Investigating variations in tunnelling volume loss – a case study

J.R. Standing & J.B. Burland
Imperial College London, UK

ABSTRACT: During construction of the Jubilee Line Extension (JLE), London, large variations in tunnelling volume loss, from 1.1 to 3.3%, were measured between Waterloo, south of the Thames, and the area north of St. James's Park (about 2 km). A detailed investigation was undertaken in James's Park two years after construction to establish reasons for the differences of 1.2 to 3.3% observed north and south of the park. Three primary causes are identified: tunnelling method and control; differences in clay cover from past erosion and; divisions within the London Clay with markedly different geotechnical characteristics – in particular the permeability. A key point is the necessity to control construction operations very closely when tunnelling through clays containing water-bearing silt and sand partings. This case study highlights the importance of understanding the engineering geology, even in London with decades of tunnelling experience and well characterised ground conditions. The message is equally applicable to many cities where large subsurface infrastructure projects are planned.

1 INTRODUCTION

During tunnelling operations there are usually small ground movements in towards the tunnel as a consequence of stress relief before the lining is installed. These manifest themselves at the surface as a settlement trough. There are three primary quantities that control the settlement and its extent: depth to the tunnel axis, z_0; trough width parameter, K, and; volume loss, V_L.

The trough width parameter, K, can be estimated reasonably reliably (O'Reilly and New, 1982). However the volume loss, V_L, is dependent on a number of factors such as the type of ground, groundwater conditions, tunnelling method, length of time in providing positive support and the quality of supervision and control.

Realistic assessments of ground movements and potential building damage require reliable estimates of volume loss. During the planning and design stages for the Jubilee Line Extension (JLE) running tunnels a volume loss of 2% was assumed. The fact that values well in excess of 3% were measured in the Westminster area was of considerable concern. Establishing the reasons for these unexpected volume losses was considered essential to avoid unrealistically high predictions of settlement and building damage for future tunnelling proposals.

As there was a marked change in volume loss from south to north of St. James's Park, this area was chosen for study. Pairs of borings were made at five sections across the park (Figure 1), spanning the area where the change in volume loss occurred, so that the ground

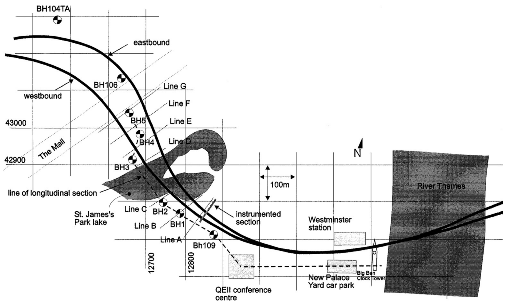

Figure 1. Plan of Westminster and St. James's areas showing JLE route, JLE and research monitoring arrays, borehole locations and other major excavations.

conditions could be characterised in both geological and geotechnical terms.

South of the lake in St. James's Park an instrumented greenfield monitoring section had been set up prior to JLE construction as part of a research project looking into ground and building response to tunnelling (Jardine, 2001). The analysis of the monitoring data from the research site is given by Nyren (1998), along with detailed accounts of the method of running tunnel construction.

2 DETAILS OF TUNNEL CONSTRUCTION

The route of the JLE running tunnels passing through the Westminster area is shown in Figure 1. The distance between the tunnels increases as they pass beneath

St. James's Park. At the southern end of St. James's Park the axis of the westbound (WB) tunnel is about 31 m deep and that of the eastbound (EB) is about 20.5 m deep. Moving northwards their axis levels gradually rise, but by no more than 2.5 m. Throughout this area the tunnels are located entirely in the London Clay. The WB tunnel was constructed first and passed under St. James's Park from east to west during late April 1995 followed by the EB tunnel in early January 1996.

An open-faced shield of 4.85 m outer diameter with face excavation by back-hoe was used for the tunnelling from Waterloo to Green Park. The length of the shield was 4.2 m and precast concrete linings, expanded with two wedge-shaped key segments at the 'knees', were erected behind it after shoving forward off the previously constructed ring. An important feature of the back-hoe is that a reach of 1.9 m in front of the shield was possible, allowing potential over-excavation without proper support.

Components of the overall volume loss relating to this method of tunnelling can be identified, e.g. from over-excavation, thickness of the bead for reducing frictional drag, steering corrections, tunnel alignment curvature, inadequate support at the rear of the shield where there are 'trailing fingers' for temporarily supporting the exposed clay (Muir Wood, 2000; Burland *et al.*, 2004). Back-grouting behind the erected lining was seldom necessary.

3 OBSERVATIONS DURING CONSTRUCTION OF THE JLE RUNNING TUNNELS BENEATH ST. JAMES'S PARK

The location of the greenfield monitoring section at St. James's Park is shown in Figure 1. Standing *et al.* (1996) give details of the surface and subsurface instrumentation installed there. In addition, the JLE contractor set up seven sections on which surface settlements were measured. These are also marked on Figure 1. These sections had only a limited number of monitoring points allowing S_{max} to be measured and V_L to be roughly estimated.

3.1 *Vertical displacements during the construction of the westbound tunnel*

Figure 2a shows the measured short-term transverse settlement profile from the passage of the WB tunnel beneath the research reference site. A maximum vertical displacement of 20.4 mm at the tunnel centreline was measured immediately after the tunnel had passed. The volume loss V_L, was 3.3%, assuming symmetry about the westbound centre-line.

The contractor's levelling data for monitoring lines *A*, *B* and *C*, south of the lake (Figure 1) showed maximum settlements of between 18 and 20 mm with volume losses estimated to be about 3.5%.

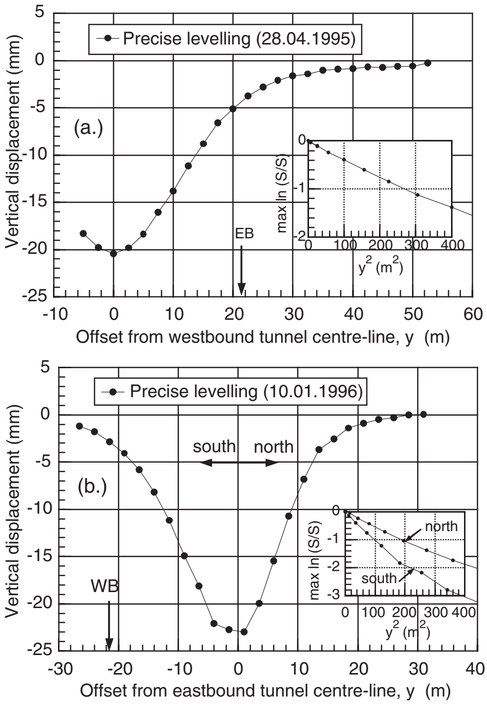

Figure 2. Incremental short-term surface settlement troughs for (a) the west- and (b) eastbound running tunnels.

North of the lake (Figure 1), the magnitude of centre-line settlements at lines *D* to *G* was recorded as between 9 and 11.4 mm, with estimated volume losses of between 1.5% and 2.0%.

3.2 *Vertical displacements during the construction of the eastbound tunnel*

Figure 2b shows the incremental transverse shortterm settlement profile from construction of the EB tunnel where the maximum settlement was 23.4 mm. The overall volume loss, V_L, was 2.8%, being made up of 1.2% and 1.6% for the north and south sides of the settlement trough. The influence of the ground disturbance caused by the WB tunnel is evident from the asymmetry of the settlement profile.

Levelling data for the monitoring lines at the northern end of the park (data are only available for lines *F* and *G*) indicated the centre-line settlements to be 10 mm, and the volume losses are estimated for both monitoring lines to be between 1.2% and 1.4%.

4 GEOLOGY AND GROUND CONDITIONS ACROSS THE SITE

The surface of the park comprises grassed topsoil beneath which is Made Ground. The lake within

St. James's Park is roughly midway along the length of the section investigated. Post-glacial alluvium underlies the Made Ground and is in turn underlain by River Terrace Deposits of sand and gravel deposited during the Pleistocene (Gibbard, 1985).

The London Clay Formation underlies the gravels to depths in excess of 40 m below ground level and thicknesses of at least 32 m. The depth of the Lambeth Group deposits, beneath the London Clay, was not established in this investigation. They are underlain in turn by the Thanet Sand Formation and Chalk Group of considerable thickness.

The London Clay Formation comprises silty clays, clayey and sandy silts, and subordinate sands, with a thickness of over 150m in South Essex (King, 1981). The facies types correspond to marine, shallow marine and coastal environments. King used five major transgressive-regressive cycles to define divisions *A* to *E*. Details of the soils within each division are given by Hight *et al.* (2003).

Two aquifers exist in the London Basin: (1) a deep aquifer capped by either the London Clay or the clays of the Lambeth Group; and (2) a perched water table within the River Terrace Deposits above the London Clay (or the Lambeth Group clays). This upper aquifer is recharged from surface precipitation and locally from the Thames.

During the JLE site investigation, the upper aquifer was observed at ~3 m below ground level in the River Terrace Deposits between Green Park and Westminster Station.

Piezometers installed in the London Clay at the instrumented site indicated a near-hydrostatic pore water pressure distribution from the top of the River Terrace Deposits.

5 SITE INVESTIGATION WORKS AND DESCRIPTION OF CORES

The purpose of the study described here was to examine whether variations in ground conditions and properties could have been a significant contributory factor to the larger than expected volume losses in St. James's Park south of the lake. It was necessary to establish detailed comparative soil profiles and the pore pressure characteristics through the London Clay at the locations of high and low volume loss.

Five locations across the park were selected at which pairs of boreholes were drilled to 40 m depth. Continuous open-driven 100 mm diameter (U100) samples were taken in one borehole and in the other, Standard Penetration Tests (SPTs) were carried out at 4-m intervals with U100 samples taken at intermediate depths for laboratory testing.

The samples from the continuous U100 boreholes were extruded, split and described to give a detailed visual and tactile profile at each location. The second boring can be considered as a strength-profiling borehole. Two standpipe piezometers were installed within one of the boreholes at each section at the axis levels of the WB and EB tunnels. These were used to establish pore pressures and to determine the *in-situ* permeability across the site.

6 VARIATION IN GROUND CONDITIONS ACROSS THE SITE

Results from the investigation are now discussed. In the text, 'site' refers to the investigation area within St. James's Park. Reference is made to conditions south and north of the lake (i.e. Boreholes 1 and 2 south; and 3, 4 and 5 north) as the lake roughly divides the two regions of the park with different volume losses and surface settlements. Elevations are given as 'above Project Datum' (aPD), this being 100 m below Ordnance Datum.

6.1 *Appraisal of borehole logs and Pleistocene geology*

The site stratigraphy determined from the borehole logs is shown on the longitudinal section in Figure 3 and is supplemented with information from the House of Commons Car Park and the Queen Elizabeth II Conference Centre investigations (Burland and Hancock, 1977 and Burland and Kalra, 1986).

It can be seen that the upper level of the London Clay Formation reduces markedly in elevation (by about 4.5 m) from the boreholes immediately north and south of the St. James's Park lake. The upper surfaces of the London Clay either side of the lake are essentially horizontal, indicating that the section which runs roughly perpendicular to the Thames, crosses a terrace feature. Gibbard (1985) describes the sequence of Thames terraces, and it can be deduced that it was the older Kempton Park gravel that was encountered in Boreholes 3, 4 and 5 to the north of the lake. This was eroded south of the lake in a later glacial period along with the 4.5 m of London Clay. Assuming that the thickness of the Kempton Park gravels was the same as at present (i.e. about 5 m), it can also be deduced that a total of about 9.5 m of ground was unloaded from the London Clay in the area south of the lake.

The Shepperton gravels were deposited later, having a thickness similar to the Kempton Park gravel beneath the north of the park. The overlying alluvium and fill were deposited during post-glacial times, leaving the present surface profile.

The terrace feature and the unloading of the London Clay in this area have direct implications with regard to the engineering characteristics of the clay and in relation to the differences in tunnelling-induced settlements and volume losses.

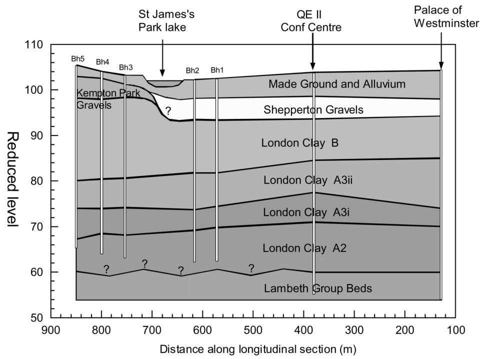

Figure 3. Longitudinal section across the St. James's Park site and Westminster showing divisions of the London Clay.

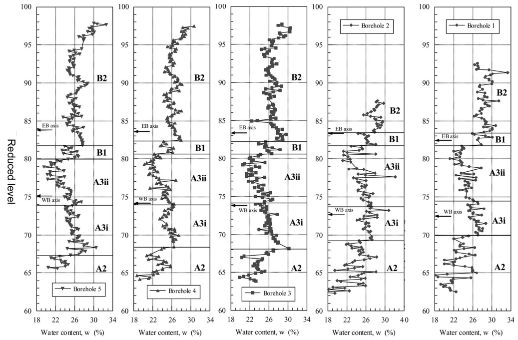

Figure 4. Water content profiles with depth (in terms of reduced level) for Boreholes 1 to 5.

6.2 *London Clay lithology*

The London Clay divisions were identified using the detailed descriptions of the split continuous U100 samples and moisture content profiles. Four distinct horizons were identified within the London Clay. Two match those established by King (1981) and the other two together form another of King's divisions. Summary descriptions of the divisions based on the examination of site samples are given below, working from the top of the profile downwards.

(1) STIFF becoming VERY STIFF fissured, faintly laminated dark grey brown silty becoming very silty CLAY with larger vertical fissures towards base. This horizon corresponds to King's division *B*.
(2) VERY STIFF faintly laminated dark grey brown very silty becoming silty CLAY with frequent silt/sand partings, dustings, pockets and lenses and occasional fissures. This horizon corresponds to the upper part of King's division *A*3 and is denoted *A*3*ii*.
(3) VERY STIFF fissured (heavily in zones), faintly laminated dark grey brown silty CLAY. This horizon corresponds to the lower part of King's division *A*3 and is denoted *A*3*i*.
(4) VERY STIFF becoming VERY STIFF to HARD interbedded dark grey brown and in zones dark brown grey slightly sandy very silty CLAY with little visible fabric (strongly bioturbated) and laminated silty CLAY and slightly sandy (often in the form of dustings) very silty CLAY. This horizon forms the basal beds and corresponds to King's division *A*2.

Axis levels of the WB and EB running tunnels lie within the *A*3 and *B* divisions respectively. The boundary between *B* and *A*3*ii* is very clear, being evidenced by the sudden appearance of sand and silt partings. It can be seen from the longitudinal section (Figure 3) that there is reasonable continuity across the site of the interfaces between these divisions.

6.3 *Water content profiles*

The profiles of water content with depth from the continuous samples provided an invaluable graphical means of identifying the divisions within the London Clay and also of indicating changes across the site as can be seen in Figure 4. Scatter within the individual graphs is generally small, but very distinct horizons are evident where moisture contents change noticeably by several percent. Changes in water content across the site can also be directly related to changes in the undrained strength of the clay, which tends to reduce as water content increases. In the upper divisions *B* and *A*3*ii* there is a gradual increase in moisture content across the site from north to south (Borehole 5 to 1). It is very likely that this resulted from the unloading and consequent swelling of the London Clay, discussed in Section 6.1.

6.4 *Undrained shear strength of the London Clay*

The undrained shear strength of the London Clay was obtained from triaxial tests on the U100 samples and can be assessed indirectly from the *in-situ* SPTs.

Profiles of triaxial undrained shear strength with depth are given in Figure 5a. Strengths generally increase with depth, with values from Boreholes 1 and 2 being lower than those at similar elevations north of the lake. This correlates with the increased moisture contents south of the lake.

SPT N-values (given as blows/0.3 m in Figure 5b) are used to supplement the laboratory test data. Again there is a trend for the SPT N-values from Boreholes 1 and 2 to be lower than those north of the lake.

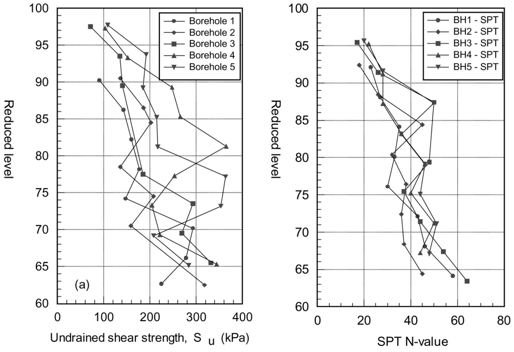

Figure 5. Profiles from each of the five boreholes across the St. James's Park of (a) undrained shear strength and (b) SPT N-value with depth.

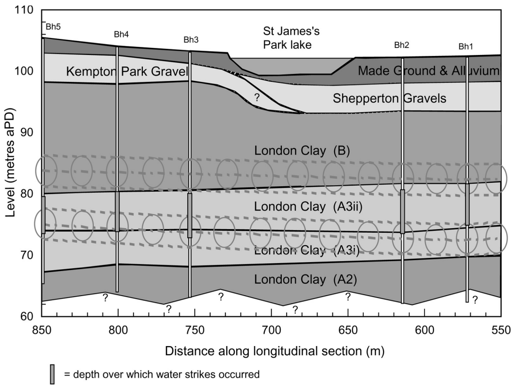

Figure 6. Section across St. James's Park site showing locations of water strikes and tunnel alignments.

7 GROUNDWATER CONDITIONS AND SOIL PERMEABILITY

7.1 *Water strikes encountered during drilling*

The main water strikes (i.e. a rapid sudden inflow of water) occurred at the top of sub-division *A3ii* where there is the highest concentration of sand and silt partings. The elevations at which water was encountered and the depths over which flow was noted to have occurred are marked on Figure 6.

7.2 *Standpipe piezometers*

Two standpipe piezometers were installed at each section with the tips located roughly at the axis levels of the west- and eastbound tunnels.

Coefficients of permeability, k, were calculated from falling head tests and from the initial equilibration period. The values of k for the upper division B of London Clay, were about 4×10^{-11} m/s south of the lake where erosion and unloading took place, decreasing to 1×10^{-11} m/s north of the lake.

Although no piezometers were installed in the *A3ii* division, it is evident from the water strikes and from the physical description given in Section 6.2, that the permeability of this layer was much greater than that of division *B*.

8 TUNNEL CONSTRUCTION AND LOCATION

Few detailed records are available concerning the construction of the tunnels beneath the site. Their vertical alignments in relation to the divisions of the London Clay are shown in Figure 6.

8.1 *Westbound tunnel*

Rates of advance in the Westminster area were high, being about 40 to 45 m per day beneath the control section. The procedure for construction of the WB tunnel was to excavate by up to 1.9 m in front of the shield, removing almost the full tunnel diameter. Volume losses were in excess of 3%.

North of the lake, three other methods of excavation were used, where shorter lengths in front of the shield were excavated and greater thicknesses of the soil annulus left around the perimeter of the face to be cut by the shield.

Volume losses dropped to less than 2%, although the rate of advance remained almost the same as south of the lake. The lower volume losses coincide with the closely supervised and more rigorous excavation methods, along with the changing ground conditions from south to north of the park.

The deeper WB tunnel is almost entirely within the *A3i* sub-division at the south. Heading north, its axis level rises so that only the invert is within the *A3i* sub-division, most of the diameter being in the overlying *A3ii* layer with the sand and silt partings.

Nyren (1998) inspected the WB tunnel and found the lining was dry to Borehole 3 (Figure 6). Further north, damp patches became more frequent with a sharp transition to a wet section, where the crown of the tunnel is within the upper zone of the subdivision *A3ii*, with increased sand and silt partings.

8.2 *Eastbound tunnel*

The JLE shift reports give no indication of any changes in the excavation method along the drive. The speed of the EB tunnel progress was about half that of the WB drive and the volume loss for the EB tunnel alone (i.e. uninfluenced by the WB tunnel) was about 2.4% south of the lake, considerably less than the equivalent section of the WB tunnel. This compares with a value of 1.4% north of the lake.

The shallower EB tunnel intersects both subdivisions *A3ii* and *B* at the south of the site. Moving northwards, at about the location of Borehole 3 the tunnel invert is entirely within the *B* division (see Figure 6), which is considered to have the lowest permeability. Nyren's tunnel inspection revealed that the linings became almost entirely dry, with only occasional damp patches at this point.

9 FACTORS INFLUENCING VOLUME LOSS

A number of factors have been identified that would have influenced the magnitude of volume loss.

9.1 *Geology and lithology*

(i) A river terrace feature straddles the site, the upper surface of the London Clay south of the lake in St. James's Park being 4.5 m lower than that north.
(ii) *In-situ* and laboratory tests indicate that the erosion of the London Clay and ground above it south of the lake (a thickness of ~9 m) has resulted in swelling and softening of the clay and an increase in its mass permeability.
(iii) Four divisions with different engineering characteristics have been identified within the London Clay beneath St. James's Park. These are consistent with classifications given by King (1981).
(iv) Division *A3ii* contains frequent silt/sand partings and lenses. Major water strikes were encountered in this layer, especially south of the lake.
(v) Throughout its length, the crown of the WB tunnel is located in division *A3ii*, just beneath the layers containing the silt/sand partings and lenses.
(vi) The axis and crown of the EB tunnel is always within division *B* of the London Clay. The mass permeability of this layer is comparatively low.

9.2 *Influence of mass permeability*

(vii) There is a greater propensity for the clay in the immediate vicinity of the tunnel to loosen and soften in ground with higher mass permeability (e.g. *A3ii* with the sand/silt partings) during the time when the tunnel face is unsupported and prior to the permanent installation of the lining. Also pre-existing fissures would tend to open with the stress relief from the open face of the tunnel.
(viii) During open-face tunnelling, vertical extensional strains occur above the tunnel together with shearing in concentrated zones emanating from positions at roughly knee and shoulder level and extending radially outwards over a distance of about one tunnel diameter. These disturbances would locally increase permeability, resulting in loosening and softening of the ground above the tunnel crown.
(ix) The location of the WB and EB tunnels in relation to the different divisions of the London Clay north and south of the lake in the park would have contributed to the observed variations in volume loss values for the reasons given in (vii) and (viii).

9.3 *Influence of tunnelling procedure*

(x) The degree of support provided at the tunnel face is crucial to minimize the potential for loosening and softening of the clay above the crown and hence volume loss. Leaving up to 2 m of unsupported tunnel in front of the shield with little or no soil left around the tunnel circumference to be cut by the shield would therefore exacerbate volume loss.
(xi) The stricter control exerted north of the lake on WB tunnel construction, with increased face support, appears to have been effective in substantially reducing the volume loss, even though the crown and axis of the tunnel were located in division *A3ii*.

10 CONCLUSIONS

The larger than expected volume losses south of the lake are a result of a combination of effects. These include reduced undrained strength, the presence above the crown of the westbound tunnel and below the invert of the eastbound tunnel, of a layer containing water-bearing sand/silt partings and lack of adequate support of the tunnel face during the tunnelling operation. The combination of the latter two effects is probably the dominant influence.

Awareness of basic geological features and their influence on geotechnical parameters, combined with good construction control can help minimize ground movement and consequent building damage, perhaps even obviating the need for expensive, indirect protective measures such as compensation grouting.

Comprehensive details of this case study are given by Standing and Burland (2005).

ACKNOWLEDGEMENTS

The research described in this paper was financed by London Underground Limited and the authors are grateful for their support.

REFERENCES

Burland J.B. and Hancock R.J. (1977). Underground car park at the House of Commons, London: Geotechnical

Aspects. *The Structural Engineer*, Vol. 55, No. 2, pp 87–100.
Burland J.B. and Kalra C.J. (1986). QE II conference centre: Geot'l aspects. *Proc. ICE*, Part 1, Vol. 80, pp 1479–1503.
Burland J.B., Mair R.J. and Standing J.R. (2004). Ground performance and building response to tunneling. *Proc. Skempton Conf: Advances in Geotechnical Engineering*, vol 1, Thomas Telford, London, pp 291–342.
Gibbard R. (1985). *Pleistocene history of the Middle Thames Valley.* Cambridge University Press.
Hight D.W., McMillan F., Powell J.J.M., Jardine R.J. and Allenou C.P. (2003). Some characteristics of London Clay. *Proc. Conf. Characterisation and Engineering*, National University Singapore. Tan T.S., Phoon, K.K., Hight D.W., Leroueil S. (eds). Balkema, Vol. 2, pp 851–907.
Jardine F.M. (2001). The LINK CMR research project. *Building response to tunnelling. Case studies from the Jubilee Line Extension, London, Vol 1*, Burland J.B., Standing J.R. and Jardine F.M. (eds). CIRIA Special Publn 200. CIRIA and Thomas Telford, pp 45–56.
King C. (1981). The stratigraphy of the London Basin and associated deposits. *Tertiary Research Special Paper*, Vol. 6, Backhuys, Rotterdam, p158.
Muir Wood A. (2000). *Tunnelling: management by design*. E & FN Spon, London.
Nyren R.J. (1998). *Field measurements above twin tunnels in London Clay*. PhD thesis, Imperial College Uni. of London.
O'Reilly M.P. and New B.M. (1982). Settlements above tunnels in the U.K. – their magnitude and prediction. *Proc. Tunnelling '82*, London, IMM, pp 173–181.
Standing J.R. and Burland J.B. (2005). An investigation into unexpected tunneling volume losses in the Westminster area, London. Submitted to *Géotechnique.*
Standing J.R., Nyren, R.J., Burland J.B. and Longworth T.I. (1996). The measurement of ground movements due to tunnelling at two control sites along the JLE. *Proc. Int. Symp. Geotechnical Aspects of Underground Construction in Soft Ground*, Mair R.J. and Taylor R.N. (eds.), Balkema, Rotterdam, pp 751–756.