Long-term settlements due to tunnelling

In this article, Benoit Jones looks at published case studies of ground movements from Crossrail and what they might mean for our understanding of long-term settlements.

CROSSRAIL, A NEW East-West mainline railway across the middle of London, is one of the largest infrastructure projects ever undertaken. It involves 21km of tunnels through central London. The amount of monitoring required to ensure safe tunnelling and look after third party assets was huge, and the timescale over which readings have been taken is also longer than for most projects. This article will review some of the published papers and will try to see what can be learnt, with a focus on long-term settlements.

Introduction

In preparation for this article I read Volumes 1, 2 and 3 of "Crossrail Project: Infrastructure design and construction", which contain 94 technical papers on civil engineering aspects of the project, and several other papers written in journals and conferences. I expected that these papers would be a goldmine of information on ground movements due to tunnelling given the vast amounts of monitoring undertaken for the project.

While reading the Crossrail technical papers, I was pleasantly surprised by the breadth of subjects covered: geology, construction methods, TBM transportation, numerical modelling, health and safety, architecture, compensation grouting, instrumentation and monitoring, station design and dewatering, some of which are rarely reported on. But there was very little on my topic of interest, ground movements due to tunnelling. I was beginning to lose heart, when I found two outstanding papers by Hill & Stärk (2015 & 2016), in Volumes 2 and 3. It turns out that long-term settlements are much larger and more important than we thought and these papers will have a big impact on how surface settlement monitoring data is interpreted in the future.

Surface settlements due to sprayed concrete tunnelling

The quality of the data and interpretation in Hill & Stärk's papers is of a standard not seen before and much can be learnt from their experience. It also provides two detailed case studies that will be of great value in improving future predictions of ground movements. I would recommend that anyone involved in surface settlement prediction or monitoring should read them.

Hill & Stärk's first paper is a careful, detailed and concise assessment of short and long-term settlements due to two tunnels at Whitechapel; the C510 PTW-W tunnel (the westward drive of the westbound platform tunnel of Whitechapel Crossrail station) at Kempton Court and the C510 EBRT-W (eastbound running tunnel) under Vallance Road. Both these tunnels had the same construction sequence with a 32.77m² pilot tunnel followed approximately 3 months later by an enlargement, resulting in a final tunnel cross-section of 94.36m² for PTW-W and 73.10m² for EBRT-W. Their second paper updates the data set with more measurements and discusses the interpretation of long-term settlements in more detail.

Hill & Stärk show that ahead of the face of an advancing tunnel, the trough width is wider (Figure 1). The assumption usually made since Attewell & Woodman (1982) is that the trough width is constant ahead of the face, so this is interesting. It then narrows to a minimum while the face is passing under, stays approximately constant until about 3*i* distance behind the face, then gradually widens over time as long-term effects predominate. Then the same happens again for the enlargement tunnel. For interpretation of the monitoring, the following phases can be distinguished:

1. 'First direct influence' until 'last direct influence' of the pilot tunnel construction = the short-term settlement due to pilot tunnel construction
2. 'Last direct influence' of pilot tunnel until 'first direct influence' of enlargement = long-term settlement due to pilot tunnel construction for 3 months
3. 'First direct influence' to 'last direct influence' of enlargement = the short-term settlement due to enlargement construction
4. 'Last direct influence' onwards = long-term settlement due to enlargement construction (and to some degree also ongoing long-term settlements due to the pilot tunnel construction)

They present results from two methods of Gaussian curve-fitting, 'DCSMAX' and 'Minimum SAE', as defined by Jones & Clayton (2013). I will just reproduce the 'Minimum SAE' results in Table 1, as there is not much difference.

Figure 1: Trough width variation with time for the PTW-W pilot tunnel (from Hill & Stärk, 2015)

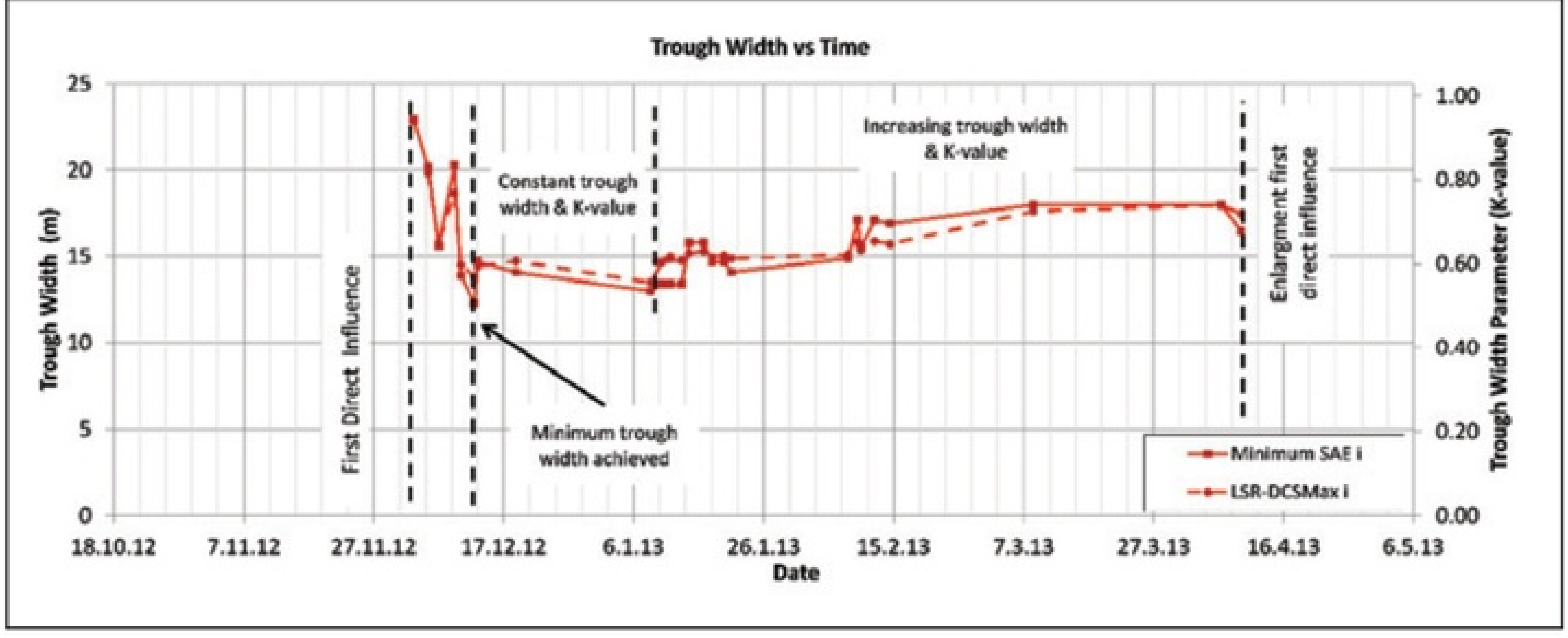


Table 1: Phases of settlement for the PTW-W tunnel (after Hill & Stärk, 2015). *Volume loss calculated based on pilot tunnel cross-sectional area 32.77m². †Volume loss calculated based on enlargement heading cross-sectional area 61.59m². ‡Volume loss calculated based on full tunnel cross-sectional area 94.36m².

	Settlement influence	Vol. loss *	Vol. loss †	Vol. loss ‡	Trough width *i*	Trough width parameter *K*
1	Pilot short-term	0.98 %			13.4m	0.55
1+2	Total settlement from pilot first direct influence to 3 months after last direct influence	1.89 %			16.4m	0.67
3	Enlargement short-term settlement on its own		0.71 %		9.6m	0.39
1+2+3	Total settlement to end of enlargement short-term			1.08 %	12.8m	0.53
1+2+3+(4)	Total settlement 3 months after enlargement			1.34 %	13.4m	0.55
1+2+3+4	Total settlement 17 months after enlargement			1.99 %	15.6m	0.64

It is interesting that when the enlargement settlements are considered on their own in Table 1 row 3, we can see that the trough width is narrower than for the pilot tunnel, even though the enlargement is obviously bigger and wider. Current empirical prediction methods would not predict this, as they assume the trough width is dependent on geology and so would be the same for both the pilot and enlargement. Hill & Stärk hypothesise that this may be due to disturbance of the ground during pilot tunnel construction.

Hill & Stärk (2015) rightly find the fact that the trough width is constantly varying unsatisfactory, and hypothesise that if a Gaussian curve were fit to each phase separately, then added together, then the trough width may remain constant within each phase. However, this would be difficult to achieve for the PTW-W tunnel, due to the effect of the parallel eastbound platform tunnel 45m away on the wide long-term settlement trough with a maximum settlement midway between the tunnels. Therefore, a very long transverse settlement array along Vallance Road over the EBRT-W tunnel, which was constructed without any other tunnels in the vicinity, was analysed.

Vallance Road was monitored continuously for 3 years, and it was found that the whole area is undergoing continuous settlement of about 4mm per year. Assessment of this kind of background movement, as well as seasonal movements, is described in detail by Hill & Stärk, and is of vital importance if long-term settlements are to be interpreted accurately.

During construction, the same effect of varying trough width was found when Gaussian curve-fitting was attempted on total settlements in phases 2-4 as defined above. However, by fitting curves to each phase independently, the trough width within each phase remained constant, and

Table 2: Best fit Min. SAE parameters from multiple Gaussian analyses for EBRT-W tunnel at Vallance Road (after Hill & Stark, 2015). *Heading cross-sectional area is the value used in the volume loss calculation in the adjacent column. ‡Values from Hill & Stärk (2016).

	Settlement influence	Heading cross-sectional area *	Vol. loss	Trough width *i*	Trough width parameter *K*	*Δz*
1	Pilot short-term	32.77m²	0.98 %	15.8m ‡	0.53 ‡	-
3	Enlargement short-term	41.33m²	0.94 %	12.5m	0.42	-
1+3	Combined short-term settlement	73.10m²	0.96 %	-	-	-
2	3 months long-term settlement after pilot	32.77m²	0.55 %	33m ‡	1.1 ‡	-0.9mm
4	3 months long-term settlement after enlargement	73.10m²	0.44 %	22.2m	0.74	-0.9mm
2+4	Combined long-term settlement	73.10m²	0.68 %	-	-	-1.8mm
1+2+3+4	Total settlement 3 months after enlargement	73.10m²	1.67 %	-	-	-
1+2+3+4	Total settlement 16 months after enlargement ‡	73.10m²	2.2 %	-	-	-

when added together they gave a better fit to the total settlement as well. Wongsaroj et al. (2013) encountered similar issues, but they used a modified Gaussian curve with extra parameters to make it fit, which is a less elegant solution.

The best fit Gaussian curve parameters for each phase of construction are shown in Table 2. Table 2 shows that the short-term trough width parameter for the pilot tunnel is similar to what should be expected from previous case histories in London Clay, at 0.53. However, as noted earlier, the enlargement short-term trough width parameter is perhaps lower than expected, at 0.42. The short-term volume losses of both the pilot tunnel and enlargement, and both combined, are typical for a sprayed concrete tunnel in London Clay.

The long-term parameters for both the pilot and enlargement in Table 2 describe a very wide and shallow settlement trough, and the curves fit much better than when trying to fit to a combined short- and long-term settlement trough. The offset Δz caused by the long-term subsidence of the whole area has been removed from the data before curve fitting.

The total settlement, with a volume loss of 2.2 % after 16 months, is higher than expected. Long-term monitoring at St. James's Park highlighted the possibility that long-term settlements in London Clay could be significant (Mair, 2008), but short-term volume loss for this tunnel was high at 3.3 %. The monitoring for Crossrail has shown that long-term settlements can be quite large even when short-term volume losses are relatively small. The implications are that we need better prediction methods for long-term settlements so that we can safeguard utilities and structures, and that monitoring cannot always be switched off as soon as the short-term movements have ceased.

In the second paper, Hill & Stärk look at even longer term data (2 ½ years in the case of PTW-W) and fit hyperbolic curves to the long-term settlement vs time graph. Being able to fit a curve and predict the rate allows engineers to plan monitoring resources and allows an estimate of ultimate settlement to be made. Hill & Stärk (2016) show by making predictions at different times that it would be difficult to predict the ultimate long-term settlement with any certainty until at least 1 year after construction.

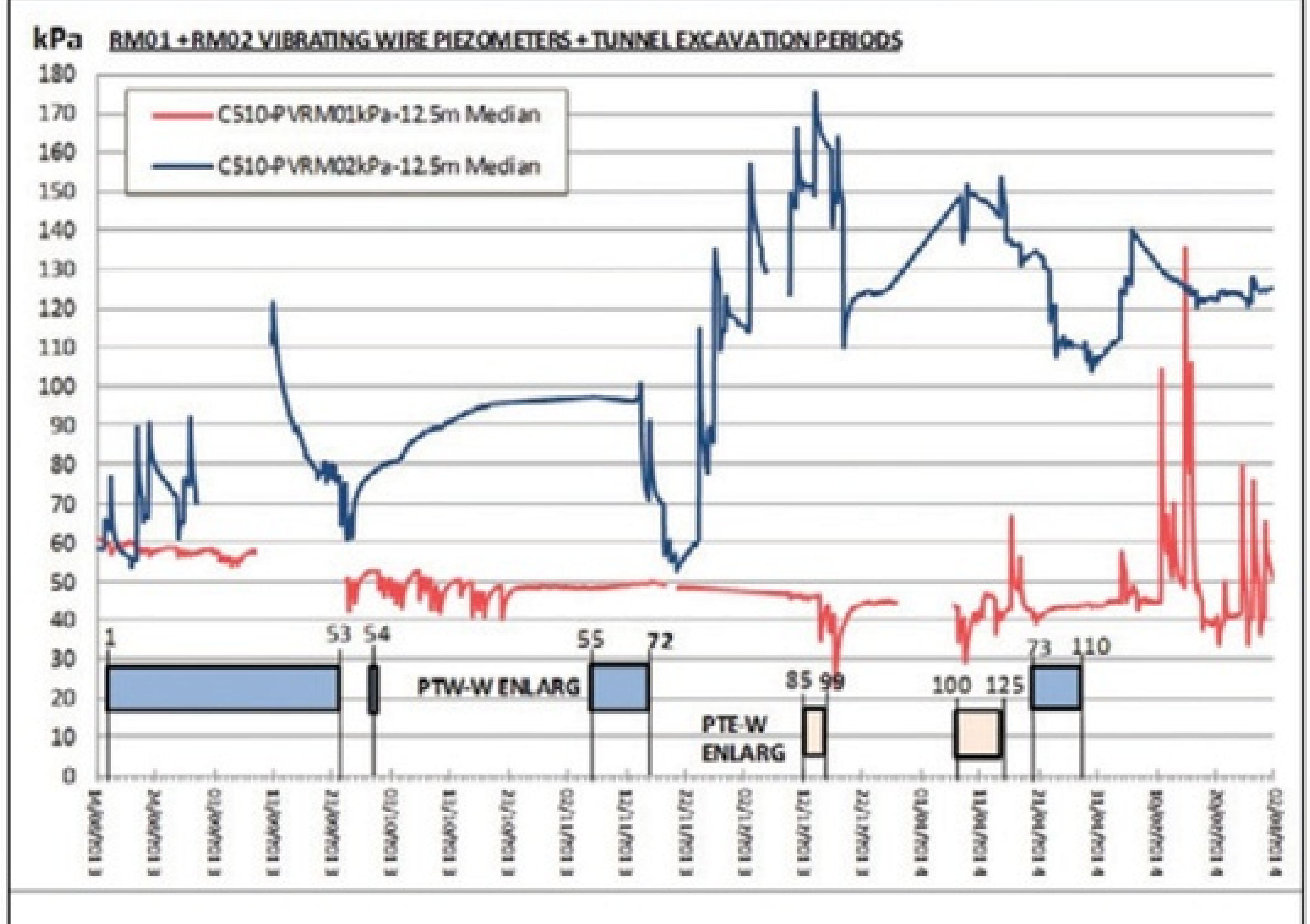
Hill & Stärk (2016) also show that the development of the long-term settlement trough increases ground slopes and deflections and increases their extent. Therefore, the assumption often made in the past that the widening of the trough width associated with long-term settlements does not increase the risk of building damage, is not valid.

What causes long-term settlements?

Hill & Stärk (2016) note that the hyperbolic shape of the long-term settlement development is what one would expect from consolidation. Consolidation occurs after positive excess pore pressures are generated in a low permeability soil due to an increase in loading. Since water is relatively incompressible, this increase in loading doesn't cause a change in volume in the short-term. However, as the water is gradually drained from the pores over time and stress transfers to the soil particles themselves, which are more compressible, the soil reduces in volume. The converse is also true: during unloading negative excess pore pressures are generated in a soil, and gradual equilibration of those negative excess pore pressures over time causes heave.

One thing to always remember is that excess pore pressures are excess to a future steady state, and this isn't necessarily the same as the initial state before construction. For instance, if a tunnel acts like a drain, the future steady state that pore pressures will equilibrate to (and hence are 'excess' to) will involve a draw-down of pore pressures around the tunnel that wasn't there before construction. If a tunnel is completely impermeable, then in hydrostatic conditions the future equilibrium may be the same as the initial state. If a tunnel is completely impermeable but the soil is underdrained (as it is in much of central London), then the future steady state is one in which water is flowing down past the tunnel, and the impermeable tunnel will actually be an obstruction to this flow, making the future steady state different to the initial state.

Figure 2: RM01 and RM02 VWTs pore pressure against mining periods in PTW-W and PTE-W at Liverpool Street Station, detail of the period between August 2014 and February 2014 (from Soler Pujol & Stärk, 2015).



Tunnelling generally causes an unloading of the ground around the heading. In overconsolidated clays such as London Clay this generates negative excess pore pressures, as illustrated by Figure 2 taken from Soler Pujol & Stärk (2015). Although complicated by positive pore pressure changes caused by compensation grouting nearby, there seems to be a clear correlation between mining periods and negative changes in pore pressure.

This effect is also exemplified by piezometer readings of pore pressures close to an advancing sprayed concrete lined tunnel side-drift in New & Bowers (1994), a pipe-jack in Marshall et al. (1996), an open face TBM tunnel in Nyren (1998) and a top heading, bench, invert sprayed concrete lined tunnel in van der Berg (1999), which all show a relatively sudden decrease in pore pressure as the tunnel approaches, followed by a very slow rebound. An example from New & Bowers (1994) is shown in Figure 3. This effect appears to be independent of excavation method as long as the ground is unloaded.

Negative excess pore pressures should cause heave in the long-term as the clay draws in water and swells. So what is causing the long-term settlements? Numerical modelling by Shin et al. (2002) shows that if the tunnel is acting as a drain, then there will be long-term settlements, and if the tunnel lining is impermeable, then there will be a slight heave of the ground in the long-term. This is because a permanent reduction in pore pressure caused by the tunnel draining the ground around it will cause consolidation, in the same way as tree root suctions will cause settlement of a building.

Numerical models by Wongsaroj et al. (2007 & 2013) and others presented by Mair (2008) demonstrate that in London Clay even slight changes in permeability of the lining or the ground can have a significant effect on long-term settlement magnitude and extent. Wongsaroj et al. (2007) also found that their numerical model matched the piezometer and extensometer results from the Jubilee Line Extension at St James's Park better when the London Clay was given a higher permeability in the horizontal direction compared to the

Figure 3: Movement, stress and pore pressure development with time as tunnel face passes (from New & Bowers, 1994)

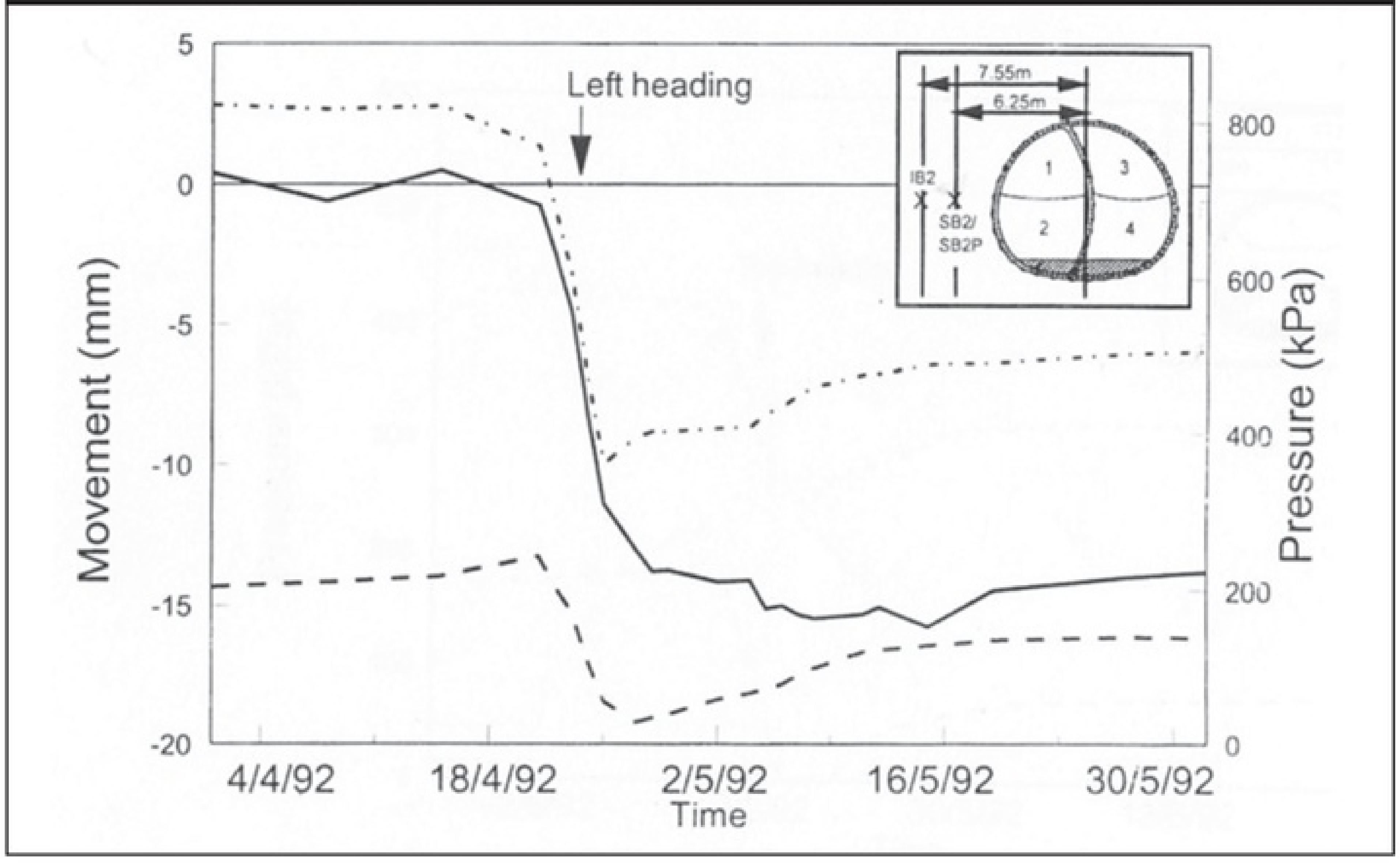


Table 3: Values of lining permeability required for lining to be considered impermeable, based on Wongsaroj et al. (2013) equation for relative permeability.

Soil permeability	Lining permeability required for RP = 0.1
1 x 10^{-8}m/s	1.5 x 10^{-11}m/s
1 x 10^{-9}m/s	1.5 x 10^{-12}m/s
1 x 10^{-10}m/s	1.5 x 10^{-13}m/s
1 x 10^{-11}m/s	1.5 x 10^{-14}m/s

vertical, which increased the lateral extent of the drainage effect.

Analysis of many numerical models by Wongsaroj in his PhD thesis (presented in Wongsaroj et al., 2013) identified a 'relative permeability' *RP*, defined as:

$$RP = \frac{k_{lining}}{k_{soil}} \cdot \frac{C}{t_L}$$

where k_{lining} is the permeability of the lining in m/s,

k_{soil} is the permeability of the soil in m/s,

C is the clay cover above the crown in m, and

t_L is the lining thickness in m.

If $RP < 0.1$ then the behaviour approximates to an impermeable lining and no long-term settlement will occur, and if $RP > 100$ then the behaviour approximates to a permeable lining. In between these limits the tunnel lining will be partially draining the soil.

Assuming a clay cover of 20m and a lining thickness of 0.3m, the lining permeability required to achieve a relative permeability of 0.1 and hence exhibit impermeable behaviour is given in Table 3. The permeability of the London Clay is usually less than 1 x 10^{-9}m/s and can easily be as low as 1 x 10^{-11}m/s (e.g. Wan & Standing, 2015), so the lining permeability needs to be at least better than 1.5 x 10^{-12}m/s and possibly as good as 1.5 x 10^{-14}m/s, which is the permeability of a very good sprayed concrete without accounting for construction joints, shrinkage cracks or other imperfections. Therefore, if long-term settlements are to be avoided, then the tunnel probably needs a waterproof membrane or a watertight secondary lining.

Conclusions

The high quality data from Hill & Stärk (2015 & 2016) at Whitechapel Crossrail station is a valuable case study of long-term settlement in London Clay. The surveying methods, interpretation of background movements and curve-fitting set a standard for others to follow.

The probable cause of the long-term settlements, as was concluded by Hill & Stärk (2016), is that the tunnel lining is acting as a drain and that this is causing consolidation of the clay around the tunnel. The wide lateral extent of settlements is probably due to a higher permeability in the horizontal direction relative to the vertical direction.

If long-term settlements are undesirable, Wongsaroj et al.'s (2013) relative permeability equation shows that in low permeability soils such as London Clay a very low permeability lining is required that may not be achievable with primary sprayed concrete. Conversely, tunnel linings in more permeable soils will not need to be as watertight to minimise long-term settlements.

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