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SURFACE AND SUBSURFACE STRUCTURAL RESPONSE ON THE CITY OF LONDON CABLE TUNNELS PROJECT

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Abstract

This paper presents surface and subsurface ground and structural response to the excavation of an urban cable tunnel within London clay and the Lambeth Group strata. Project specific tunnelling volume losses were estimated and found to be dependent on face advance and geology. The presence of adjacent buildings reduced predicted ‘greenfield’ settlements. The tunnel passed below a continuous section comprising basements, box rail tunnels and other structures. These structures generally responded at the level of their foundations. The presence of a pile group through which the tunnel passed only reduced surface settlement by ~50%. Passing below two existing segmentally-lined LUL tunnels these responded immediately and as predicted, although with somewhat increased trough widths indicating a stiffening effect. A multi-span bridge directly above the LUL tunnels on deep pier foundations, part of the Holborn Viaduct, settled more slowly and twice as much as anticipated. A possible general effect of tunnelling on heavily loaded foundations including end-bearing piles is discussed.

Keywords
Tunnelling, structures, surface, subsurface, settlement, trough, modification

Conference Theme:
The effect of building stiffness, different configurations and time.

1 INTRODUCTION

1. This paper is principally a case study of settlements monitored during construction of a cable tunnel. The next two sections describe the project settlement monitoring programme and the approach taken to measuring and predicting settlements. In Sections 4 and 5 a description and interpretation of measured surface and subsurface response is given.
2. Typical of such projects in the congested London environment, a major challenge was alignment selection and obtaining approval from interested Third Parties. Central to these aspects was the prediction of settlements and ground-structure interaction effects together with a detailed monitoring programme during construction.

2 PROJECT OUTLINE

1. The City of London Cable Tunnels project is part of the process to reinforce and upgrade the area’s electricity supply via 132 kV circuits. The project involved the installation of a 2300 m long 2.87m diameter TBM-excavated tunnel which influenced a wide range of surface and underground structures including buildings, utilities, over- and underground railway tunnels, the Holborn Viaduct, and underground car parks (Fig. 1).
2. The main tunnel route was driven using a Lovat TBM with the capability to operate either in open or closed face mode depending on ground conditions. A 180 mm thick pre-cast segmental lining was installed. This was typically an expanded lining where the alignment is straight, or bolted and grouted on curves or where ground conditions were difficult.

3. The strata encountered in the tunnel were weathered and unweathered (‘brown’ & ‘blue’) London Clay and the Lambeth Group / Woolwich and Reading beds.

3 SETTLEMENT MONITORING AND PREDICTION

1. Surface settlement was routinely monitored in the street above the tunnel alignment at intervals of ~50 m. Measurements were taken with a Zeiss Digital Precise Level and a bar-coded invar staff. Settlements were measured relative to 2 remote stable points at least 20 m from the alignment, with a third used to check closure. The monitoring system stability and field accuracy were good and estimated to be 0.1 mm.
2. One of the major difficulties with assessing the response of structures in urban areas is calculating the actual volume loss. Project specific volume losses in the first 1600m of the drive were therefore evaluated as shown in Figure 2.
3. Short-term surface settlements varied between 3 mm – 7 mm over the first 800 m of the alignment, and between 2 mm – 5 mm from Ch. 800 to Ch. 1650. Using procedures developed by Macklin (1999), which relate volume loss for clay soils to tunnel geometry, depth and undrained shear strength, the values given in Figure 2 were derived. These data were then used for settlement prediction at critical structures further along the alignment.

Figure 1: Cable tunnel project route map

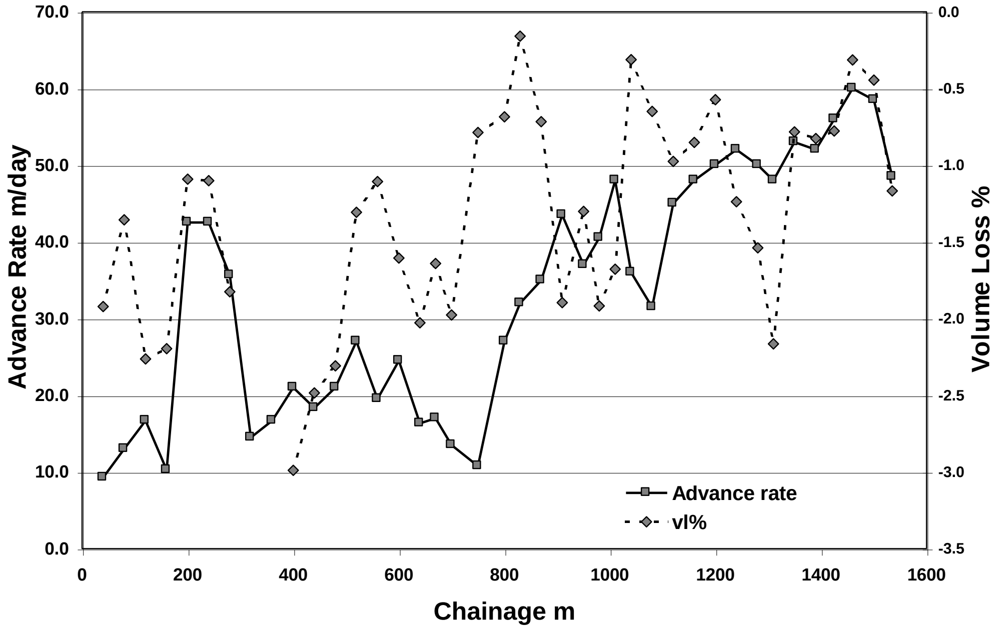

Figure 2 Project-specific volume losses vs advance rates to chainage 1650m

4. It was found that the volume loss typically varied from 0.5% to 2.5%, but that there was a correlation with the strata encountered in the drive and with the advance rate. The tunnel alignment was generally close to the bottom of the London clay beds, and sometimes entered the upper Lambeth Group. When this occurred, the advance rate slowed and the volume loss increased to 2.0% - 2.5%. Lenses of cohesionless water-bearing soil occurred in the Woolwich and Reading beds, which were associated with minor instabilities, caused difficulties with lining erection.
5. Between chainages 685 m – 705 m transverse settlements were also measured, giving the opportunity to assess the effects of adjacent structures on the settlement profile. Figure 3 shows settlements recorded on the carriageway and pavement in front of the building facades up to an offset of 7.5 m from the tunnel centreline. A best fit to the observed settlements is also shown. This is compared with a greenfield profile that would give the same centreline settlement, in this case requiring a volume loss of 1.8%. It is seen that the effect of the adjacent buildings is to significantly reduce both offset settlements and the trough width compared with the greenfield situation.

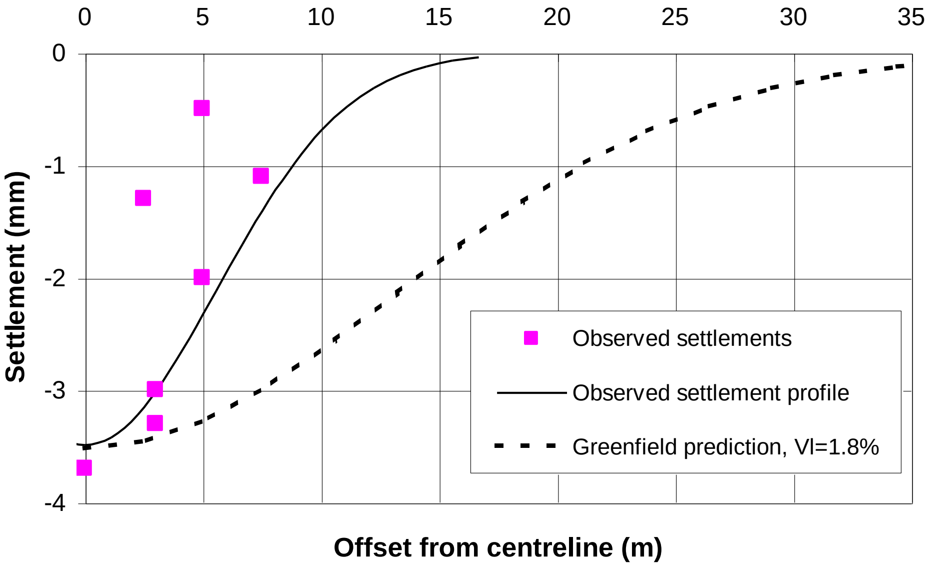

Figure 3: Settlements vs Offset from the Tunnel Centreline Chainages 685 – 705m

4 CHARTERHOUSE STREET

1. The cable tunnel passed along Charterhouse Street situated just north of the Smithfield Market for a length of 275m, running approximately under the centreline of the street. The tunnel axis depth was 20m below street level. The street is bordered on both sides by a variety of masonry buildings and is ~20m wide between building frontages. Due to the presence of a number of subsurface structures, for most of the length of Charterhouse Street the street level is not the actual ground level, as shown in Figure 4. Subsurface structures include cut and cover underground metro lines, an underground car park and building basements. The average founding level of these structures is 6m below street level, although some are piled deeper.
2. Monitoring by precise levelling was carried out along the centreline of the road and by means of studs attached to the building frontages. The location of monitoring points was chosen as far as possible to coincide with key subsurface structures so that the effects of the tunnelling operations upon them could be assessed.
3. Figure 5 shows the response of two points on the road 68 m apart to the passage of the tunnel heading. The average rate of advance of the tunnel at these points was 20m per day. The high quality nature of the data indicates a small heave ahead of the face, with a total short-term settlement of about 3mm. The short-term surface response to the passage of the TBM below takes two days at which time the face is some 40 m distant.

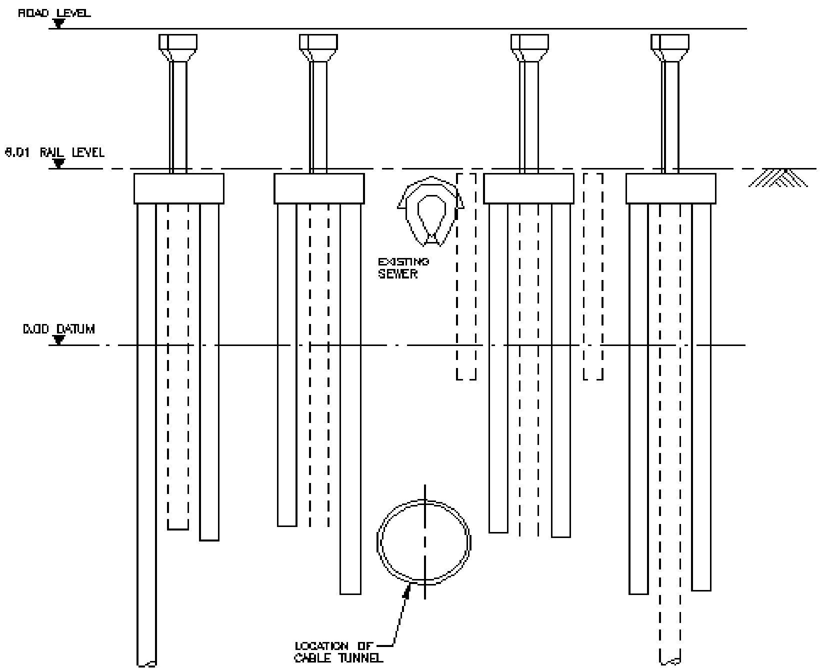

Figure 4: Tunnelling beneath piled railway sidings at Charterhouse Street

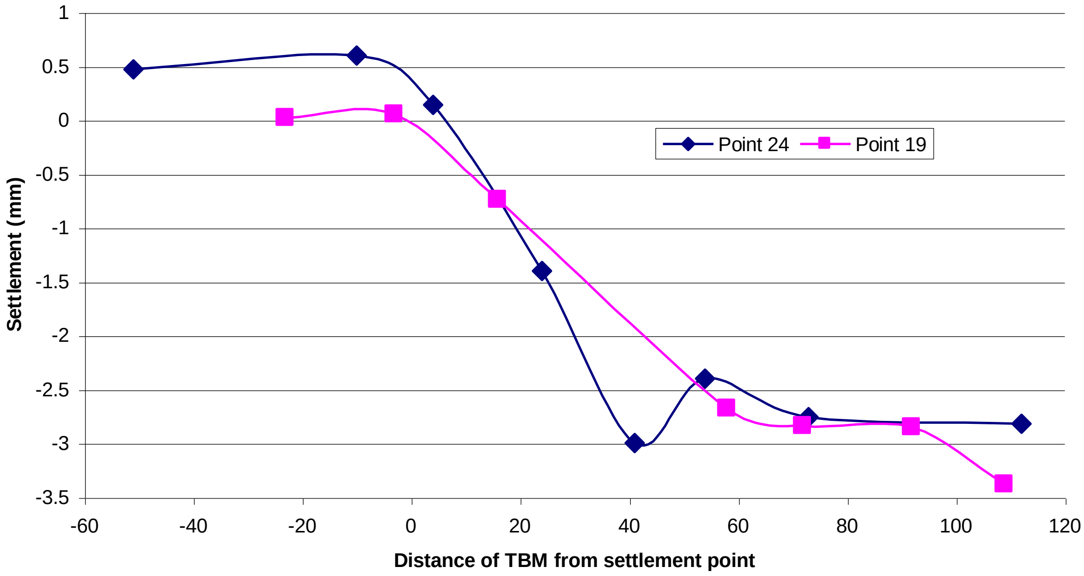

Figure 5: Response of typical settlement points to tunnel advance

4. Figure 6 shows the immediate settlements and the settlements observed after 4.5 months along the centreline of the street. The long-term settlements are an increase by a factor of 2 to 3 on the immediate settlements. This is a greater increase in the long term than is normally observed in tunnelling in London clay (typically a factor of 2), and may be due to the presence of many subsurface structures that respond more slowly than a greenfield site, thus reducing the apparent immediate or short term settlements.
5. As the drive proceeded along Charterhouse Street initially in London clay, it encountered the Lambeth Group at about Chainage 1900. Beyond this point the advance rate slowed significantly and the correlation from Figure 2 indicated that higher volume losses could be expected. In addition, at Chainage 1900 the TBM slowed for a 70 m radius as it turned out of Charterhouse

Street. The process of negotiating the curve, which involved using bolted-grouted linings and a very small amount of over-excavation, is not seen as significant. No additional settlement was noted on the curve at the top end of Charterhouse Street. The increased settlement observed at this location is most likely due to a combination of geology and reduced advance rate due to the locally steep tunnel grade.

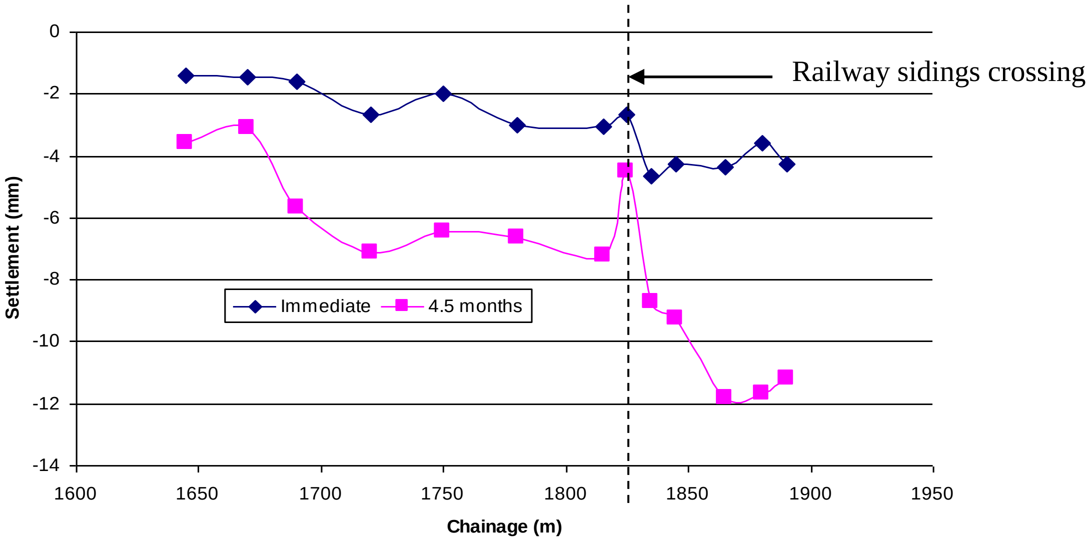

Figure 6: Short & long-term settlements along centreline Charterhouse Street

6. . The immediate settlements along the centreline of the street and on the facades on the north and south sides are shown in Figure 7. From these data, the surface trough width parameter *i* was estimated generally to be in the range 6m to 9m. A value of *i* of 10m might be expected for a greenfield tunnel 20m deep below ground level in London clay. The observed surface troughs were found to correspond to the general foundation level of the subsurface structures. Buildings were therefore responding at the level of their foundations.
7. One of the most interesting structures is situated where railway sidings pass underneath the street at Chainage 1825. The supporting piers beneath the street have been underpinned with large diameter bored piles, the toe levels of which range from axis level of the cable tunnel to 2m below invert level. It was necessary to choose the horizontal alignment of the tunnel to pass between pile groups (Fig. 4). It can be seen from Figure 6 above that although the settlements appear to reduce locally at Chainage 1825, there is still movement of over 4mm in the long term. This shows that vertical movement of piled structures still occurs even when the tunnel passes between pile groups rather than beneath them.

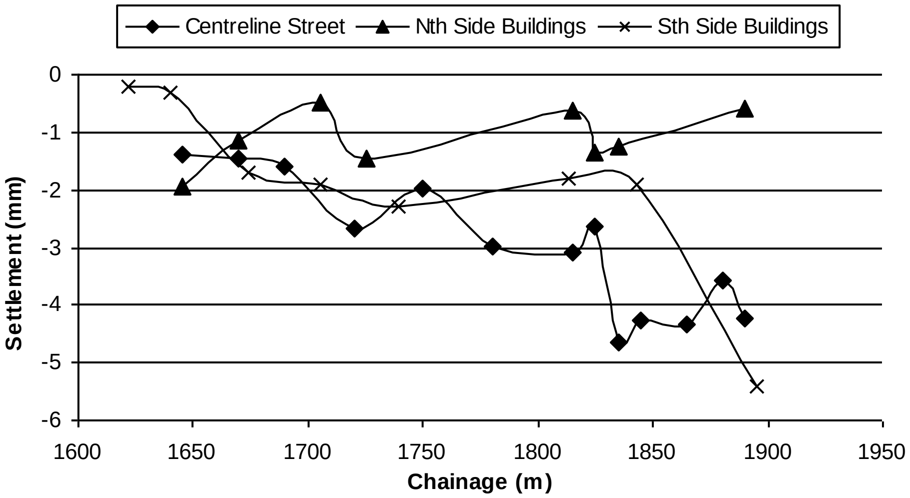

Figure 7: Street and building facade settlements along Charterhouse Street

5 FARRINGDON ROAD – CENTRAL LINE & HOLBORN VIADUCT

5a CENTRAL LINE

1. In Farringdon Road the cable tunnel passes beneath two existing London Underground Limited (LUL) Central Line tunnels (3.9m OD) and a surface bridge structure – the Holborn Viaduct. A unique aspect of the site is that the crossing occurs simultaneously beneath the surface and subsurface structures. Thus a single volume loss may be back calculated, which must apply to both structures.
2. The cable tunnel passed beneath the LUL tunnels at a skew of 35° and a minimum clear distance of 3.4m. The axis of the cable tunnel is 20m below ground.
3. The movements of the LUL tunnels were monitored continuously by electro-levels. The processed results of the settlements with distance along the tunnels during the passage of the tunnel heading on 16th/17th August 1999 and one month later are shown in Figure 8. The results show that the majority of the short-term settlements (approx. 90%) occurred immediately, with the small remainder over the following month after which monitoring ceased. The asymmetric development of the settlement troughs (due to the skew relative to the tunnel drive) with time may be clearly seen.
4. Prior to construction, predictions of the maximum movement of the LUL tunnels were made using the Kirsch equation (a lower bound elastic solution) and by the upper bound elastic-plastic mechanism analysis proposed by Mair and Taylor (1993). The resulting predictions were 5.3mm and 7.7mm. Thus the agreement between predicted and observed maximum movements is reasonably good and on the conservative side.
5. It is also important to be able to evaluate the width of the trough of the deflected existing tunnel structures to estimate the deflection ratio and predict damage. For this purpose, the settlements of the existing tunnels after one month were replotted against the perpendicular distance from the axis of the cable tunnel (Fig. 9). The Eastbound running tunnel is ~0.75 m closer to the cable tunnel, resulting in ~1 mm greater settlement.
6. The resulting trough shapes are approximately Gaussian, as commonly assumed in the literature, but with slight distortion with increased settlement on the centreline of the trough. This effect is likely to be due to the close proximity of the tunnels, and makes the estimation of a single trough width parameter '*i*' more difficult. A value of '*i*' of 4.0 – 5.0m is estimated for both tunnels. This compares with 3m estimated from the method of obtaining subsurface troughs assuming Greenfield conditions proposed by Mair et al (1993). The apparent volume loss calculated from the average of the eastbound and westbound results is 0.9%.

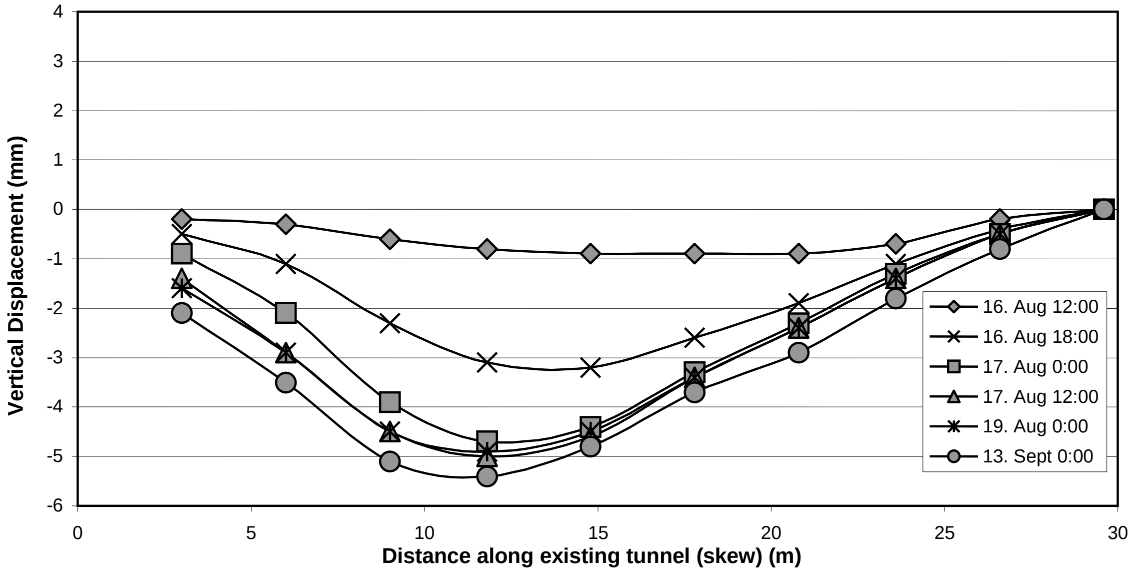

Figure 8: Observed Settlements along LUL Central Line Eastbound Tunnel

7. Thus the presence of the tunnel structures gives a wider apparent settlement trough than the greenfield situation. Although segmentally lined, the two running tunnels appear to have a stiffer response than the surrounding ground. This corresponds in general to the response of long continuous structures to tunnel excavation in close proximity discussed by Lu et al (2001).

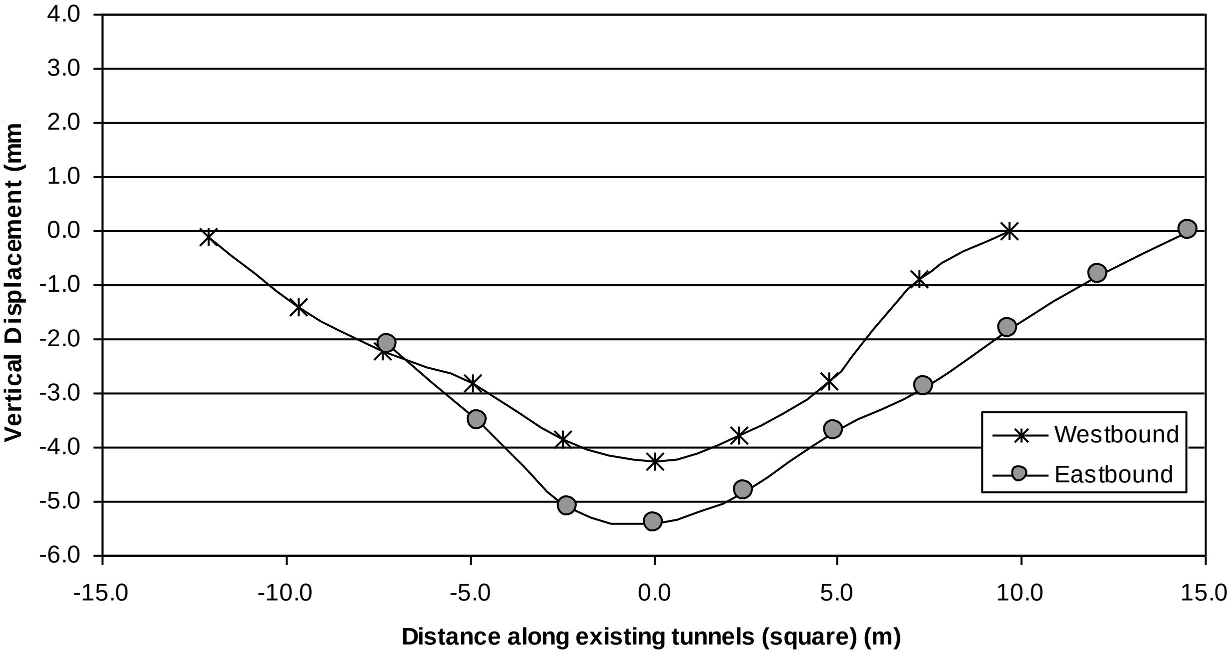

Figure 9: Final settlements of LUL tunnels against perpendicular distance from cable tunnel axis

5b HOLBORN VIADUCT

8. The other key aspect of this site was the response of the Farringdon Road Bridge. This structure forms part of the Holborn viaduct and is a three-span structure crossing over Farringdon Road. The viaduct itself was beyond the zone of influence of the tunnelling operations. The original structural form of the Bridge superstructure was cast iron arch ribs continuous over the two intermediate pier supports and simply supported on the two end abutments. These arch ribs have been overlain by a steel/composite concrete bridge deck that now carries all the traffic loading above. It was thus expected that this structure would be reasonably tolerant to differential settlement but may exhibit small longitudinal bending stiffness due to the arch ribs. The piers and abutments are of brick masonry construction, founded deep in the London clay, 10m below ground level and about 10m above the axis of the cable tunnel.
9. The cable tunnel was driven north to south along the centreline of Farringdon Road, crossing perpendicular to the bridge axis under the middle of the central span. Monitoring of the movements at the north and south sides of each of the abutments and piers was carried out as the tunnel passed. As stated above, the position of the bridge and the underlying LUL tunnels are approximately coincident.
10. The development of settlements at the north side of the Bridge with time as the tunnel passes is given in Figure 10. The response of the Bridge is somewhat slower than that of the LUL tunnels, taking several days to reach the final settlement.
11. Figure 11 shows the final settlements for the bridge's north and south data points together with predictions assuming the structure followed the greenfield subsurface trough (Mair et al 1993) at foundation level. The observed settlements are consistently greater than would be expected in the greenfield with the known 0.9% volume loss back-calculated at this location from the Central Line tunnel data. The settlements of the bridge in fact correspond closely with a 2% volume loss greenfield prediction. Hence the magnitude of the bridge settlements appears to be approximately twice what would be expected from following a greenfield response. The trough width appears

unmodified from greenfield conditions, indicating that the structure has responded with relatively little longitudinal bending stiffness as broadly expected.

12. The assumed explanation for the increased settlements is that the weight of the structure, acting below the piers, is interacting with the tunnelling-induced ground movements resulting in increased settlements. An approximate calculation is that the gross bearing pressure locally beneath the pier foundations is 400kN/m^2, which is twice overburden pressure.
13. The effect of building weight in driving increased settlements has been observed by researchers carrying out two-dimensional numerical analyses (e.g. Liu et al, 2000). In 2-D analyses, there is a limitation that the weight of the building as modelled increases the average vertical stress across the whole field, increasing the stability number of the excavation. This would be expected to increase volume loss and hence increase settlements. However in this case history, the weight of the bridge cannot possibly have a significant effect on the stability number at the tunnel due to the three-dimensional nature of the problem. The volume loss in any case is known to be unaffected at 0.9%. Thus it seems that another mechanism is occurring that allows the excess vertical pressure to drive settlements locally in ground affected by tunnelling excavation. This phenomenon is relevant to any situation where high concentrated loads act on the ground, such as end bearing piled foundations.

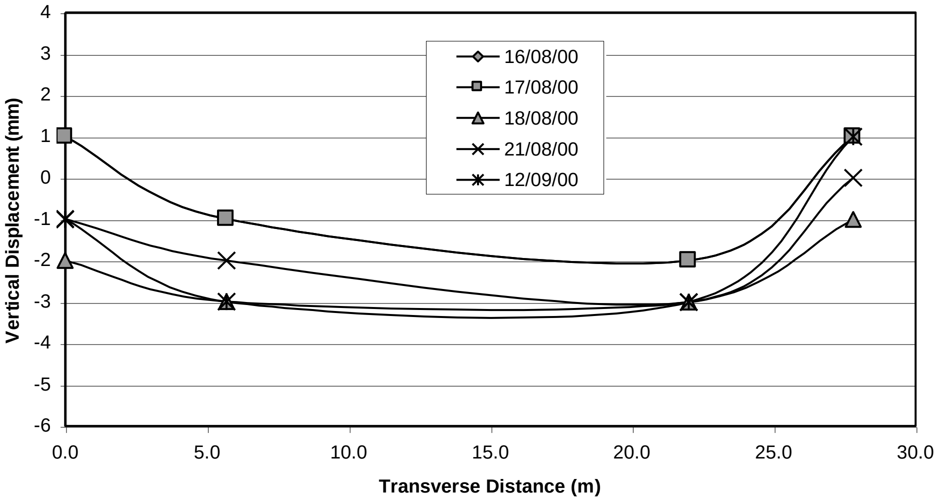

Figure 10: Development of settlements of north side of Farringdon Road Bridge

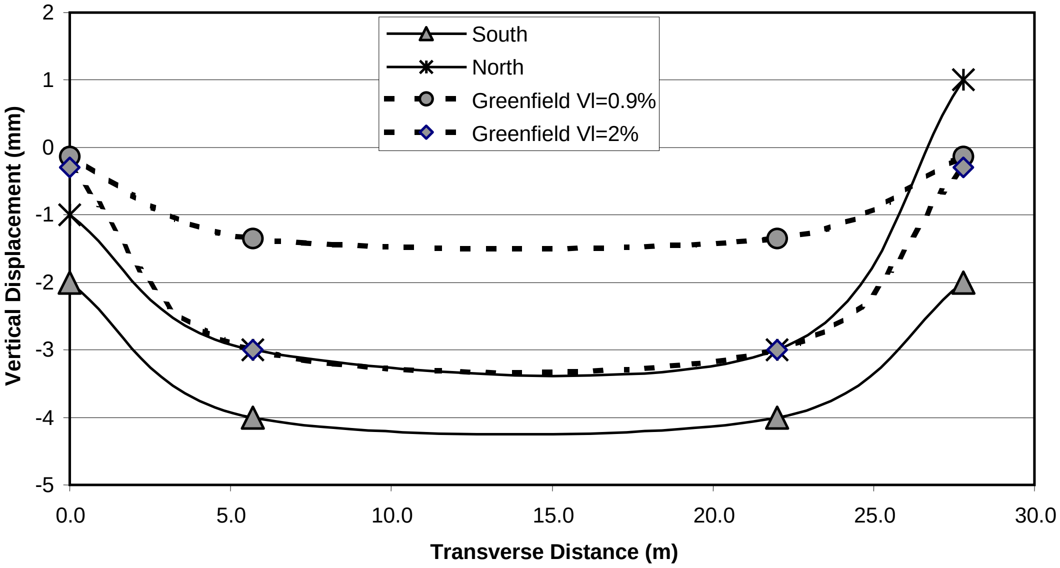

Figure 11: Final Bridge settlements and comparison with predictions assuming greenfield subsurface settlements

6 CONCLUSIONS

The subject of this paper is the observation of ground and structural response, both surface and subsurface, to the excavation of a cable tunnel within London clay and the Lambeth Group strata.

Project-specific tunnelling volume loss for the first 1600 m was estimated at 0.5% - 2.5%, with larger values associated with slower face advance and the Lambeth Group strata which included lenses of cohesionless water-bearing soil. Settlements away from the tunnel centreline indicated that adjacent buildings reduced greenfield trough widths.

The tunnel passed below Charterhouse Street, which is located above basements, box rail tunnels and other structures. The settlement data indicated that the structures responded at the level of their foundations. Short-term surface response appeared to be reduced by the presence of the structures and developed over some two days. Long-term movements occurred up to 4 months after tunnelling. The tunnel also passed between, but close to the base of, the pile groups of an underpinned subsurface structure. Vertical surface movements still occurred, indicating the sensitivity of piled structures to tunnelling works.

At another location, the tunnel passed within about 1.5 diameters below two existing segmentally-lined LUL tunnels. These responded immediately to tunnelling. Their deflected shape was essentially Gaussian but distorted by increased peak settlements. The value of peak settlement correlated quite well with established analytical methods of prediction for ground movements close to tunnel drives. The overall effect of the existing LUL tunnels was to widen the settlement trough compared to the Greenfield subsurface trough, indicating a stiffening effect.

At the same location the tunnel passed beneath a multi-span bridge on deep pier foundations, which is part of the Holborn Viaduct. The structure settled twice as much as anticipated, believed to be associated with the high foundation loads. This observation may have important consequences for assessment of tunnelling effects on heavily loaded foundations including end-bearing piles.

The prediction of deformations and structural response was made entirely using closed-form analytical solutions. Close correspondence was found between measured and predicted settlements.

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