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Ground movements caused by tunnelling with an earth pressure balance machine: A greenfield case study at Southwark Park, London

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ABSTRACT: This paper reviews ground movements induced by a 5m diameter earth pressure balance machine at an extensively monitored greenfield site on Contract 105 of the Jubilee Line Extension. Tunnelling was at a depth of 21m through dewatered dense granular soil. Only small ground movements occurred: a maximum settlement of 5mm was observed at the ground surface and 12mm just above the tunnel crown. Movement in front of the tunnelling shield was negligible, most settlement was associated with convergence of soil around the shield and into the tail void. Long-term monitoring has shown no evidence of consolidation; in fact seasonal surface ground movements are of similar magnitude to those caused by the tunnelling. Tunnelling machine parameters measured during the drives are presented and discussed in relation to the ground movements.

1 INTRODUCTION

On the Jubilee Line Extension in London, Southwark Park was chosen as a primary greenfield site to measure ground movements due to earth pressure balance (EPB) shield tunnelling through the variable conditions of the Lambeth Group. Surface and subsurface ground movements were monitored - the emphasis being to capture each phase of ground movement in conjunction with tunnelling activity.

2 GROUND CONDITIONS AND INSTRUMENTATION

The soil profile at Southwark Park is detailed relative to the position of the tunnels and instrumentation in Figure 1. The tunnels were bored through Glauconitic sands with the invert perhaps close to the interface with the Thanet Sands. The Glauconitic sands comprise a stiff sandy clay at the tunnel crown but change to dense fine and medium sands through most of the face. The Thanet Sands are also a dense fine to medium sand. The axes of the twin 5m diameter tunnels are at a depth of 21m and are 27.5m apart. The westbound tunnel was bored first beneath the instrumentation in January 1996; the eastbound tunnel was constructed beneath the site in June 1996. Due to the 5-month gap between tunnelling episodes it has been possible to separate the effects of each tunnel. The dense granular layers surrounding the tunnels were dewatered prior to the construction of both tunnels. The dewatering was a consequence of the deep level pumping undertaken during the construction of Canada Water station, some 400m to the east of the Southwark Park monitoring site. The instrumentation includes a line of surface settlement points aligned transverse to the tunnels (arranged at 2.5m spacings) and an array of magnetic extensometers installed within seven boreholes positioned above and between the tunnels. Along each of the borehole extensometers, magnets are positioned at up to 10 different depths. Further details of the instrumentation and monitoring techniques are given by Standing *et al.*, 1996 and Standing *et al.*, 2001. At depths of approximately 1m, 4m, 10m and 15m, measured ground movements were used to derive volume loss and transverse settlement trough parameters.

3 TUNNELLING MACHINE

The Kawasaki earth pressure balance machine was 5.03m in diameter and 6.95m long (Fig. 2). The screw conveyor feeds into the front chamber below axis level. Excavation and spoil removal was aided by the injection of foam through six ports at the cutting face (one on each cutting arm). The ports are arranged at various radii. Each ring of the lining is 1.2m long and is assembled within the tail of the shield. A ring is constructed from five precast concrete segments plus one key segment. Segments in a ring are bolted circumferentially and longitudinally (to the segment in the adjacent ring). The external diameter of the lining is 4.900m. There is nominally a maximum gap of 130mm behind the shield between the excavation and the lining at the crown. Use of the copy cutter at the cutting face would increase the size of this gap, but at Southwark Park the copy cutter was not used. A system of back-fill grouting was employed, grout being injected through the lining two rings behind the shield tail with every ring advance.

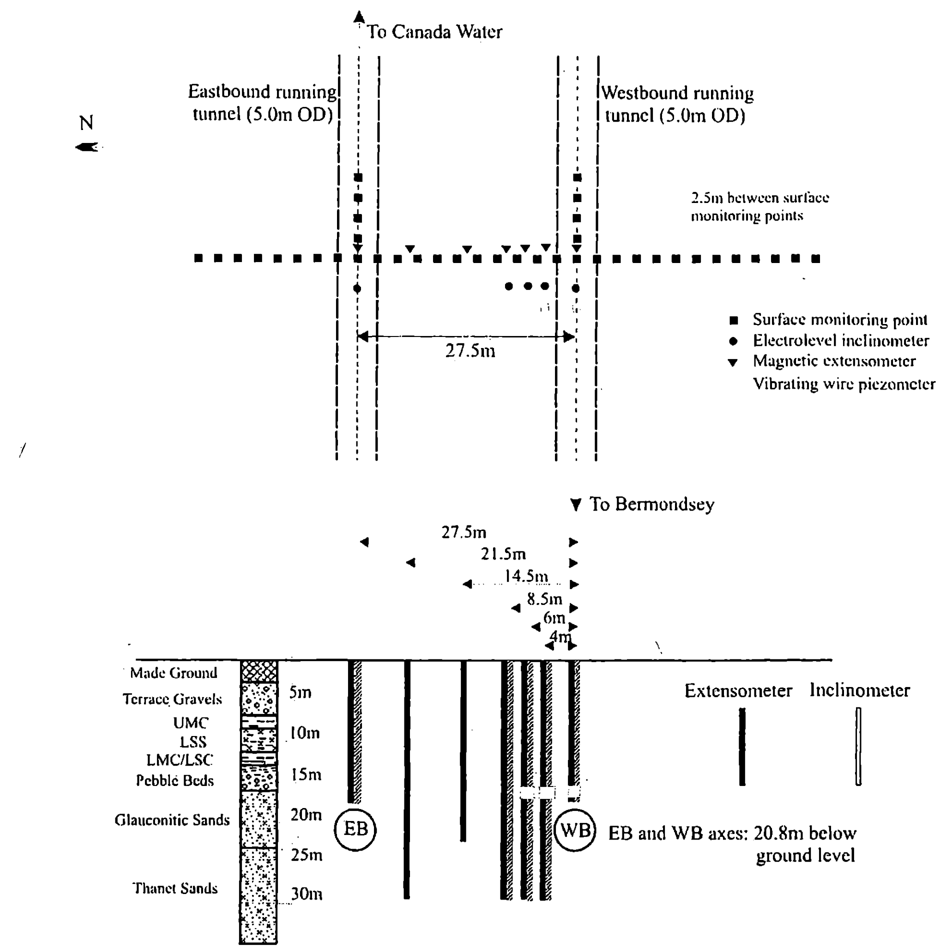


Figure 1. The soil profile, tunnels and instrumentation at Southwark Park greenfield site

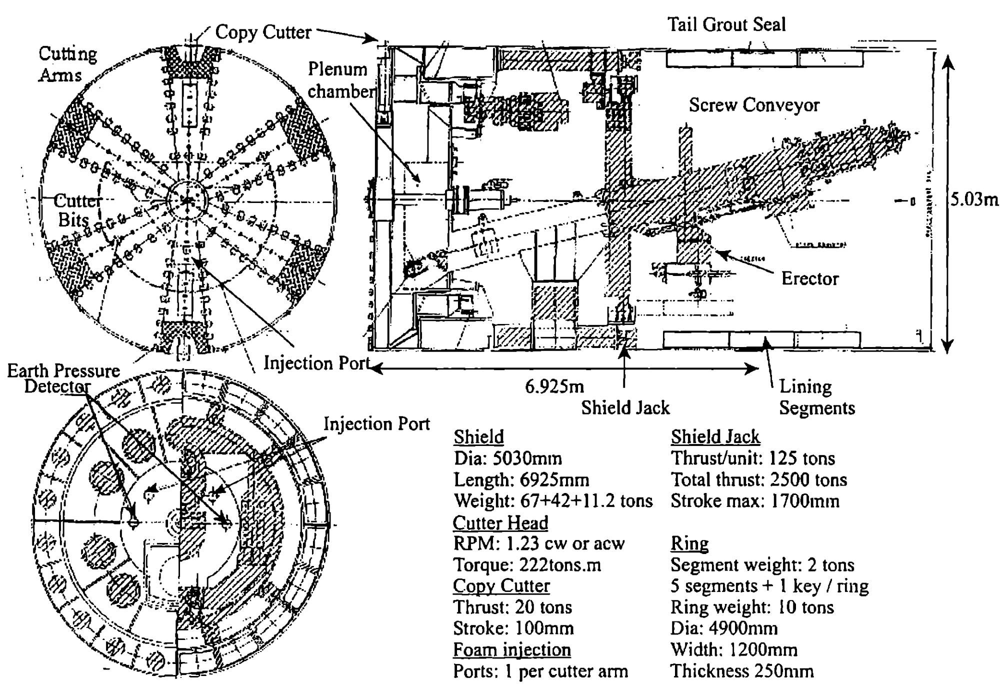


Figure 2. Details of the Kawasaki EPB machine used to tunnel beneath Southwark Park greenfield site

Various tunnel machine parameters were measured during the course of tunnelling, such as the tunnel face pressure, cutter torque and shield thrust. The grout quantity, which was injected behind the lining in order to restrict the ingress of soil into the tail void, was also recorded.

4 GROUND MOVEMENTS

The volume loss and the trough width for the ground surface were calculated directly from the settlement profile measured on the surface settlement points. The parameters for the surface settlement profiles were derived using both sides of the settlement trough. The calculation of subsurface volume loss and trough width from extensometer readings, however, relates to only one half of the transverse settlement profile, since extensometers were only positioned above and between the two tunnels. Also, the calculations for volume loss and trough width at depth, derived from extensometer readings, were based on the assumption of a Gaussian settlement profile since there were only a few extensometers across the settlement profile. The volume of the settlement trough, Vs, and the volume loss, V_L, were inferred from Equations 1 and 2 (Mair *et al.*, 1993; O'Reilly and New, 1982):

$$Vs = \sqrt{2\pi} \times i \times S_{\max} \qquad (1)$$

$$V_L = Vs \div \left(\pi d^2 / 4\right) \qquad (2)$$

where $S_{\max}$ = maximum settlement
i = trough width parameter (offset to point of inflection)
d = tunnel diameter

The volume loss for westbound and eastbound tunnels was about 0.5% at the surface increasing with depth above the eastbound tunnel to between 0.7% and 0.8% just above the tunnel crown, as shown in Fig.3. The lower volume loss at the surface is believed to be due to dilation in the dense sandy layers immediately above the tunnel.

The trough width parameter i can be related to distance above the tunnel axis by the expression:

$$K = i/(z_0 - z) \qquad (3)$$

where z = depth of subsurface settlement trough
z_0 = depth to tunnel axis

The offset to the point of inflection, i, was 9-10m ($K \approx 0.45$) at the surface and 5-7m at 15m depth (K=0.9-1.2), as shown in Fig. 4. Also shown on Fig. 4 is the relationship derived by Mair *et al.* (1993) from field records and centrifuge model tests for tunnels in clays. The data from Southwark Park are in reasonable agreement with this relationship.

The maximum surface settlement was 4mm for the westbound tunnel and 4.3mm for the eastbound tunnel (Figure 5). The settlement profiles were approximately Gaussian except for the north half of the westbound trough and the southern extremity of the eastbound trough (i.e. the left half of Fig. 5 for the WB trough and extreme right of the graph for the EB trough).

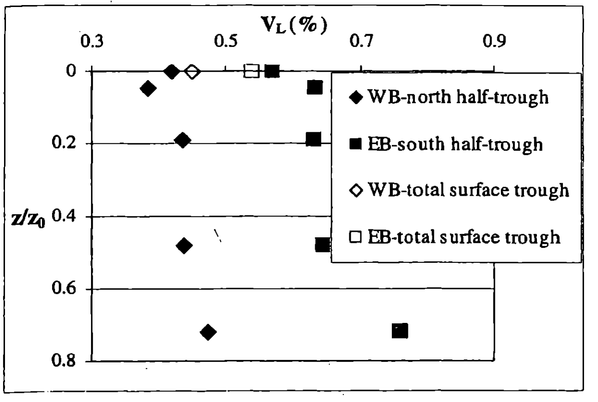


Figure 3. The variation of volume loss with depth at Southwark Park.

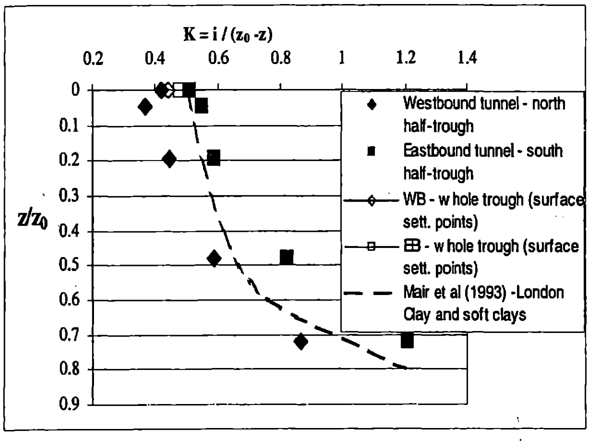


Figure 4. The variation of the trough width parameter K with depth at Southwark Park against tests for tunnels in clays

The non-Gaussian nature is believed to be due to interference from the instrument boreholes. The distribution of settlement with depth is shown in Figure 6. The maximum settlement at the tunnel crown was about 11mm for the westbound tunnel and 12mm for the eastbound tunnel. The longitudinal settlement above westbound and eastbound tunnels is shown in Figure 7, approximately 25% of surface settlement occurred in front of the

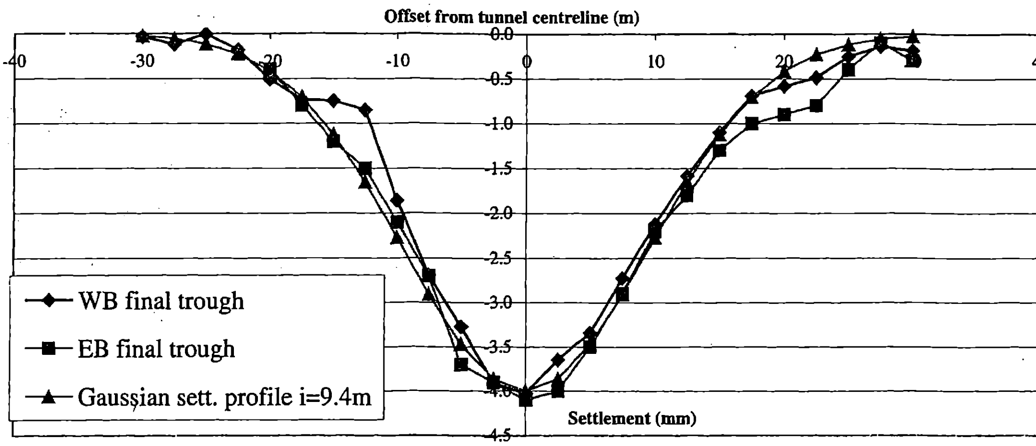
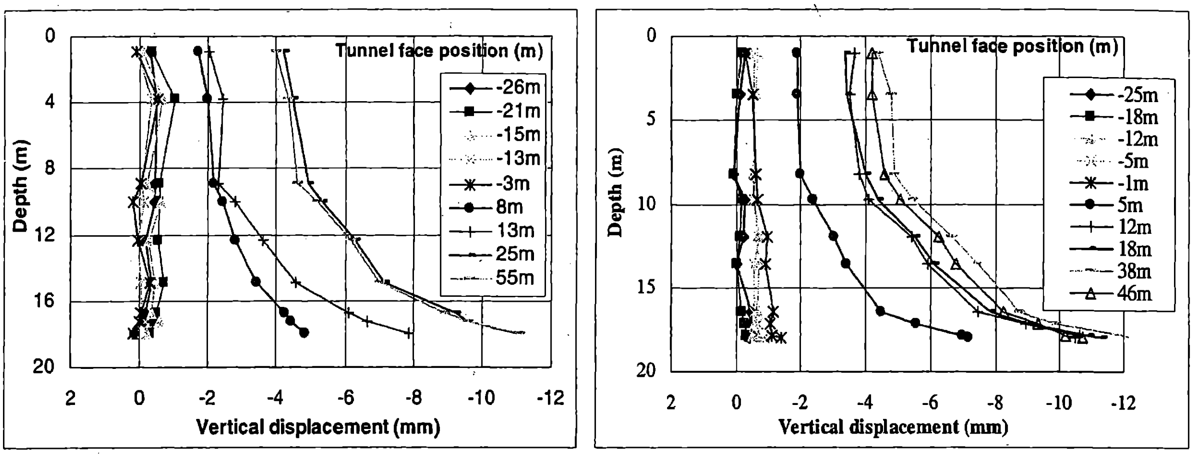


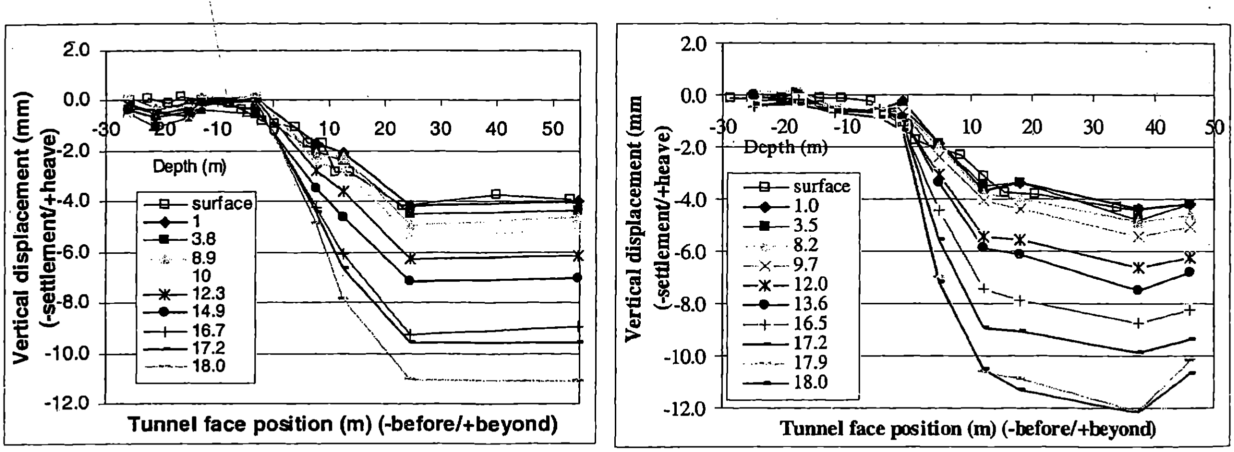
Figure 5. The transverse surface settlement trough due to tunnel construction at Southwark Park



a) westbound tunnel

b) eastbound tunnel

Figure 6. Vertical displacement with depth above the tunnels at Southwark Park



a) westbound tunnel

b) eastbound tunnel

Figure 7. Vertical displacement above the tunnels with tunnel face position

tunnelling shield, 20% around the shield and 55% was associated with convergence onto the tail void. There was no long-term movement associated with tunnel construction; seasonal ground movements are of similar magnitude to those caused by the tunnelling.

5 TUNNELLING MACHINE PERFORMANCE

Face pressures for both tunnels were approximately 1 bar beneath Southwark Park (Fig. 8),

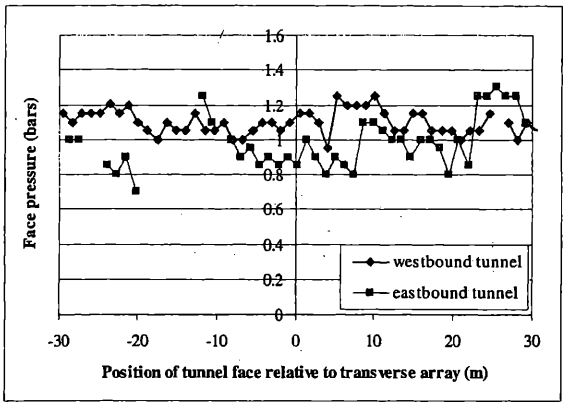


Figure 8. Tunnel shield face pressure on the drives beneath Southwark Park

representing about 25% of the total vertical stress in the ground. The pressure was measured by two sensors at the rear of the plenum chamber positioned at axis level (Fig. 2). This pressure resulted in only small movement in front of the tunnel shield, leading to about 1mm at the ground surface. The torque for construction of the westbound and eastbound tunnels was relatively constant at approximately 200ton.m, as shown in Fig. 9.

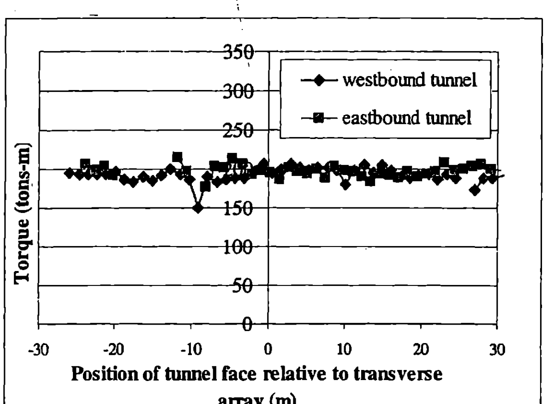


Figure 9. Tunnel shield torque on the drives beneath Southwark Park

The total thrust on the tunnelling shield differed, with nearly twice the force being applied at the rear of the EPB shield for the westbound drive than for the eastbound tunnel (Fig. 10). It is believed that the higher thrust used for the westbound drive was due to the greater pitch of the tunnelling shield (deviation of shield from horizontal), see Figure 11. However, the higher thrusts measured for the westbound tunnel might also be related to ground conditions, given that settlements and volume losses were smaller than for the eastbound tunnel drive.

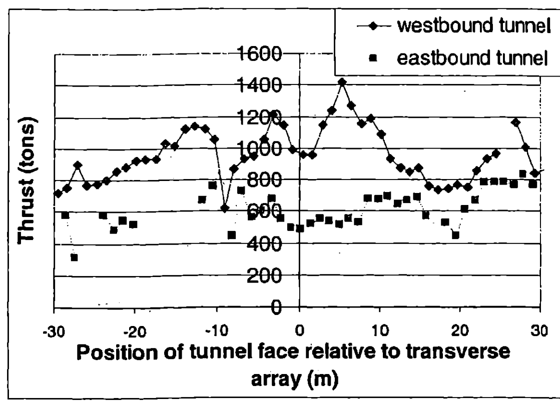


Figure 10. Tunnel shield total thrust on the drives beneath Southwark Park

Grout was injected into the tail void after every ring advance, and was performed through the tunnel lining two rings behind the shield tail. For both tunnels, in the vicinity of the instrumentation, approximately 1.2m^3 of grout was injected per ring-this equates to the volume of the theoretical tail void. The variation of grout volume injected for the two tunnels is shown in Fig. 12.

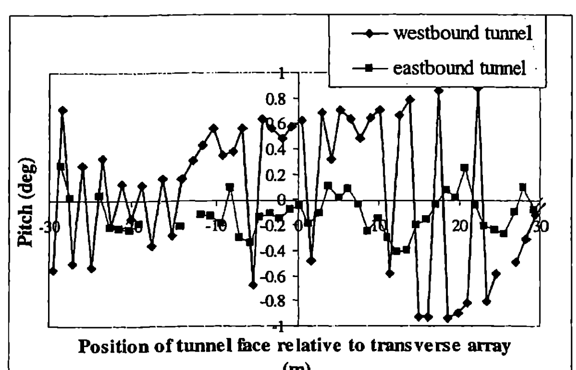


Figure 11. Tunnel shield pitch on the drives beneath Southwark Park

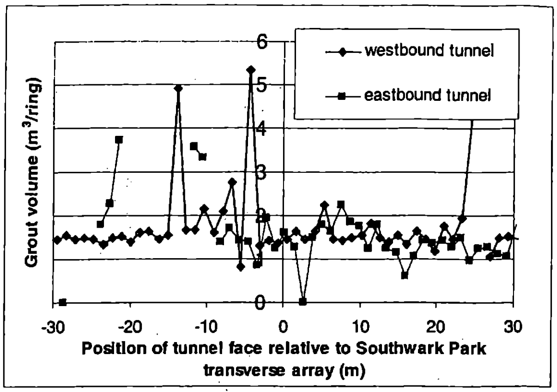


Figure 12. Grout volumes injected behind tunnel shield on the drives beneath Southwark Park

6 CONCLUSIONS

The earth pressure balance tunnelling beneath Southwark Park greenfield site resulted in only small ground movements: a maximum settlement of 5mm was observed at the ground surface and 12mm just above the tunnel crown. Tunnelling was performed by a 5m diameter shield through dewatered dense granular sands at 21m depth. The volume loss for the eastbound tunnel was about 0.8% at 15m depth reducing to 0.5% at the ground surface, reflecting some dilation in the dense sandy layers immediately above the tunnel.

Profiles of trough width with depth suggest that the settlement trough caused by the eastbound tunnel is slightly wider than the trough associated with the westbound tunnel. This suggests a possible difference in ground conditions between the two tunnels and hence further site investigation is planned. Furthermore, the asymmetry of the westbound surface transverse settlement profile is unexplained and may indicate an obstruction to settlement on the north-side of the tunnel.

For both tunnels, ground movement in front of the tunnelling shield was insignificant, most settlement being associated with convergence of soil around the shield and into the tail void. Although measurements by earth pressure sensors indicated approximately equal face pressures for the two tunnels, the total thrust on the shield for the westbound tunnel was twice that for the eastbound. However this was probably due to a greater deviation of the shield from horizontal, resulting in greater shear forces acting on the shield. The volumes of grout injected were similar for both tunnels.

Long-term monitoring has shown no evidence of consolidation, seasonal surface ground movements being of similar magnitude to those caused by the EPB tunnelling.

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