Discussion of pore water pressure and total horizontal stress response to EPBM tunnelling in London Clay

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Introduction

This discussion relates to not just this current paper but also the two companion papers by the authors. For ease of reference these are referred to here as Papers 1 (Wan et al., 2017a), 2 (Wan et al., 2017b) and 3 (Wan et al., 2019). We were involved with the research and collaborated with the Imperial College team by way of providing regular updates on the TBM progress each day when the field monitoring was running on a 24-hour day basis and subsequently providing details about the TBMs themselves and the operational variables relating to the relevant sections of each drive (westbound and eastbound). On reading the detailed papers that have been produced – the authors are to be congratulated on the quality of the data and their interpretation and integration with the construction works and operational variables – we want to contribute further to supplement their findings and relate them to practice. We, as tunnelling engineers, see the value in these research findings to aid others involved in urban tunnelling projects and discuss them here in terms that relate to applied tunnelling practice. We also want to explain some of the dilemmas faced 'at the face' when tunnelling beneath sensitive structures in an urban environment. Crossrail contract C300, where the research measurements were made, running through the heart of London's West End, provides a prime example.

Discussion on TBM operations

Volume loss – measured values

Volume loss (VL), sometimes referred to as 'face loss' (although this suggests that the loss is only local to the cutter-head), is a key quantity frequently referred to and discussed in projects involving tunnel construction. Most UK projects now specify contractual VL limits. Common practice is to estimate volume loss through measurements of surface settlement troughs as described in Paper 1. In Paper 1, the authors compare volume losses at Sections X and Y at the Hyde Park site, the former being a more greenfield location with the latter being close to the existing London Underground (LUL) Central Line tunnels. At Sections X and Y, the measured volume losses were less than 1% and 0.5% respectively for the first westbound tunnel construction (Fig. 11, Wan et al., 2017a). The authors attribute this potentially to: (i) the presence of the existing Central Line tunnel; (ii) effects from the deep datum used; and (iii) the fact that tunnelling was carried out with greater care in the vicinity of the existing operational tunnels than when passing beneath the open space of Hyde Park. With respect to the third point, we the tunnelling contractors did in fact have contractual volume loss tolerances that we had to comply with, generally limited to 1%. In the vicinity of the Central Line tunnels (and also a Thames Water strategic main beneath the nearby Sussex Gardens) it was tightened (following structural assessments at sensitive locations) and limited to 0.5%. This was achieved according to our own surface settlement measurements in Sussex Gardens and Bayswater Road, and also as far into

Hyde Park as the authors' Section Y (0.44%, Fig. 11b, Wan et al., 2017a) for the westbound tunnel drive. However, during the eastbound tunnel drive the volume loss values at Section Y increased, as would be expected, because of the ground disturbance caused by the first tunnel (0.82%, Fig. 13b, Wan et al., 2017a). As the TBMs passed into Hyde Park, the volume loss was generally less than 1% for the first westbound tunnel construction as seen (Fig. 23, Wan et al., 2017a).

After gaining experience and achieving a satisfactory volume loss (i.e. keeping within the specified limit) for the first tunnel drive beneath Hyde Park, the client agreed to relax to contractual VL limits as there were no structures or utilities located here. We the tunnelling contractor took the opportunity of performing trials to investigate the effect of enhancing the TBM productivity on volume loss for the second tunnel drive. These were performed by reducing the face pressure for about 60-80m at two locations (near chainage 2450m and 2700m). The outcomes from the trials are evident from two of our surface monitoring sections (Transect 2 and Transect 5) as presented in Figure 23 of Wan et al. (2017a) which shows estimated values of volume loss with other TBM variables: face pressure, tail-skin grout pressure, weight of spoil and tail grout volume. A primary objective of this exercise was to investigate whether the influence of these TBM variables on volume loss was significant or negligible.

Volume loss is also assessed through subsurface measurements in Paper2. As the measurement locations are much closer to the TBM it is possible to attribute the contributions of the individual components of the tunnelling operation to the overall volume loss measured at the surface (Wan et al., 2017b, Figures 23 and 24). Some of these, e.g. face pressure and tail skin grout pressure, along with other controlling factors are now discussed.

Volume loss – controlling factors

Controlling volume loss is not simply a case of specifying various pressures and other variables to achieve a fixed value. It is a fine art involving a myriad of operational variables and many of these need to be watched with great vigilance and adjusted as appropriate to maintain/achieve set values. It is very much an iterative process.

Face pressure. Most tunnel contractors have in-house guidelines concerning the face pressure to apply to achieve a certain volume loss. In practice this usually acts as a starting point, after which the TBM is 'calibrated' in the ground: this is the Tunnel Manager's responsibility. The C300 Contractor's designers, having reviewed the entire tunnel alignment, its depth and proximity to strategic infrastructure (e.g. LUL tunnels, key water tunnels and Network Rail (NR) Permanent Way), prepared TBM operational variables to achieve the specific VL at each location, providing face and tail skin pressure ranges. Essential for maintaining control is to plot measured surface ground settlement, along with the variables controlled within the TBM against chainage (or ring number). These data were assessed daily by the Shift Review Group (SRG, comprising representatives from Crossrail, the tunnelling framework consultant, the tunnelling contractor and at sensitive locations representatives from LUL, NR and utility engineers), which met to provide continuous feedback to the TBM operator and help maintain good control and productivity. We aimed to achieve 'repeatability' via the SRG review, throughout the tunnelling in the London Clay, the recommended TBM operational variables achieved the specified VL criteria.

At the same time as wanting to minimise volume loss (and so settlement) there is a need to optimise this with TBM productivity. Increasing face pressure (i) requires more energy as greater thrust and hence greater torque needs to be applied; and (ii) leads to greater wear on the tools and the need for more frequent stops of the TBM to replace them, both with time, cost and health and safety implications. Therefore, a key factor investigated was whether the TBM performance (e.g. rate of

advance) could be improved without compromising volume loss and without exacerbating wear on the cutter-head tools. One way to negate cutter-head tool wear is through the use of foams or polymer muds injected within the cutter-head, plenum chamber and auger screw. These are routinely used to 'condition' the soil to optimise its flow up the Archimedes screw, i.e. such that it is not too liquid and not too solid, the former makes it difficult to control the pressure and the latter might lead to blockages. There are many varieties of foam and polymer muds commercially available and a new super polymer from BSAF was used on the Crossrail C300 contract discussed here.

In a similar fashion different amounts of compressed air and water were injected into the plenum chamber of the cutter-head. All these factors would change the condition of the spoil in the plenum chamber and result in variation in the face pressure. It would be interesting to correlate the amount of foam, compressed air and water with the face pressure and the measured pore water pressure responses.

Tail skin grouting. Tunnel annulus grouting through the tail skin is another operation through which volume loss can be controlled to some degree. The primary intention of the tail skin grouting is to fill the annulus between the extrados of the tunnel lining and the excavated volume. At the ground surface there is little evidence of its influence (Wan et al., 2017a), i.e. there is no 'recovery' of ground movement and hence volume loss. However, the ground near to the tunnel can be seen to respond, with reversals in displacement, particularly in the case of the first westbound tunnel (Wan et al., 2017b: e.g. vertically, Figure 3b and horizontally, Figures 10b, 12b and 13) which must help reduce subsequent surface volume loss developing. The effect of tail skin grouting is also evident from the pore water pressure responses shown in Wan et al. (2019, Figures 7a, 9a, 10a and 13) and total stress responses (Figure 12b). In fact, the schematic shown in Figure 13 of Wan et al. (2019), which is based on the field monitoring data, clearly shows the influence of the face pressure and tail skin grouting on pore water pressure.

It is interesting to note that in most of these cases the responses are observed before the rear of the shield, where tail grouting takes place, reaches the monitoring point. The changes occur when the body of the shield is about midway beneath the monitoring point. As the tail skin grout gels in a matter of seconds it seems unlikely that the grout is flowing towards the front of the shield, which would be detrimental to the tunnelling operation. The data suggest that more probably a bulb of pressure develops as the grout is pumped, emanating from the injection point, and this starts to influence the monitoring devices in advance (e.g. rod extensometer anchors, piezometers), as these are always installed a finite distance above the expected extrados of the tunnel lining. Do the authors have any comments on the development and extent of such a bulb?

TBM progress is strongly controlled by the tail skin grouting operation. There are often technical problems with this operation. If the grouting pressure is too high there is a risk of clogging the tail seal brushes. It is estimated that 60% of the TBM non availability on the Crossrail C300 contract arose because of grout blockages. It is important to note that tail skin grouting is different to and more complex than grouting through the lining rings which is sometimes adopted. Although less effective in reducing volume loss than tail skin grouting, blockages occur much less frequently.

Instantaneous advance rate. Time, and in particular the speed at which the TBM shield progresses, also has an influence on volume loss. The shove speed relates to a number of factors besides the overall production rate (often expressed as rings per day). During EPBM tunnelling on contract C220 for the Channel Tunnel Rail Link (CTRL), fast rates of about 100 mm/min were used, compared with about 50 mm/min on the Crossrail C300 drives. Although control of the shove speed is part of the armoury available to the TBM team, in fact the rate at which the shield is advanced does not make

much difference to the production rate as the ring still needs to be built. A faster shove rate has the disadvantage that frequently more cutter-head interventions are needed, taking time and requiring the use of compressed air with consequent health and safety issues (especially when tunnelling beneath the river).

Lining deformation. Deformation of the lining is the final contributing factor given in Wan et al. (2017b, Figure 24). The volume loss contributions from the lining deformation for the westbound and eastbound tunnels were 0.020 and 0.025 m^3/m respectively, which relate to volume loss values of about 0.05%. This value seems too high.

On C300 dowels were used to interconnect segments, resulting in a rigid lining structure. This was done because on C220 of the CTRL, dowels or bolts were sometimes left out and it was observed that this could lead to rings turning (with a roll of less than 10°). On Crossrail C300 the influence of the dowels was evident from measurements made of the tunnel ovalisation. This was specified to be less than 1%. In practice, from measurements made over a 150-m length, extending beneath the instrumented site, ovalisation values were less than 0.1% (i.e. no greater than 6 mm shortening of the vertical diameter of the lining ring). This is important regarding the size of the kinematic envelope required for the running trains. This measured lining ovalisation should only amount to about 0.02% to 0.03% of the excavation area (and hence volume loss), which is about half the volume loss (0.05%) due to lining deformation inferred from the extensometer measurement by the authors (Wan et al., 2017b, Figure 24, n.b. 0.025 m^3/m shown in the figure relates to a volume loss of 0.05%).

Summary

In conclusion the three papers discussed here have provided detailed insight into the ground response around the TBM as it advances. The discussion is intended to contribute to some of these observations from a practical, operational perspective. An important point to reiterate is that the control of volume loss is not straightforward. It is an iterative process, often requiring a pragmatic approach, balancing numerous operational variables. Further details are given by Thomas and Parker (2013).

Authors' reply to the Discussion

The authors are most grateful to the discussers for their valuable contribution to the papers. Having this tunnelling contractor's perspective greatly helps in terms of understanding the tunnelling operations in London Clay beneath the instrumented site at Hyde Park and the consequent ground response which is the focus of the papers. It will also help with future major urban tunnelling projects (such as High Speed 2 and Crossrail 2). The discussion concerning the application of face pressure and tail grout pressure, among other EPBM operations that are likely to influence the volume loss, is particularly relevant and insightful. This important information aids and enhances the interpretation of the field measurements. The authors have carefully been through each of the points raised in the discussion, and provide further clarification and comments as follows.

Face pressure and tail grout pressure

As described by the discussers, the application of face pressure involves a sophisticated and iterative process including injecting of foams, compressed air and water into the plenum chamber. It seems that this is a more controlled process than the application of tail grout pressure. This helps explain the more consistent face pressure compared with the tail grout pressure, as shown in Figure 4 of Wan et al., 2019 (Paper 3).

Tail skin grouting

It is observed that 'recovery' of subsurface displacements and pore water pressures started to occur when the body of the shield was about midway beneath the monitoring point (5 m < x_f <10 m). The discussers suggest that this is more likely to be attributed to the development of a stress bulb emanating from the tail grout injection point. This suggested explanation, based on the contractor's experience and knowledge about the fast-setting tail grout, is greatly appreciated.

The authors reviewed again the hourly automatic measurements of the piezometers and spade-cells taken during both EPBM passages. Figure 1 shows the sensors at which the tail-grout related 'recovery' was observed for TBM1 and TBM2 passages. Spade cells HP36 and HP37, to the northeast of the eastbound tunnel, are not included in the figure as measurements to these devices were taken manually and so unlikely to be frequent enough to capture any 'recovery'. It is recalled that the sensor at 24.5 m below ground level (m bgl) within multi-level piezometer HP32 was reported to be faulty in Wan et al., 2019 (Paper 3) as it registered unrealistically large magnitudes of pore water pressure change. However, in terms of 'recovery', it exhibited the same response to tail-grouting as the sensor at 31.0 m bgl.

Tables 1 and 2 show the distances from the tunnelling shield extrados of the instrument sensors where 'recovery' has been observed for the TBM1 and TBM2 passages respectively. For the multi-level piezometers (HP32 to HP34), the distances of the furthest sensors with measurement 'recovery' are provided. It can be inferred that the extent of the stress bulb emanating from the tail grouting of TBM2 (approximately 14 m) was greater than that of TBM1 (approximately 9 m).

It is also evident from Figure 1 that the inferred stress bulbs extend further vertically (upwards) than horizontally. This can be explained by the fact that the two upper-level grout injection ports are located close to the crown, as shown in Figure 2.

It is worth noting that the tail-grouting related 'recovery' effect in terms of ground settlement above the tunnelling shield measured via extensometer HP20 (for TBM1) was only observed at the two nearest anchors (i.e. at 29 m bgl and 26 m bgl, or 2 m and 5 m above shield crown: see Figure 3(b) of Paper 2). Observable 'recovery' of horizontal displacement was recorded at inclinometers up to a horizontal distance of about 7 m from the shield extrados. At a distance of about 2 m from the tunnelling shield, the magnitude of the measured vertical and horizontal displacement 'recovery' was about 1-2 mm (see Figure 3(b) and Figure 13 of Paper 2). This is thought to constitute an elastic deformation of the ground around the tunnelling shield, caused by the application of tail grout pressure.

Lining deformation

In order to aid the discussion, the magnitudes of the five main components of the volume loss (see Figures 23 and 24† of Wan et al., 2017b (Paper 2)) inferred from the extensometer measurements are tabulated in Table 3. The discussion makes reference to Component 5 (lining deformation), where the volume loss of approximately 0.05% for each EPBM passage was attributed to longer-term effects including the deformation of the lining upon loading from the ground.

Based on their experience, the discussers suggest that the bolted reinforced concrete segmental lining rings are relatively rigid. This statement is supported by the small magnitudes of measured tunnel lining ovalisation that they report, being less than 0.1% (6 mm out of 6.2 m lining internal diameter), which corresponds to a volume loss component of only about 0.02% to 0.03%. In view of this, the discussers propose that the volume loss component ascribed to 'lining deformation' reported by the authors to be 0.05% (as inferred from the extensometer measurements), appears to be too large for both the westbound and eastbound tunnels. The authors thank the discussers for this useful information

concerning the lining deformation measurements. With this insight it is evident that the magnitude of volume loss attributed to lining deformation does not tally with the magnitude of lining ovalisation recorded. In Wan et al., 2017b (Paper 2), the authors mention that grout shrinkage is likely to contribute to this component of the volume loss. This new information lends weight to and corroborates this suggestion.

Summary

The discussers' contribution, providing a tunnelling contractor's perspective, has highlighted some important points that should be considered as part of the assessment of tunnelling-induced ground response. The discussers' hands-on experience and knowledge of the different EPBM operations have proved to be most valuable, allowing a better and more accurate interpretation of the field monitoring results. The discussion highlights the benefits of the tunnelling contractors, engineers and researchers working closely together in order to understand more thoroughly the impact of different EPBM operations on the surrounding ground and structures. This helps refine the process of controlling volume loss, potentially providing great benefit for future urban tunnelling projects.

References

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† In Figure 24 (b), the title of the horizontal axis should read 'Distance of TBM2 cutter-head from instrument' instead of 'Distance of TBM1 cutter-head from instrument'.

Tables

Measurement type	Borehole	Transverse offset from TBM1 centre-line, y (m)	Depth of sensor, z (m)	Distance from tunnel extrados (m)
Pore water pressure	HP32	10.8	No 'recovery' observed	
	HP33	16.0	No 'recovery' observed	
	HP34	2.5	-22	9.3
Total horizontal pressure	HP35	11.0	-34.3	7.5
	HP39	16.4	No 'recovery' observed	

Table 1. Distance from the tunnelling shield extrados of sensors measuring tail-grout related 'recovery' for TBM1 passage.

Measurement type	Borehole	Transverse offset from TBM2 centre-line, y (m)	Depth of sensor, z (m)	Distance from tunnel extrados (m)
Pore water pressure	HP32	-5.1	-18.0	13.8
	HP33	0.0	-17.0	14.0
	HP34	-18.6	No 'recovery' observed	
Total horizontal pressure	HP35	-5.1	-34.3	1.6
	HP39	0.2	-29.2	1.8

Table 2. Distance from the tunnelling shield extrados of sensors measuring tail-grout related 'recovery' for TBM2 passage.

Volume loss component	TBM1	TBM2	Remarks
1. Face movement	0.22%	0.34%	Ground softening effect by TBM1 passage is evident
2. Over-excavation	0.13%	0.33%	Manual measurements not frequent enough to distinguish the two components
3. Shield tapering			
4. Tail void closure	0.26%	0.25%	Ground softening effect by TBM1 passage is not apparent
5. 'Lining deformation'	0.05%	0.05%	

Table 3. Magnitudes of the volume loss components inferred from extensometer measurements for the westbound and eastbound construction.

Figures

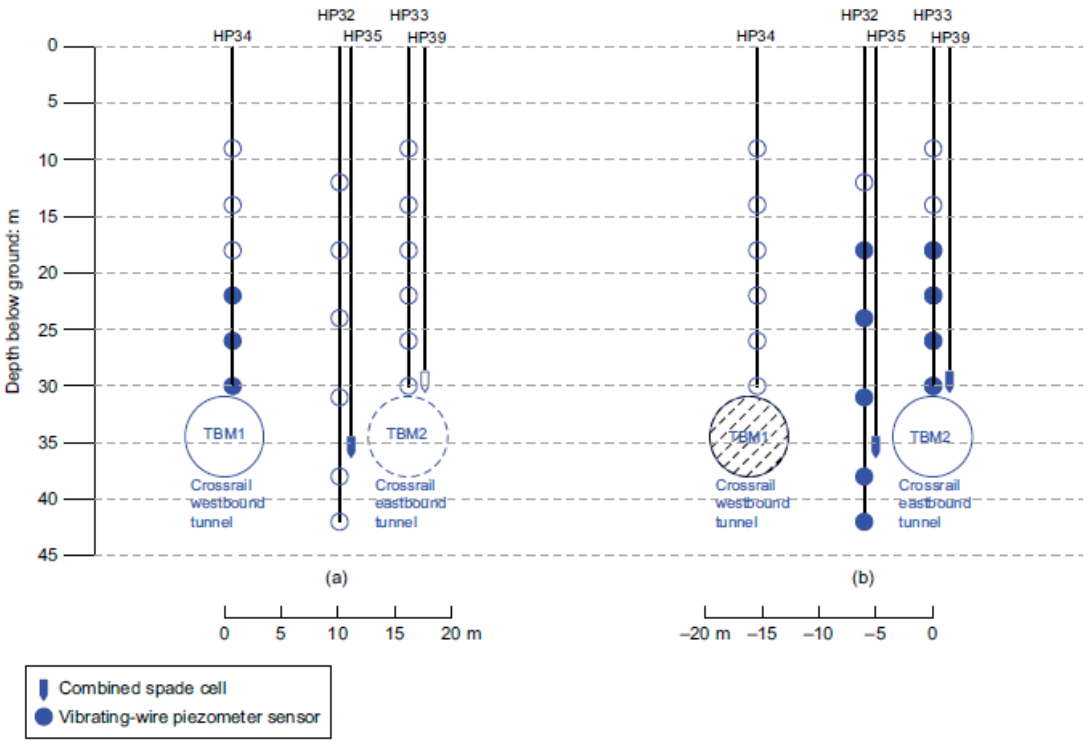


Figure 1. Measurement 'recovery' related to tail grouting of piezometer and spade cell sensors with hourly automatic measurements (a) for TBM1 passage; (b) for TBM2 passage.

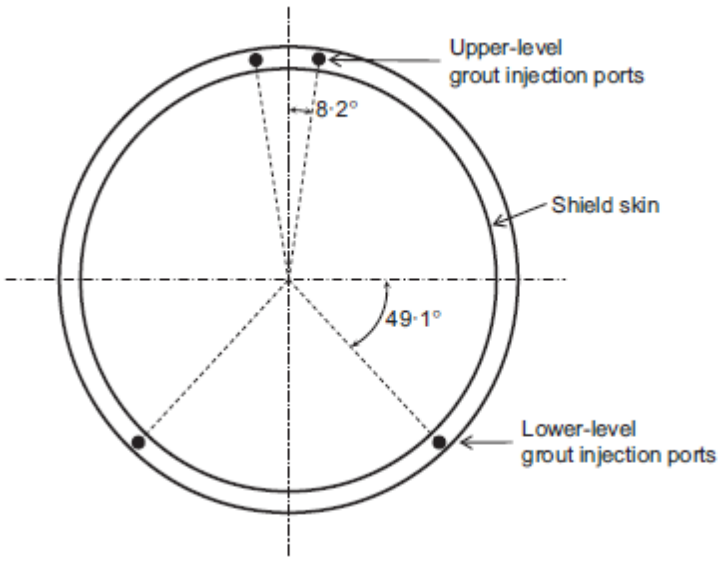


Figure 2. Location of tail skin grout injection ports.