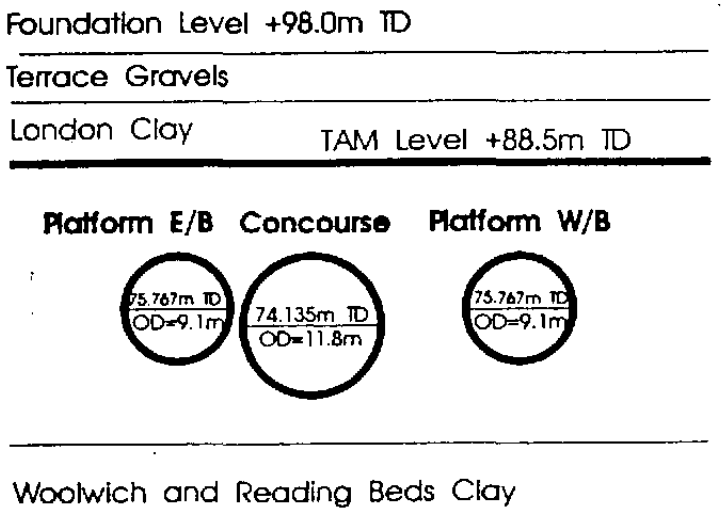

Fig. 15 Cross-section through tunnels and compensation grouting tubes (TAM's) at Waterloo Station (Harris et al, 1996)

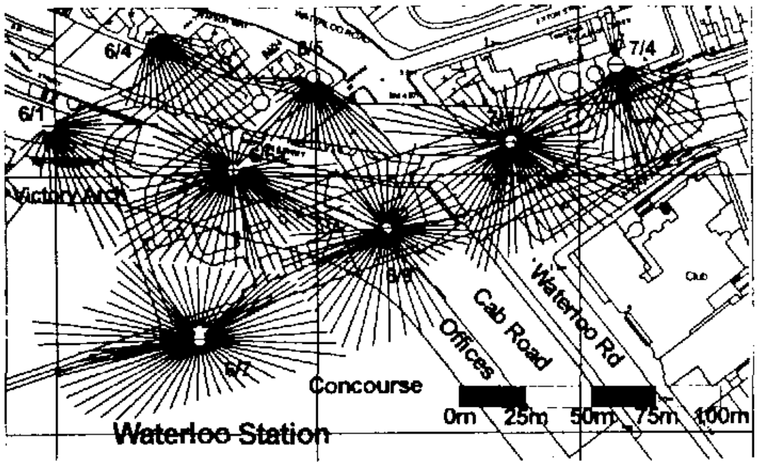

Fig. 16 Shaft and grout tube layout for compensation grouting at Waterloo Station (Harris et al, 1996)

The vital importance of good quality monitoring in achieving effective compensation grouting is illustrated in Figure 17 (Osborne et al, 1997). Compensation grouting was undertaken close to the crown of a 10m diameter upper concourse tunnel, which was also constructed beneath Waterloo Station for the JLE project (in this case using hand excavation methods and SGI cast iron segmental linings). Deep settlement pins were installed above and below the TAM's through which grout was injected during tunnel construction. Figure 18 shows the observed settlement of these pins during enlargement of the tunnel from a 5.75m diameter pilot tunnel to the final size. The pin below the level of grouting settled by almost 90mm. In contrast the pin immediately above the grouting tubes, and the overlying building, settled by no more than 20mm. The detailed monitoring of the ground and building movements ensured that the grouting operations were undertaken in a controlled manner in response to the observations.

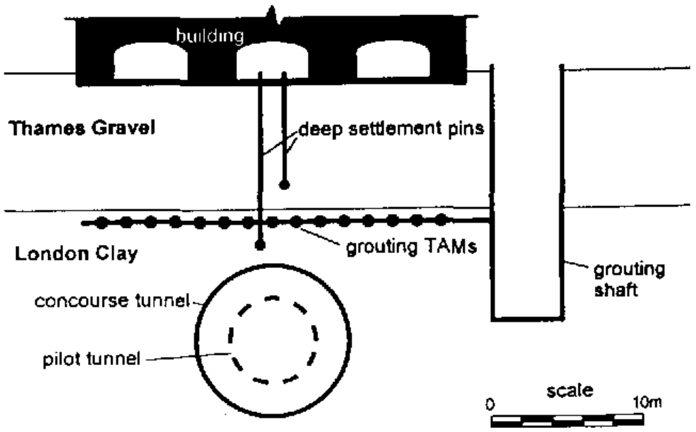

Fig. 17 Deep settlement pins for monitoring compensation grouting (after Osborne et al, 1997)

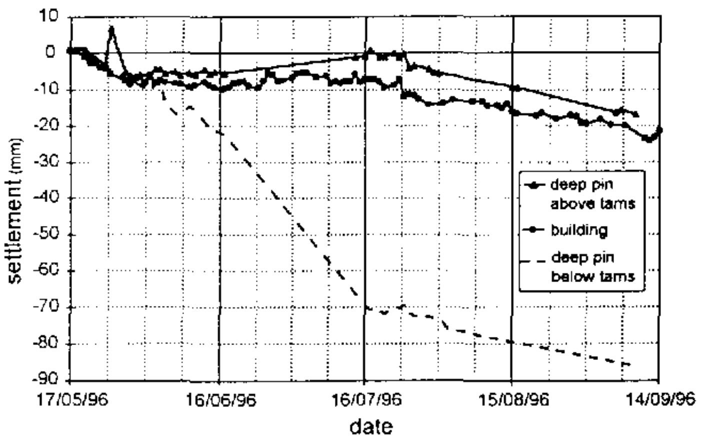

Fig. 18 Settlement of deep pins and building during tunnelling and compensation grouting (after Osborne et al, 1997)

Compensation grouting has been successfully used on the Jubilee Line Extension project to control settlements of a significant number of historic structures in London. Probably the most famous of these is the "Big Ben" clock tower at the Houses of Parliament in Westminster. Figure 19 shows a cross-section through the 40m deep box structure and twin platform tunnels comprising the new Westminster Station. The ground movements resulting from the construction of the deep box and the tunnels were predicted to affect the clock tower, which is located on shallow foundations 33m from the edge of the station box. Horizontal compensation grouting tubes were installed beneath the clock tower foundations by drilling from an adjacent shaft. The potential tilt of the tower towards the new station during construction has been successfully limited by the compensation grouting, which was undertaken at regular intervals for a period of 21 months.

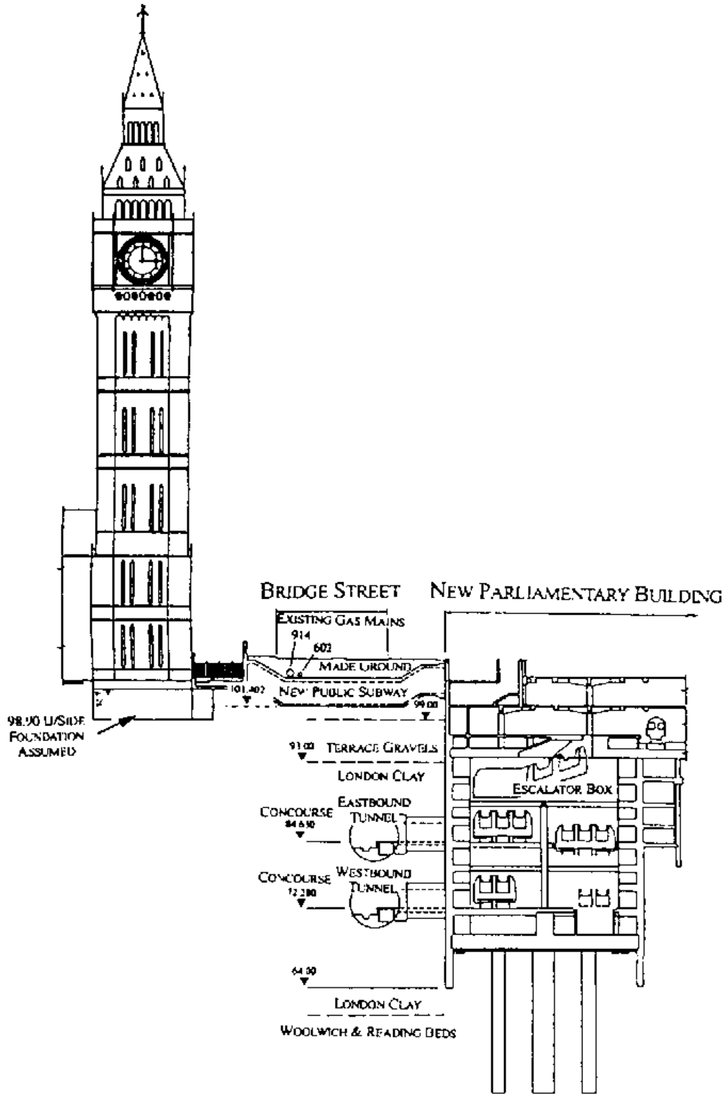

Fig. 19 Cross-section through new Westminster Station and 'Big Ben' clock tower (from Carter et al, 1996)

CONCLUSIONS

There has been a long history of construction of tunnels and deep excavations in the London area going back about 150 years. The techniques developed by the Victorian engineers in construction of the early tunnels have formed the basis of modern shield tunnelling used world-wide.

Early experiences of tunnelling and deep excavations were already focusing on the difficulties associated with resulting ground movements and their effects on overlying buildings. The prediction of ground movements and the assessment of the potential effects on the infrastructure is an essential aspect of the planning, design and construction of any tunnelling project in the urban environment.

Many of the latest developments in soft ground tunnel construction have been used on the recent Jubilee Line Extension project, namely sprayed concrete linings and closed face pressurised tunnelling machines (both slurry shields and earth pressure balance machines). All of these techniques have been very successful. Deep excavations in London had hitherto been to depths of up to about 25m, but the station box excavation at Westminster to a depth of 40m is a considerable advance.

The Jubilee Line Extension project has involved detailed predictions of ground movements and of their potential effects on buildings, a large number of which are historic and of fragile masonry construction. Of the various protective measures employed, compensation grouting has been the most extensively used. This relatively new technique has proved to be very successful in controlling deformations of buildings and preventing damage.

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