Monitoring the impact of tunnelling-induced ground movements on a gas main and sewer

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Abstract

With increasing exploitation of urban underground space, understanding the response of utilities to tunnelling-induced ground movements and whether their serviceability might be compromised is crucial. This case study assesses surface ground movements and the response of a buried gas main and sewer beneath Farringdon Road, London to the construction of 7.8-m diameter Sprayed Concrete Lining (SCL) Crossrail westbound (WB) and eastbound (EB) tunnels. Field monitoring data are processed and analysed to interpret: the surface volume loss; subsurface settlements and horizontal displacements and strains in the sewer; and induced axial and bending strains in the gas main. These were compared with prediction methods commonly used in practice to estimate tunnelling-induced displacements. Details of the interpretation and analysis of the monitoring data are provided.

The data indicate that empirical predictive methods provided good representations of surface and subsurface settlements from construction of the first, WB, tunnel. However, there were increased displacements for the EB tunnel, resulting in a non-Gaussian settlement curve, although maximum settlement values were consistent, with volume losses calculated as 0.5% and 0.4% (WB and EB respectively). During the EB works, settlement of the sewer was better represented using a method that accounts for the stiffness of the sewer.

The calculated axial and bending strains in the gas main were not consistent with the values interpreted from the strain gauge measurements. The actual strains in the utilities were significantly smaller in magnitude compared with those predicted and also, significantly, smaller than thermally-induced strains. Overall, the gas main and sewer experienced very small strains and their structural integrity and durability were not at risk.

Keywords: Services/utilities, tunnelling, serviceability, displacements, bending and axial strains

1. Introduction

There is an ever-increasing concentration of ‘utilities’ buried beneath the streets, buildings and infrastructure of London. Maintaining the condition and functionality of these utilities is imperative to avoid consequent damage. In London, as in many of the world’s largest cities, surface congestion of buildings and roads, together with a growing population, is forcing more new construction underground in the form of deep basements and tunnels. Such construction gives rise to ground movements where many of the buried utilities are located. These need to be assessed in relation to the expected extent of the movements and their effect on the utilities in question. This paper concentrates on the effects of tunnel construction on a pipeline and sewer. Tunnelling-induced movements cause stresses and strains in the utility that can jeopardise its integrity and durability: a matter of considerable importance and concern to utility owners and designers alike.

Reliable predictions of ground movement around tunnels can usually be made for greenfield conditions (where no structures are present). The schematic in Fig. 1a shows typical tunnelling-induced movements. Settlement magnitudes and extents depend on the tunnelling method adopted and the ground conditions. These also control ‘volume loss’, (V_L), the inward ground movement that occurs due to stress relief when a tunnel opening is excavated. Volume loss is expressed as the volume of inward movement divided by the tunnel volume (per metre advance). When assuming undrained conditions, the ground volume moving into the tunnel opening is taken to be equivalent to that of the surface settlement trough. A permanent ‘transverse’ trough develops perpendicular to the tunnel. This in most cases has the form of an inverted Gaussian distribution curve and is usually the focus of predictions. Surface settlement can be estimated using Eqn. 1 (Burland, 1995).

$$s = \frac{0.313 V_L D^2}{i^2} e^{\frac{-y^2}{2i^2}} \qquad \text{(Equation 1)}$$

where s = settlement, D = tunnel diameter, y = horizontal offset (see Fig. 1a&b), and i = distance to the point of inflection. The distance i is usually estimated as the product Kz_0, where K is the trough width parameter, which falls in narrow ranges and z_0 is the depth to the tunnel axis (O'Reilly and New, 1983). Horizontal displacement, u, can be estimated using the point-sink assumption shown in Fig. 1c and similar triangles, Eqn. 2.

$$u = \frac{sy}{z_0} \qquad \text{(Equation 2)}$$

Horizontal strains, ε_h, can then be determined by differentiating the displacements. It is well established that subsurface settlement troughs become narrower and deeper with depth (Mair et al., 1993). This is relevant when assessing underground structures such as the sewer and gas main.

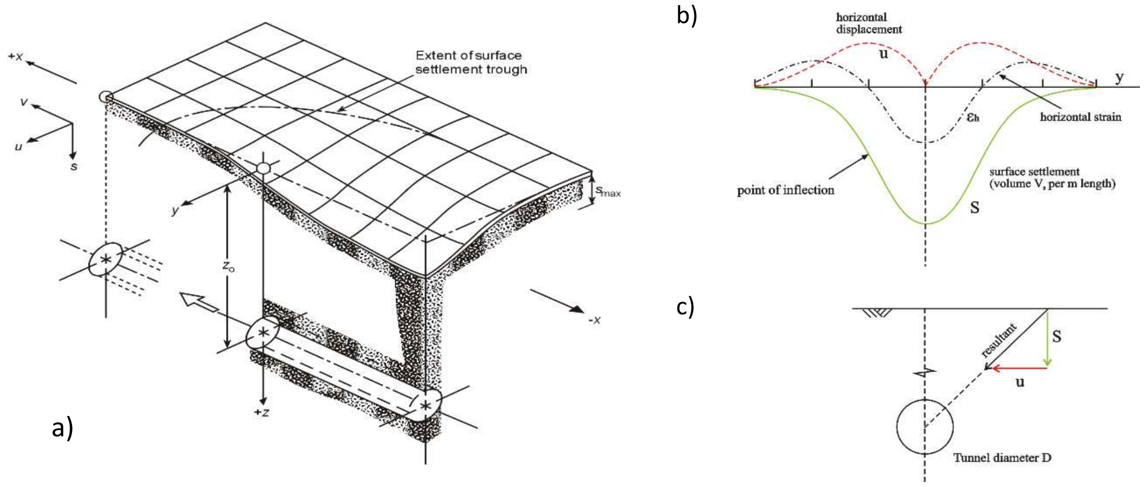


Figure 1: Greenfield surface ground movements from tunnelling: (a) 3-D representation (Attewell et al., 1986); (b) transverse profiles of settlement, horizontal displacement and strain; and (c) point-sink assumption for determining horizontal displacements.

When surface or subsurface structures are present, complex soil-structure interactions take place. These modify the greenfield response to tunnelling, depending on the relative ground-structure stiffness and the geometry of the structure (Potts and Addenbrooke, 1996). Predicting structural responses is challenging: an example of how the presence of a pipeline affects the ground response to tunnelling is shown in Fig. 2. Differential settlements are critical, and the pipeline can distort both longitudinally and circumferentially. In the scenario in Fig. 2, curvature of the pipeline leads to bending strains, while horizontal displacement of the adjacent soil causes axial strains. These must be within the respective limits of the pipeline so that it is not at risk of failure. To estimate the response of buried pipelines to tunnelling, the resulting ground movements need to be analysed to obtain bending and axial strains and these need to be assessed accounting for relative soil-pipeline stiffness. The type, spacing and relative position of joints is another key factor, and the pipeline may be considered to behave in a rigid or flexible manner (Moser, 2001). Such considerations are outside the scope of this paper.

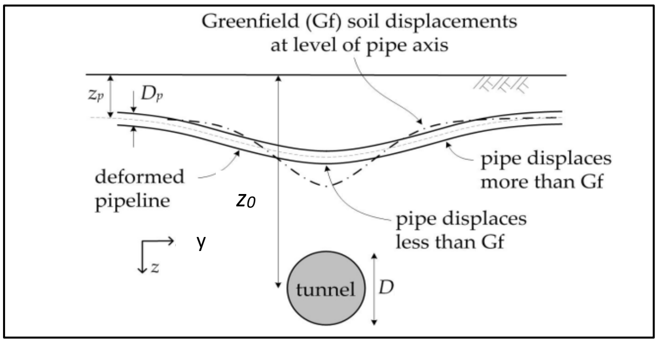


Figure 2: Effects of ground movements induced by tunnelling on buried pipeline (after Marshall, 2009).

The Crossrail project involved extensive tunnel construction and as part of the risk mitigation, risk assessment analyses were undertaken for all affected structures, including buried utilities. The identification/assignment of risk is critically dependent on the reliability of the ground movement predictions. Given the limitations of predictions and the uncertainties in the response of utilities to ground movements, monitoring plays a vital role in risk mitigation and in developing more reliable analytical approaches for the future. In this paper the monitoring data relating to a sewer and gas main adjacent to Farringdon Station, are appraised and analysed. In some instances, the data were provided in a processed form, thus precluding the opportunity to process from the raw data. This is discussed where appropriate and consequent limitations explained.

2. Crossrail site at Farringdon Road

Farringdon Road is located between Barbican and Chancery Lane stations in Central London. The WB and EB Crossrail tunnels intersect perpendicularly Farringdon Road, a 36'' gas main and a 3.0 m diameter masonry brick sewer. Tunnel alignments are shown in Fig. 3 (green) along with the gas main and sewer (yellow and orange respectively). The tunnels are of 7.8-m diameter with the tunnel invert level at about 28 m bgl (below ground level). Fig. 4 shows a cross-section of the WB tunnel with respect to the gas main and the Fleet sewer.

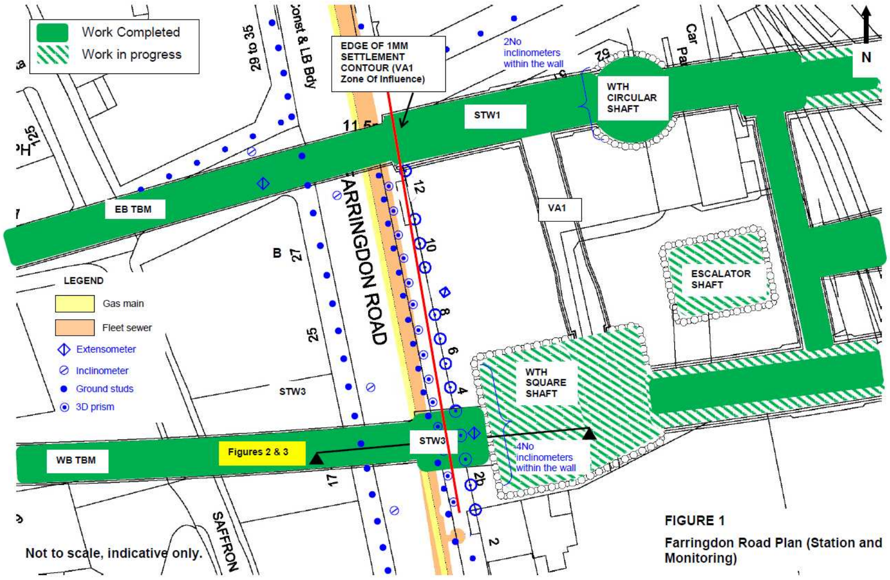
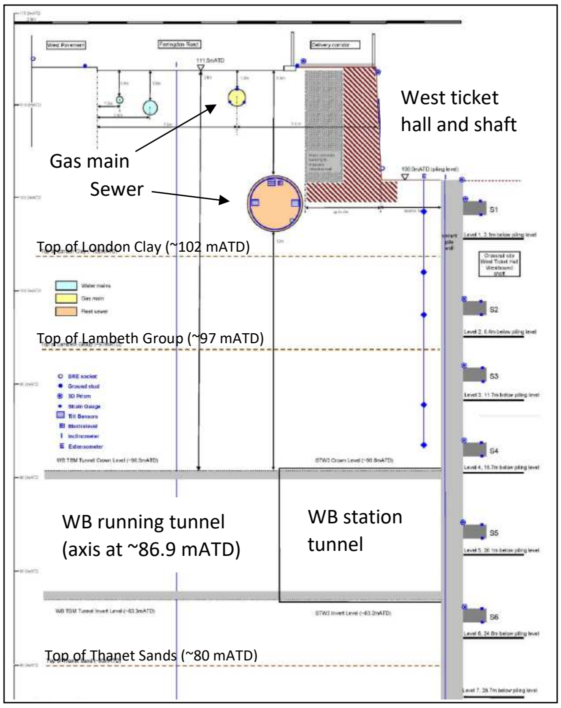


Figure 3: Farringdon Road tunnel alignment relative to gas main and sewer and instrumentation locations (Crossrail, 2014).

A free-standing 6-m high and 2-4 m thick masonry retaining wall, built in the 19th Century, supports Farringdon Road and lies between the sewer and ticket hall, as shown in Fig. 4**Error! Reference source not found.**. The geology at the site is typical of that in London, comprising Chalk overlain by the Thanet Sands, Lambeth Group and London Clay, the upper levels of these latter formations are marked in Fig. 4. Made Ground, of varying thickness, overlies the London Clay. The gas main and sewer are within Made Ground while the WB and EB tunnels were driven in the Lambeth Group.



Gas main

The 36'' gas main (~0.91 m diameter with 25.0 mm wall thickness) was constructed in 1890 and is a low-pressure cast iron pipe. Its embedment depth is about 1.5 m bgl and 2.4 m offset from the East pavement as shown in Fig. 4. The joints are every 3-4 m and 16 m above the Crossrail tunnel crown. The mains pipe was deemed to be in good condition from the findings of a CCTV survey (Crossrail, 2013). The survey found that the joints had been fitted with Weco seals, i.e. rubber rings placed around the joint inside the pipe.

Fleet sewer

The sewer was constructed to deal with the pollution problem in London during the 1800s (Crossrail, 2014). It was originally brick built and is now partly lined with composite concrete and reinforced concrete. The sewer is embedded to a depth of 5.5 m below street level and is 3 m in diameter. It is located 1 m behind the retaining wall and 12 m above the WB and EB tunnel crowns. The condition of the sewer at that time was unknown.

Figure 4: Cross-section through Farringdon Road and WB tunnel alignment relative to gas main and sewer (Crossrail, 2014). Note that the ground surface level is 111.5 m ATD (above temporary datum).

2.1 Crossrail construction works

Various stages of construction and excavation took place, starting with a secant piled wall installation for the ticket hall and shaft, then partial shaft excavation, followed by tunnelling. Stages of the construction sequence at the site are described in Table 1. The focus of this paper is the response of the ground surface, sewer and gas main to stages 3 and 4, i.e. running tunnel construction, and most monitoring data are presented incrementally for each of these stages. The tunnels were constructed using the sprayed concrete lining (SCL) technique.

Stage	Construction activity	Start date	End date
1	Secant piling works	20/09/2011	23/04/2012
2	Ticket Hall partial excavation of shaft (SHW2)	08/05/2013	30/04/2013
3	WB tunnel construction	09/09/2013	17/09/2013
4	EB tunnel construction	14/12/2014	23/12/2013
5	WB station tunnel enlargement (STW3)	05/01/2014	12/01/2014
6	EB station tunnel enlargement (STW1)	26/03/2014	24/04/2014
7	Ticket Hall shaft full excavation (SHW2)	11/04/2014	09/05/2014

Table 1: Summary of construction stages at Farringdon Station area (Crossrail, 2014).

2.2 Monitoring information

Various monitoring schemes were set up to assess surface and subsurface ground and structural responses as shown in Fig. 3. The systems referred to in this paper are briefly detailed below, along with any uncertainties arising from the fact that the authors themselves were not involved with the monitoring.

East pavement monitoring (Farringdon Road)

Road studs or pins were installed in the pavement overlying the sewer (see Fig. 3). The data supplied are expressed to 0.01 mm and so it is thought that precise levelling would have been used. Surveys were done several times a week and twice daily during periods of intense activity. 3D prisms for total station monitoring were also installed but have not been accessed. Chainages for the road studs are given in Table 2 and have been combined with other key chainages.

Vibrating wire strain gauges

Vibrating wire (VW) strain gauges were installed at seven locations along the gas main, as detailed in Table 2. At each location a pit was dug to expose the gas main and the gauges installed at three positions around its outer surface, an example is shown in Fig. 5. Gauge positions varied, presumably according to ease of access. The readings were generally taken every 3 hours and strain gauge data were provided in the form of (frequency)^2, ($\Delta 350\text{Hz}^2 = \Delta 1\mu\varepsilon$).

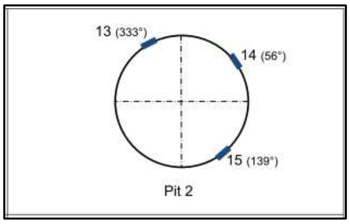


Figure 5: Strain gauge locations on gas main at Pit 2 (Crossrail, 2013).

Description	Chainages (m)	
	from	to
EB centre-line	161	
Zone 1: -2iEB to +2iEB	138	184
WB centre-line	212	
Zone 3: -2iWB to +2iWB	189	235
Levelling studs (east Farringdon Road)	235	278
Strain gauges (on gas main) (Pit numbers given in brackets)(* installed at a later date)	148.1 (1); 167.4 (2); 186.1 (3); 208.0 (4); 227.6 (5); 249.7 (6); 232 (7*)	
Electrolevels (sewer crown: 3-m long beams)	136.5	266.0
Crackmeters (sewer: 1-m long beams)	127.8	258.6

Table 2: Summary of tunnel locations and extent of instrumentation given in terms of chainages.

Electrolevels

Electrolevels mounted on 3-m long beams were installed along the crown of the Fleet sewer over chainages given in Table 2. The instruments were installed after the completion of the partial excavation of the shaft (to 7 m bgl) with measurements recorded hourly. Electrolevels measure rotation and so these need to be integrated along the length of the string of beams, usually done assuming that one of the ends is beyond the zone of influence. The data provided had already been converted to displacements and raw data were not provided.

Crackmeters

Crackmeters were located on one side of the sewer at axis level, as shown in Fig. 4 with readings taken hourly. They were installed after construction of the WB running tunnel and so data are only available for the EB drive. The extent of the crackmeters is given in Table 2. Although referred to as 'crackmeters', each one consists of a VW strain gauge mounted on a 1.0-m beam length. The data were provided in terms of horizontal displacements (mm) which had already been calculated from the strain gauge readings.

3. Field monitoring results

In the following sections, the field monitoring results are presented and discussed. The steps taken in appraising the data are described and commented on. The ground response to the tunnelling, based on the levelling data is assessed and compared with Gaussian profiles. The responses of the two utilities are then presented in terms of settlements and strains. The accuracy of the data and various contributing factors are then discussed. Recommendations are given concerning the monitoring data and achieving better results.

3.1 Initial assessment of monitoring data

A sensible first step to assessing field monitoring data is to plot the raw readings with time for the duration of the monitoring period and in particular at the start when ideally there are a number of base readings taken prior to any construction activities. Appraising the data in this way helps establish its accuracy and identify any drifts or trends in the data, that may result from sources such as malfunctioning or seasonal and thermal effects. It is also useful to mark on the plots the events from the construction time-line (given in Table 1).

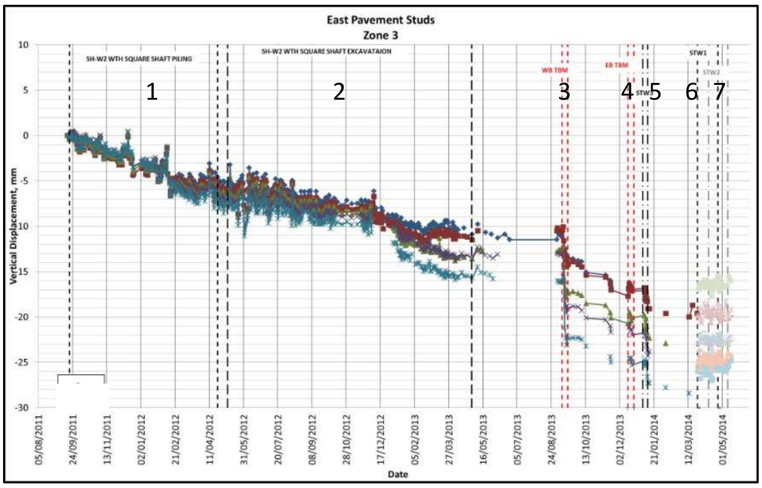


Figure 6: Precise levelling data from Zone 3, east Farringdon Road (stages from Table 1 marked).

Levelling data from the road studs in Zone 3 of Farringdon Road, covering the expected width of the WB tunnel settlement trough (chainages given in Table 2) are presented in Fig. 6. This zone also covers the extent of the shaft excavation (see Fig. 3) as reflected by the 5 to 8 mm settlement during secant pile wall construction, which is followed by further settlement from excavation (Stage 2, Table 1). During WB tunnel construction settlements increased by about 5 mm to give a maximum settlement of 22-23 mm.

When assessing points away from any construction, e.g. at chainage 278.0 m (58 m away from WB tunnel axis), vertical displacements are within about ± 2.0 mm, reflecting the accuracy of measurements (which is not high for precise levelling). By the end of the tunnelling works, the overall maximum settlement was about 25 mm.

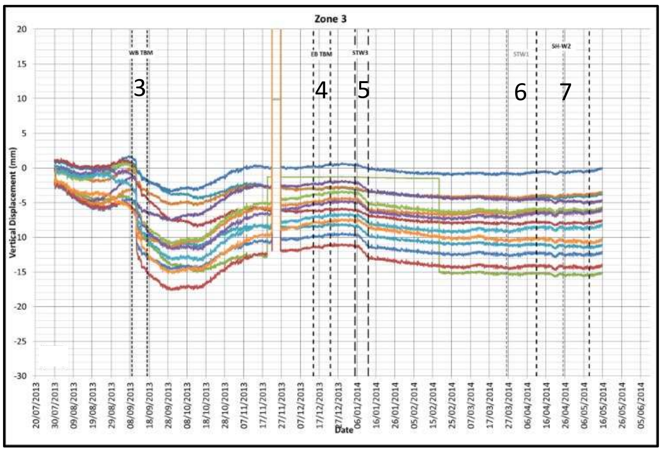


Figure 7: Electrolevel data from Zone 3, within sewer (stages from Table 1 marked).

The electrolevel strings installed along the crown of the sewer were used to determine vertical displacements which are shown for individual beams spanning Zone 3 in Fig. 7. These devices were installed almost two years after the road studs. Prior to the WB tunnel construction there are small settlements (~6 mm maximum), followed by small heave (~2 mm), for unknown reasons. All devices indicate settlement during the WB drive. No response is registered during the EB drive but small degrees of settlement occur later during station tunnel excavation. Scatter in the data during periods without activity indicate an accuracy of about ± 0.5 mm.

3.2 Comparison and back-analysis of the monitoring data

In this section the field data are back-analysed to quantify the effect of the tunnelling on the gas main and sewer. The interpreted results are compared with those estimated using current predictive methods. Measurements of the tunnelling-induced *surface* settlement are shown in Fig. 8 (solid blue/green lines) and used to estimate the volume loss (V_L) which was 0.5% and 0.4% for WB and EB drives respectively. A Gaussian curve (solid red line) was then fitted to the measured data. Deeper and narrower subsurface Gaussian settlement troughs are formulated using the Mair et al. (1993) approach using the surface V_L values (dashed red lines) and compared with the *subsurface* profiles determined from the electrolevel beams (dashed blue/green lines).

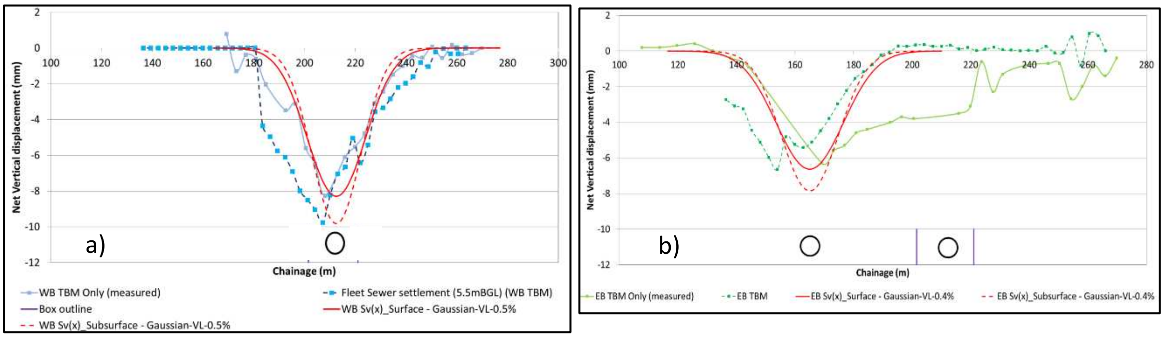
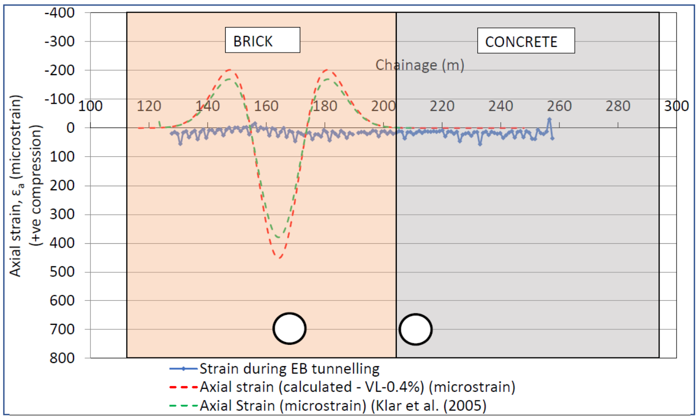


Figure 8: Vertical displacements from road stud levelling and sewer electrolevels, for Stages: (a) 3 and (b) 4.

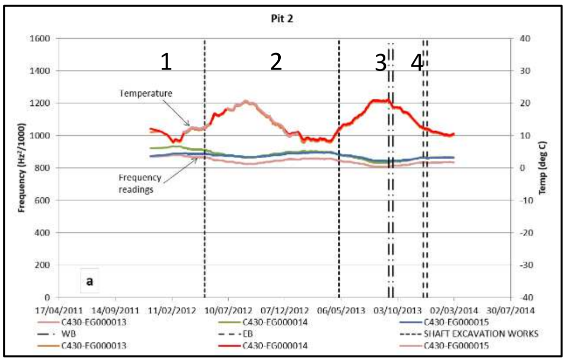
Both the monitored surface (pavement) and subsurface (sewer) settlement troughs are not that well defined, especially at the surface for the EB drive (Fig. 8b). This seems surprising but the settlements are quite small (maximum of 8 mm) and perhaps arises from studs installed in unstable paving slabs. The electrolevel data are better, being fixed in place, the end points appear stable, confirming this assumption. Occasional jumps might result from faulty individual devices. If the raw data were available, these could probably be eliminated. The measured subsurface settlements are slightly greater than those at the surface as expected.



Horizontal strains measured within the sewer from the string of 'crackmeters' are presented in Fig. 9 along with greenfield predictions based on the approach described in Section 1 and Fig. 1 using the appropriate WB V_L = 0.4% (dashed red line). A formulation taking the sewer stiffness into account (Klar et a., 2005) is also shown (dashed green line). It is evident that even accounting for the sewer stiffness, the measured horizontal strains are about an order of magnitude smaller than those predicted. Zones of compressive and tensile strain in the former are not identifiable.

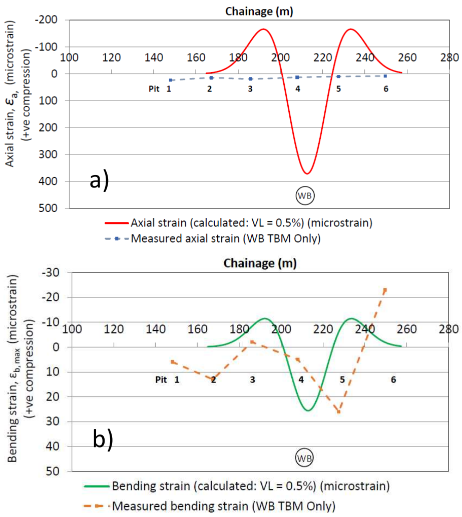
Figure 9: Horizontal strains from crackmeters within sewer, for Stages 4.

Horizontal displacements were also determined from the crackmeter data and were assessed in the same way as the levelling and electrolevel data (Figs. 6 & 7) and were stable with an accuracy of better than ± 0.1 mm. When plotted against chainage, as might be expected, no trends were evident, as observed with the strains. The sewer stiffness and slippage between the ground and the sewer has restrained their development.



Raw data from the strain gauges attached to the gas main (e.g. Fig. 5) were plotted with time to identify trends or irregular behaviour. It is evident from Pit 2 data shown in Fig. 10 that they respond to temperature changes (red lines) as might be expected from thermal expansion or contraction of the cast iron main and potentially from the gauges themselves (even if temperature compensated). Temperature changes have a far greater influence than tunnelling activities (Table 1 stages marked on Fig. 10).

Figure 10: Data from gas main strain gauges in Pit 2.



The strain gauge data were analysed to determine axial, ε_a, and maximum bending, $\varepsilon_{b,max}$, strains using an approach broadly similar to that described by Attewell et al. (1986). A neutral axis position is established between the three gauges based on their relative positions around the main in conjunction with their output. Axial strains from Stage 3, WB tunnel drive, are presented in Fig. 11a along with predicted values. The latter are much greater than the measured values which indicate an overall compression along the monitored length. Incremental strains for the EB drive were also smaller than predicted but more consistent with the expected trend. Maximum bending strains (Fig. 11b) were much smaller than axial but broadly in line with predicted magnitudes and trends. Small differences in offsets could result from discrete pit locations and the fact that the gas main comprises jointed pipe sections.

Figure 11: Incremental data from gas main strain gauges for WB tunnel drive (Stage 3) in terms of (a) axial and (b) bending strains.

4. Conclusions

The Farringdon Road monitoring data allowed the response of the gas main and sewer to be analysed. Surface settlements from the SCL tunnel drives were reasonably well predicted using the Gaussian formulation. As the two drives were about 6D apart there was little interaction between them. Volume losses were lower than expected ($V_{L\,WB}$ = 0.5%, $V_{L\,EB}$ = 0.4%). Over-estimation of V_L led to large settlement and strain predictions for the gas main and sewer, resulting in extensive monitoring to assess their response to the construction works.

Predicted axial and bending strains in the gas main, based on expected greenfield responses, generally did not fit the measured data well with much smaller strains, e.g. $\varepsilon_{a,max}$ = 20 με c.f. 370 με predicted, readings verging on the device accuracy. In appraising the strain gauge data, output from erratic or non-responsive devices were ignored: it is important to assess all raw data carefully before embarking on detailed analysis and interpretation.

The sewer settlement trough was deeper and narrower than that at the surface. Horizontal displacements were significantly less than predicted, suggesting that the ground moved relative to the sewer. The small strains measured in the sewer and gas main indicate that the tunnelling had little impact on their structural integrity.

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