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Long Term Settlement following Tunnelling in overconsolidated London Clay.

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ABSTRACT: The mechanisms and theoretical aspects of long term settlement following tunnelling in London Clay are described and the controlling parameters identified. The potential influence of compensation grouting, used to control movements during construction, on long term settlement are considered. The limited published case histories of long term settlement in London are summarised and available predictive methods are presented. The extensive records available from JLE Contract 102 for a period of up to 5 years following construction are presented and summarised.

1 INTRODUCTION

Monitoring of settlement following completion of the Jubilee Line Extension in London has continued for up to five years. This has provided a database which allows much greater insight to be gained into the significance, magnitude, duration and distribution of consolidation settlements following tunnelling.

2 SIGNIFICANCE OF LONG TERM SETTLEMENT

Settlement which develops in the long term following tunnel construction in clay is a complex subject which has received relatively little research effort and for which there are few published case histories, particularly with respect to tunnels in London Clay. Historically, long term settlement has been considered to be unproblematic, however, on JLE Contract 102 a considerable amount of attention has had to be given to the subject for a range of reasons:

Potential Damage Assessment: The prediction of long term settlement is not included in the standard "Settlement Assessment" methodology; this has been justified by the assumption that long term settlement is less damaging than volume loss movements. There is a growing awareness of the potential effects of tunnelling on overlying structures, and there is a need for case history data to justify this assumption.

Specified Limits on Settlement: Specified limits on absolute settlement, which do not take into account the potential for a substantial element of consolidation settlement, can have serious cost and programme implications. Substantial consolidation settlements can occur within the construction period particularly at station locations but also, for example, between two running tunnel drives.

Liaison with Third Parties: The lack of predictions for long term settlement meant that, in many instances, third parties were not aware of this component of movement. A great deal of time had to be expended in explaining the continuance of movement after the completion of construction. The use of the term "Settlement Assessment" and reference to the calculated settlement as a "prediction" is misleading, since only immediate, volume loss settlements are included in the standard methodology.

Actual Damage: Although damage to buildings on Contract 102 has been maintained within acceptable limits, a number of situations have arisen where damage has continued to worsen as a result of consolidation settlements.

Effect of Compensation Grouting: the widespread use of compensation grouting with large volumes of grout injected to mitigate volume loss movements during tunnel construction led to concern that increased post construction settlements may result.

De-commissioning of Protective Measures: The potential rate, magnitude and distribution of long term settlement needs to be understood to provide evidence that any protective measure implemented has fulfilled its role and can be de-commissioned.

Limit of Responsibility for Damage: Agreements with third parties frequently contained clauses relating to both settlement and the monitoring of it.

These generally stated that monitoring shall continue until movement has ceased and for a specified period thereafter. There is a need for the implications of such undertakings to be more clearly understood.

3 THEORETICAL ASPECTS

The potential for ground movements to continue for many years after completion of construction of tunnels excavated in London Clay is well understood. The mechanism for these longer term movements is that the tunnel inevitably introduces a new drainage boundary condition, since at the inside face of the lining the pressure is, by definition, atmospheric or zero. The pore pressures immediately after construction of a tunnel are not in equilibrium with the modified boundary conditions. If the tunnel is not totally impermeable, flow of pore water occurs until a steady state flow pattern is reached. The final pore pressures will generally be lower than those immediately after tunnel construction; settlement will occur as pore pressures reduce to their long term values, increasing effective stresses and thereby inducing consolidation of the clay.

The principles of soil mechanics relevant to the problem of consolidation settlement following tunnelling are well understood. Nevertheless, it is generally not appreciated how important the distribution of relative permeability is in determining the magnitude as well as the rate of consolidation movements. The initial pore pressure profile in Central London, as a result of underdrainage producing downwards flow, is controlled by the vertical permeability profile through the London Clay and Lambeth Beds clays. It is perfectly possible for pore pressures to exist anywhere between zero and the hydrostatic pressure from the upper aquifer, at any elevation within the London Clay. The location of the tunnel (or drain) within the permeability profile can similarly have widely divergent effects on the magnitude of the reduction in pore pressure in the long term, and hence on the magnitude of consolidation settlement. Illustrative examples of the effect of layering of permeability are shown on Figure 1.

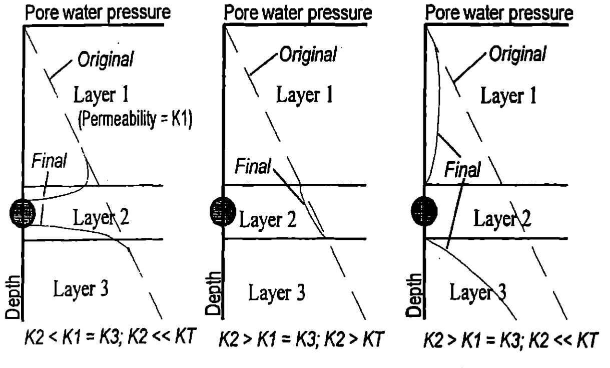


Figure 1. Effect of layering on pore pressure decrease

Of potentially great importance, also, is the permeability of the tunnel lining and the immediately surrounding ground which governs the effectiveness of the tunnel as a drain. It is usual, in London Clay, to assume that the lining is permeable relative to the ground and that the tunnel therefore acts as a perfect drain, i.e. the pore pressure at the outside of the tunnel lining is zero. Limited data is available of measured long term pressures around tunnels; these suggest a variable effect but confirm that, in the long term, a flow pattern is established towards the tunnel.

The accurate determination of the in-situ permeability of London Clay is problematic. Field measurements are usually dominated by the horizontal permeability and hence the variation in vertical permeability with depth (which governs the initial pore pressures) is particularly difficult to ascertain.

4 CASE HISTORY DATA

Only three published case histories of long term settlement following tunnel construction in London Clay have been identified. The geometry of tunnels at each location differed significantly but confirmed that long term settlement should be expected after construction of tunnels in London Clay. There is a large variation in the reported rates of consolidation settlement.

5 PREDICTION OF CONSOLIDATION SETTLEMENT

Finite Element (FE) analysis (or other numerical method) is the only practicable method of predicting consolidation settlement; there are no reliable empirical methods of prediction.

Parametric studies of post-tunnelling settlement in London Clay, using FE analyses, have been undertaken by GCG; these highlight some important points:

- if the tunnel lining is impermeable heave is predicted following construction;
- for permeable tunnels with very low initial pore pressures in the clay, heave, settlement or even no movement can be produced;
- changes in horizontal permeability alone can significantly modify the magnitude of settlement;
- movements continue for 5 to 10 years after tunnel construction and produce an "S" shaped curve when plotted against time on a logarithmic scale;
- the distribution of vertical permeability influences both the rate and magnitude of settlement;
- changes in permeability within the accuracy of standard measurement techniques can double the magnitude of movements;

· the elevation of a tunnel within a varying permeability profile can alter settlements substantially;

· clay cover and tunnel spacing are important controlling parameters;

· long term settlements occur over a wider area than volume loss movements;

· settlements and slopes can increase significantly both within and outside the extent of volume loss movements;

· increases in angular strain within the volume loss settlement trough are generally a small proportion of those from volume loss movements.

· with multiple tunnel passes, such as at a station, a large proportion of consolidation settlement can occur during the construction period and an increase in the rate of settlement is generally produced after each separate tunnel drive.

6 SUMMARY OF OBSERVATIONS

The main issues relating to long term consolidation settlement are discussed, with examples given from the monitoring results from JLE Contract 102

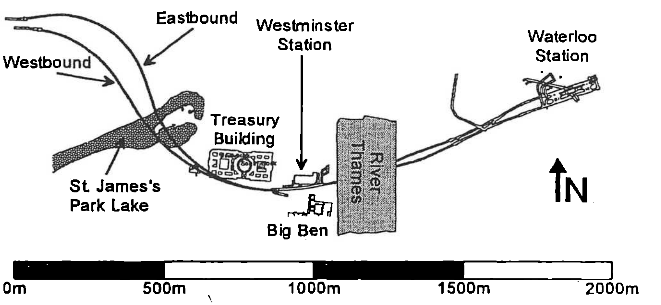
6.1 The assumption that the tunnels act as a drain

The data from Contract 102 shows that settlement continued to increase after construction over virtually the whole length of the tunnels. Most tunnels were visibly wet to varying degrees. The evidence strongly supports the concept that tunnels in London Clay do act as a drain. Substantial consolidation settlements have been recorded over tunnels in most locations irrespective of the lining type (bolted SGI and concrete, expanded concrete and in-situ concrete), including station areas where more attention is paid to waterproofing.

6.2 Magnitude of consolidation settlement

The total magnitude of consolidation settlement can only be reliably determined from settlement monitoring data where there are clearly defined construction activities of short duration. In this situation the immediate volume loss movements can be identified and subtracted from the total movement to give the element due to consolidation. However, if a tunnel is constructed relatively slowly, it can be shown, theoretically, that up to 20% of the total movement during construction could be due to consolidation rather than undrained, volume loss movements. Thus, where construction takes place over a long period or where there are multiple tunnels or compensation grouting is employed only an approximate estimate of the total consolidation settlement can be made. As an alternative, post-construction movements can be considered although this element of the consolidation settlement can be a small proportion of the total.

The layout of the tunnels on Contract 102 is shown in plan and in long section on Figure 2. Figure 3 shows both the total consolidation settlement and the post construction settlement as a long section. The long term values shown are based on movements 1000 days after the end of construction. The variation in the magnitude of settlement is substantial with values of less than 5mm and greater than 50mm above the running tunnels and almost 100mm at Waterloo and Westminster stations.



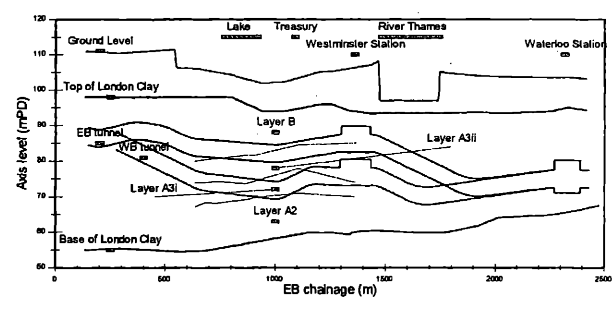


Figure 2. Contract 102 tunnels – plan and longsection

Substantial consolidation settlement (>30mm) was recorded over the length between the River Thames and the St. James's Park lake. Over this section of the route, the tunnels are close together in plan and at different elevations. As the tunnel alignments diverge to the north of the lake, the recorded movements decrease significantly (to <15mm), particularly over the Eastbound tunnel. This suggests that the majority of compression occurs at elevations close to the tunnel and that movements produced by tunnels at different elevations and relatively close spacing in plan are, to a degree, additive.

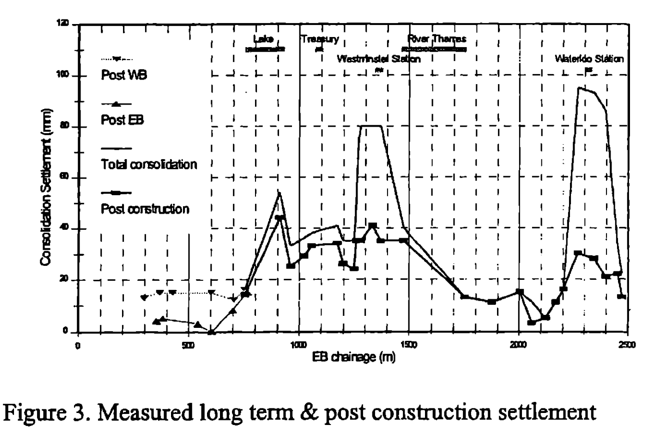


Figure 3. Measured long term & post construction settlement

South of the river, where the two running tunnels are at approximately the same elevation, maximum consolidation movement is about 15mm. Reduced movements were recorded in proximity to the Waterloo International Terminal (WIT). This is attributed to the unloading from the then recent construction of WIT and the presence of the existing London Underground tunnels below.

For the running tunnels the total consolidation settlement includes a small component (5 - 10mm) of settlement from the period between the two tunnel drives whereas at the station locations between 40 and 60mm of consolidation settlement is estimated to have occurred within the construction period. Larger consolidation movements are to be expected at station complexes due to the large close proximity tunnels and the presence of tunnels at a range of elevations. A maximum settlement of 40mm has been recorded after the end of construction, as shown on Figure 3.

London Clay is often considered to be a "uniform" material with respect to tunnelling. It has been shown here that the magnitude of consolidation settlement can vary widely. The volume losses recorded on Contract 102 also varied widely (0.7% to 3.2%). Clearly London Clay does not give uniform movements as a result of tunnelling. It is considered that layering within the Clay is one of the most important factors. A variation in permeability within the London Clay was noted by Burland and Hancock, 1972, and King, 1981, identified a number of different divisions based on depositional history. Further soil investigation in St. James's Park was commissioned by LUL (Standing & Burland, 1999). This investigation identified the divisions with the clay below St. James's. The layering is shown on Figure 2, with respect to the running tunnel vertical alignments and shows that the relative postion of both tunnels changes below the St. James's Park lake: the Westbound tunnel changes from Layer A3i to A3ii and the Eastbound tunnel passes from Layer A3ii into the overlying Layer B.

There is an overall correlation between the elevation of the tunnels and the magnitude of consolidation settlement; greater settlements are given where the tunnels are between 10 and 25m above the base of the clay i.e. in Layer A3i, and smaller movements where the distance is below 10m (Layer A2) or above 25m (Layer A3ii and B).

6.3 *Rate and duration of consolidation settlement*

The "total" consolidation settlement values quoted in Section 6.2 are from 1000 days after the end of construction. Consolidation movements are still continuing at a measurable rate in some areas over 2000 days after the end of construction.

Where two or more tunnels are constructed, an increased rate of movement due to consolidation is observed after each drive. In general, the rate of consolidation settlement will continuously decrease with time following the end of construction, but will not give a linear relationship against log time. The maximum rate of movement on a log time plot generally occurs within the first year and hence a linear fit to data over this period can be used to predict maximum further movements.

The period over which consolidation settlements are perceived to continue is related to the accuracy of measurement. On JLE Contract 102 settlement has been deemed to be effectively complete when movements are less than 2mm/year; this criterion was satisfied within 2 years where the total consolidation settlement is <15mm, whereas, where much larger movements have been recorded, the criterion was not met until for 5 years.

Examples of the development of long term settlement with time are shown on Figure 5 from a range of points above the centrelines of the tunnels differentiated into three zones: north of the St. James's Park lake for east and westbound tunnels and south of the lake for both tunnels extending to Parliament Square:

- The settlements north of the lake above the Westbound tunnel fall into a tight band for 4 points located over a 300m length of the tunnel. Very small increases in settlement occur after 1000 days.
- The data from above the Eastbound show a wider range for the area north of the lake. The data is plotted as movements after the Westbound tunnel and it can be seen from the plot that a substantial proportion of the movement recorded occurred prior to 250 days i.e before the Eastbound tunnel drive. The magnitude of settlement generally decreases from south to north as the tunnel separation increases and effects from the deeper Westbound tunnel reduces. There is a slight trend to a very small increase in movements up to 1500 days.

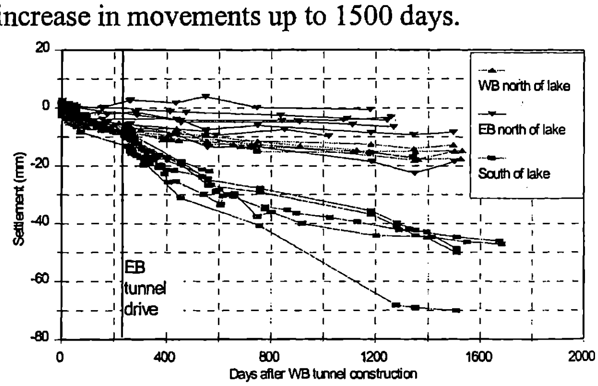


Figure 4. Measured increase in settlement after tunnelling

- South of the lake the data are similar to that for the Westbound up to about 250 days; the increase in the rate of movement at this time is due to the construction of the Eastbound tunnel. Most of the data points show similar overall behaviour but one point has a significantly greater magnitude. At least part of the scatter is attributed to seasonal effects as a number of points are close to mature trees within the park. A trend of continuing increase in settlement at 1500 days is evident for most of the data points.

Figure 6 shows data from four points to the south of the lake and includes both building and surface points. Two of the points are in the area of compensation grouting and two points are outside the grouting area. All of the data follows a similar pattern and bounds to the data shown on the figure indicate that virtually all of the individual data points fall within a range of about 7mm. It can be concluded that there are no significant differences in long term behaviour as a result of compensation grouting.

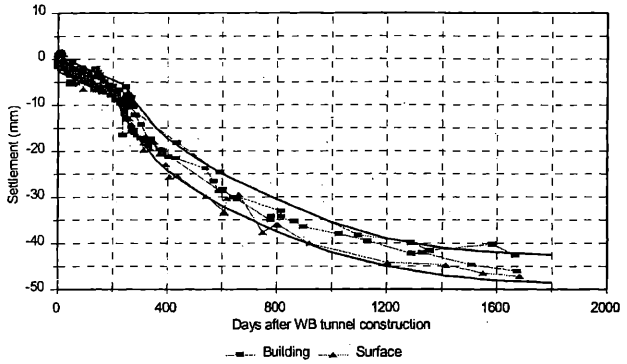


Figure 5. Settlements in areas with and without compensation grouting

6.4 *Distribution of consolidation settlement*

Consolidation settlements generally occur over a much wider zone than volume loss settlements with measurable effects up to 100m from the tunnels. The magnitude of settlements at the extremity of the trough for volume loss movements can be as high as 40mm with associated slopes of up to 1:1000. The slopes within the initial settlement trough can also be increased by long term settlement. The stiffness of structures appears to modify the shape of consolidation settlement profiles, but to a lesser extent than for immediate volume loss movements. This is generally beneficial in that it reduces the likelihood of damage occurring. Some evidence that concentration of strains can occur has been observed. Overall the contention that long term settlements are less problematic than volume loss settlement is supported by the data presented.

There are a number of notable exceptions to this conclusion where either absolute settlement or slope is the controlling criterion. Specific instances encountered on Contract 102 include the New Parliamentary Building (Harris, 2002A) and Big Ben and the adjoining Palace of Westminster (Harris, 2002B).

Examples of long term settlement profiles are shown on Figures 6 to 9. Short term movements based on observations, Gaussian curves fitted to observations or predicted Gaussian curves have been added to these figures to allow direct comparison of the magnitude and extent of the two different components of settlement. Figures 6 and 7 show profiles from within St. James's Park which are greenfield sites unaffected by buildings.

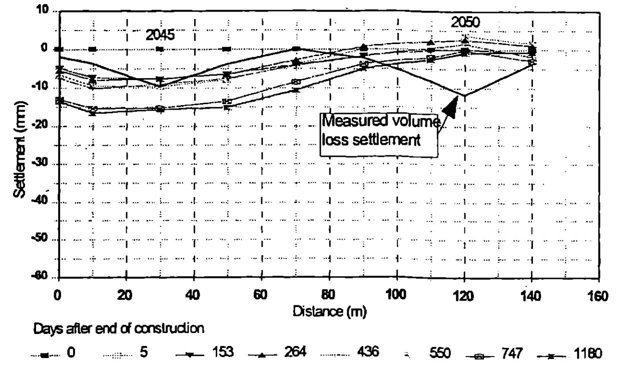


Figure 6. Volume loss and long term settlement north of lake

Figure 6 shows data from north of the Lake and illustrates the differing long term behaviour above the westbound and eastbound tunnels. Above the centreline of the westbound tunnel (point 2045) 10mm of volume loss settlement was recorded compared with over 15mm due to consolidation. Conversely above the eastbound tunnel (2050) a volume loss settlement of 12mm and virtually no consolidation settlement has been recorded. The consolidation settlement from the westbound tunnel is over a wider trough than the volume loss movement but the maximum change in slope is similar albeit at a 20m greater offset from the tunnel.

To the south of the lake, the tunnels are much closer together and Figure 7 shows that the volume loss movements from the two tunnels interact to produce a single peak settlement of just under 30mm. The consolidation settlement is also a maximum between the two tunnels and occurs over a much wider area and, although the data does not fully define its extent, the full width of the trough is about 200m. The maximum consolidation settlement is greater than the volume loss movement and at the edge of the volume loss trough, 40mm of consolidation settlement has been recorded.

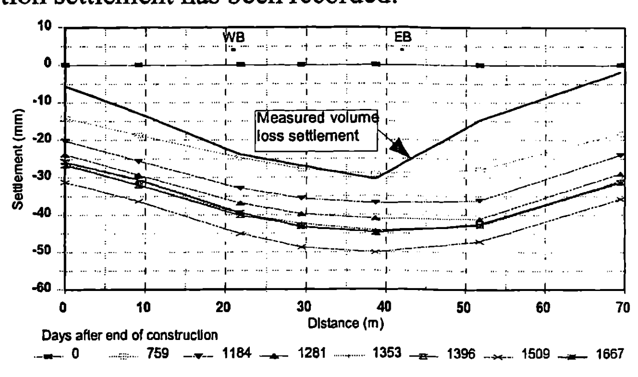


Figure 7. Volume loss and long term settlement south of lake

Figures 8 and 9 shows profiles at either end of the Treasury building. Figure 8 shows a profile including the facade of the Institution of Civil Engineers headquarters and the LINK research team monitoring (CIRIA, 1997) in the basement of the Treasury. The volume loss settlements for the westbound tunnel are shown as fitted Gaussian curves to the observations which showed a strong asymmetry due to the stiffness of the Treasury. A predicted settlement trough for both running tunnels is also shown based on the back-calculated volume loss values and a symmetric trough. The consolidation settlements are slightly asymmetric with a greater width shown below the Treasury building than the ICE building but, in contrast to the volume loss movements, the maximum settlement is not at the edge of the Treasury building but is close to the theoretical location of the maximum for the volume loss movements. The magnitude of the consolidation settlement is less than the volume loss settlement might have been if the compensation grouting carried out concurrently with the eastbound drive had not mitigated this element of settlement. Maximum settlement at the edge of the volume loss trough is 20mm.

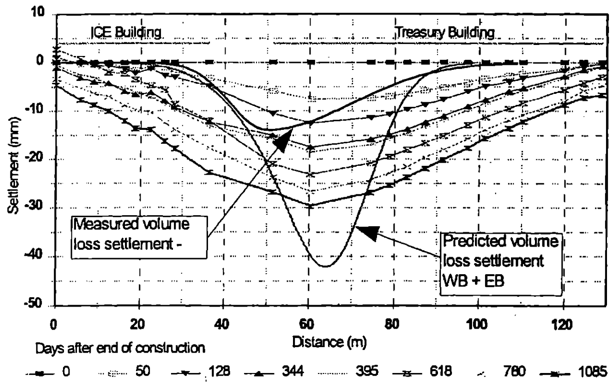


Figure 8: Long term settlement of Treasury & ICE Buildings

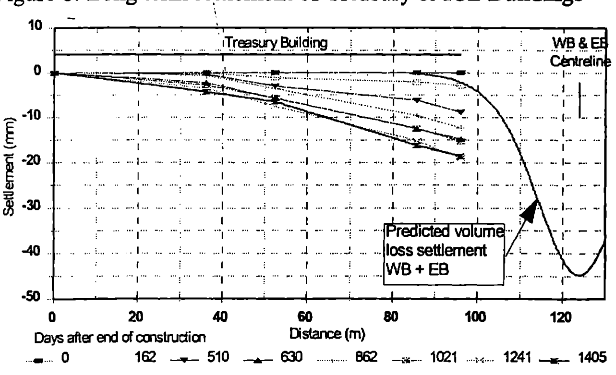


Figure 9: Long term settlement of Treasury East facade

Figure 9 shows the consolidation movements at the east end of the Treasury. The movement at a distance of 0m is zero by definition since this point has been used as a bench mark and is situated over 120m from the tunnel centerline. A settlement of 20mm is shown at the edge of the volume loss trough. A slight hogging deformation is shown but with a maximum slope of 1:3000.

7 CONCLUSIONS

The key conclusions with respect to long term consolidation settlement are:

- tunnels in London Clay act as drains and the associated reduction in pore pressure induces long term consolidation settlement;
- the magnitude of consolidation settlement varies significantly and can be substantial particularly at station locations (up to 100mm) but also above running tunnels (up to 50mm);
- consolidation settlement occurs over a period of 5 years or longer;
- a substantial proportion of consolidation settlement often occurs during construction period;
- measurable movements can occur at distances of 100m from a tunnel and 40mm movement can occur outside the volume loss settlement trough;
- consolidation settlements can be predicted using numerical analysis but detailed profiling of the London Clay is necessary to obtain realistic predictions;
- in general little damage is initiated by consolidation settlements alone but where damage has been induced during construction, or existing defects or lines of weakness exist, concentration of strain can occur and significantly increase the degree of damage.

ACKNOWLEDGEMENTS

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