The Role of Monitoring and Modelling for an Efficient Operation of EPB Machines

Davor Šimić[1]

Abstract

An important aspect of the operation of closed-faced Tunnel Boring Machines (TBMs) is the control of face pressure in order to minimize the adverse effect on the surrounding ground due to movements. Urban tunneling projects inevitably involve risks associated with construction-induced ground movements and their effects on overlying buildings and facilities. This paper describes how this problem was tackled in the EPB construction of the tunnels for Crossrail in which the performance of the TBMs is analyzed through numerical models that use parameters fitted to the field data. Integrated team and systems for monitoring TBM parameters and ground movements were continuously required during all tunnelling works with the purpose of keeping settlements to a minimum through the control of EPB operational parameters. Action was taken in the cutting wheel, muck chamber, face pressure and jacking force. Such integrated approach delivered confidence to accurately monitor and control the ground movements, as it is shown in the paper, where the specified and measured settlements are successfully compared.

Key words

EPB, Face pressure, Settlements, Numerical models

1 Introduction

Crossrail will run 118 km from Maidenhead and Heathrow in the west, through new twin-bore 21 km tunnels under central London to Shenfield and Abbey Wood in the east. When Crossrail opens it will increase London's rail-based transport network capacity by 10 per cent. BFK, the JV of which Ferrovial-Agromán takes part was awarded two main Contracts valued in the region of £ 500 million, including:

C300: bore of two 6.2 km tunnel drives between Royal Oak and Farringdon: Twin 7.1 m diameter tunnel drives from Royal Oak construction site to Farringdon station.

C410: construct early access shafts and sprayed concrete lining works for Bond Street and Tottenham Court Road station tunnels. SCL station tunnels, shafts and compensation grouting at Bond Street and Tottenham Court Road Stations.

During the construction, measurements of surface and sub-surface ground movements at free-field sites have provided essential data for evaluating the performance of different tunnel construction methods, allowing for the development of more reliable methods of prediction that justify the importance of adequate instrumentation and monitoring (I&M) schemes in any underground project. On the other hand, the available models in current literature for the interpretation of I&M data, based on analytical models and centrifuge tests (Mair et al, 1996), are very limited because they are only applicable to homogeneous soils with cohesive behaviour and without a frictional resistance component. This paper describes how this problem was tackled in the EPB construction of the tunnels for Crossrail (see figure 1 for a longitudinal

[1] Head Geotechnical Area, Ferrovial-Agroman Engineering Services. Ph.D. Professor Politechnical University Madrid. davor.simic@ferrovial.com

geotechnical profile), in which the performance of the TBMs is analyzed through analytical and numerical models that use parameters fitted to the field data. The success of such evaluation is shown by the good agreement found between model prediction and real settlement data.

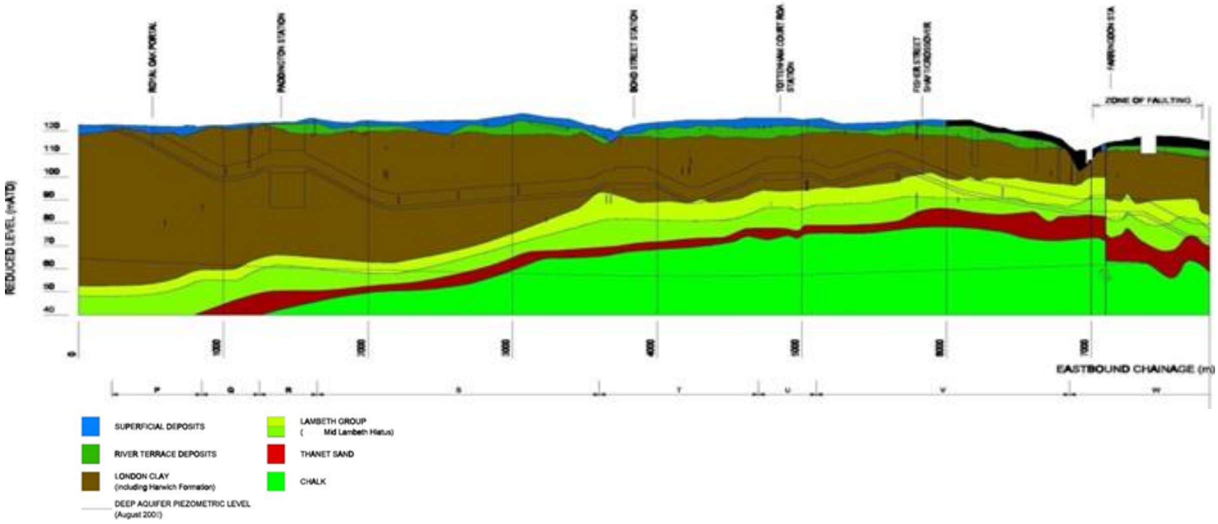
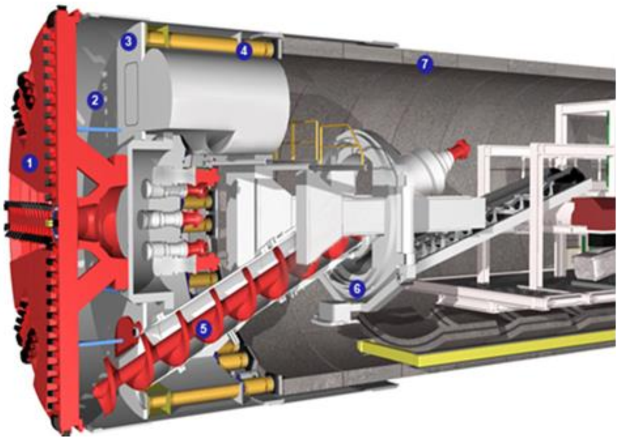


Fig. 1 Geology along the alignment

2 Operational control of the EPB excavation

Crossrail contract C300 involved construction of twin tunnels, with inside diameter, 6.2 m, running from Royal Oak portal eastwards to Farrington station. These were constructed using Earth Pressure Balance (EPB) Tunnel Boring Machines (TBM) with maximum 7.1 m diameter cutterhead and 0.30 m precast concrete lining segments forming a 6.8 m outer diameter lining system.

As it is widely recognized, integrated team and systems for monitoring ground movements are continuously required during all tunnelling works for control purposes. However, a particular strategy can be devised to reduce the tunnel induced settlement through the control of EPB operational parameters taking advantage of the real-time measurements. As shown in Figure 2, action is taken in the cutting wheel, muck chamber, face pressure and jacking force. Figures 3 to 4 show different samples of monitoring logs. Such real-time integrated approach delivered confidence that we can accurately monitor and control the ground movements. This is summarized in Figure 5, where the specified and measured settlements (quantified in terms of % of volume loss and K trough-width factor) are successfully compared, as measured volume losses fall below the specified limits and K-factors are generally higher than foreseen (Mair et al, 1996).



1 – Cutting wheel
2 – Muck chamber
3 – Face Pressure
4 – Propulsion Force
5 – Screw
6 – Erector
7 – Ring build

Fig. 2 Strategies to reduce settlement through the control of TBM parameters

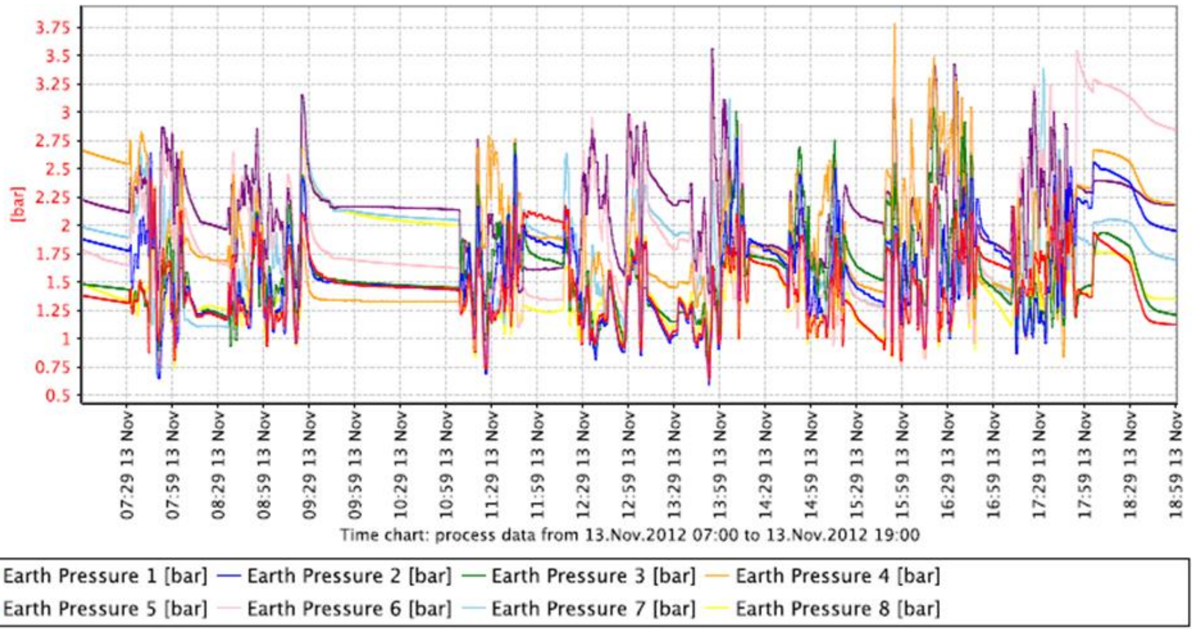


Fig. 3 Face pressure record: a sample

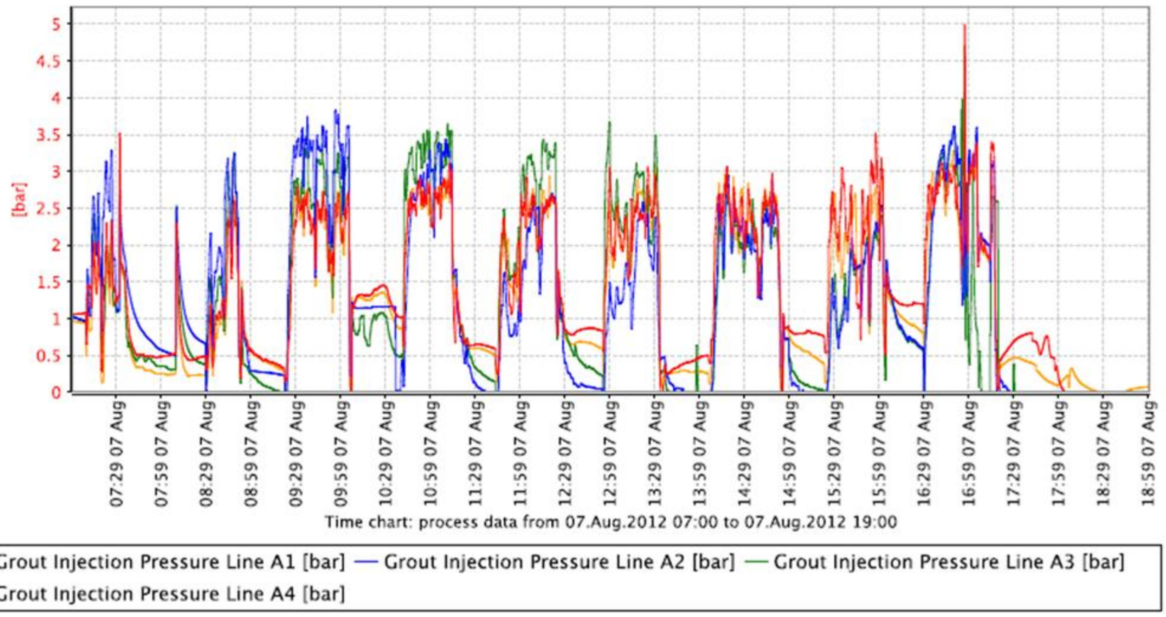


Fig. 4 Grout pressure record: a sample

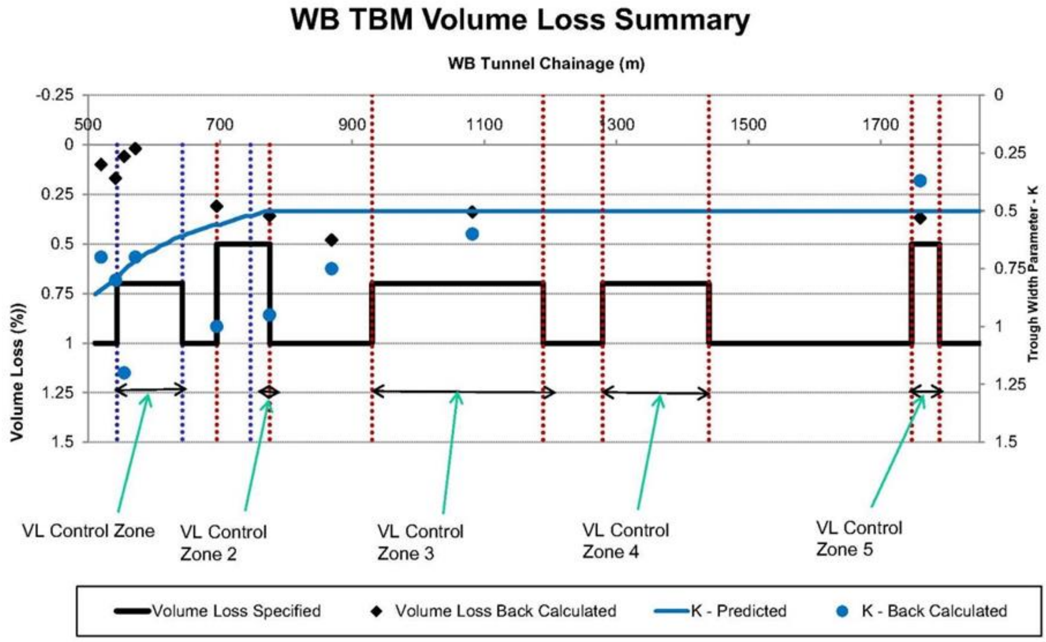


Fig. 5 Volume loss (VL) and trough-width factor (K) measured in the initial section of Westbound (WB) TBM. VL Control zones refer to areas of alignment sensitive to movements, requiring tighter settlement control

3 Instrumented site –Hyde Park

Tunnel-induced ground movements were carefully monitored as the tunnels advanced beneath Hyde Park. Surface settlements and lateral displacements were measured at several transects, using Precise Leveling Points (PLP's) and prisms, while more extensive subsurface component deformations (from extensometers and inclinometers) were obtained at one well-instrumented section. This paper fo-cuses on the leading TBM (Westbound tunnel) that passed beneath the instrumented section in January 2013. At this location the tunnel axis is at a depth, H = 33.6 m below ground level and was advancing at a rate of 3.5 m/hr with an average face pressure, pf = 175 kPa (pf/v0 = 0.54) and a grout pressure that decreased between pg = 170 - 90 kPa across the instrumented section.

The stratigraphy at the instrumented section comprised 5m of surficial sediments above the London Clay group. The underlying Lambeth group (Eocene sands and gravels 58 m bgl) is assumed to serve as a rigid base in the subsequent analyses. The groundwater table is located at the top of London clay.

On site measurements of tunnel induced-settlements obtained during the construction of the Crossrail Westbound tunnel in the alignment stretch below Hyde Park are shown in the following figures 6 and 7. As can be seen the situation is typically green-field.

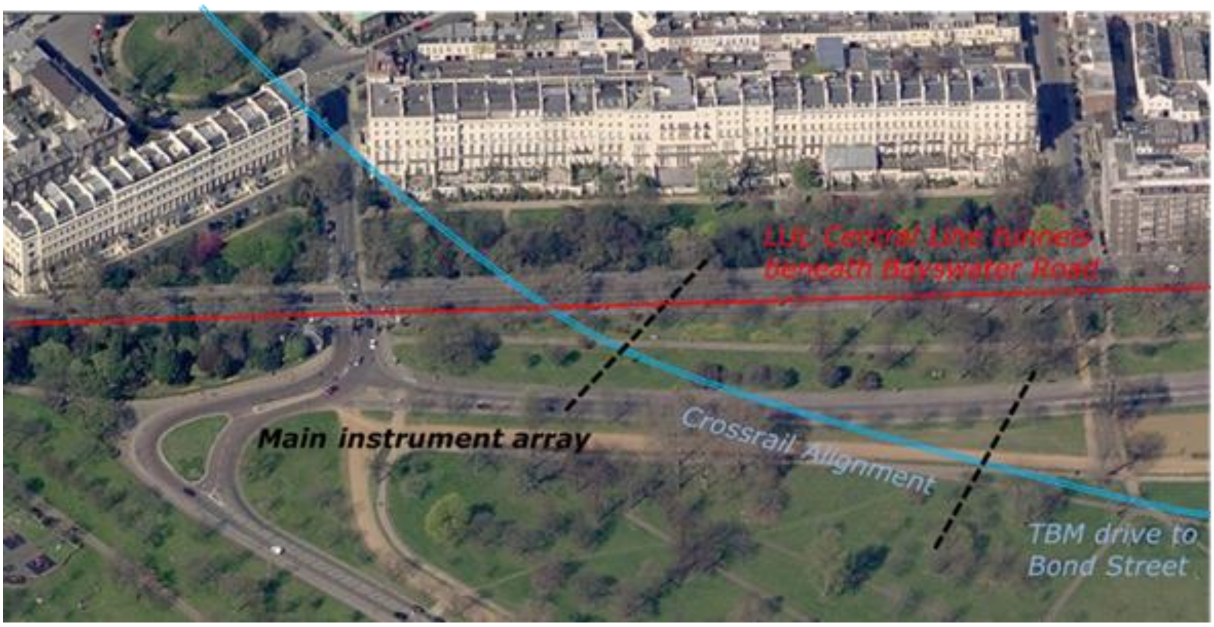


Fig. 6 Location of instrumented sections monitored in Hyde Park area

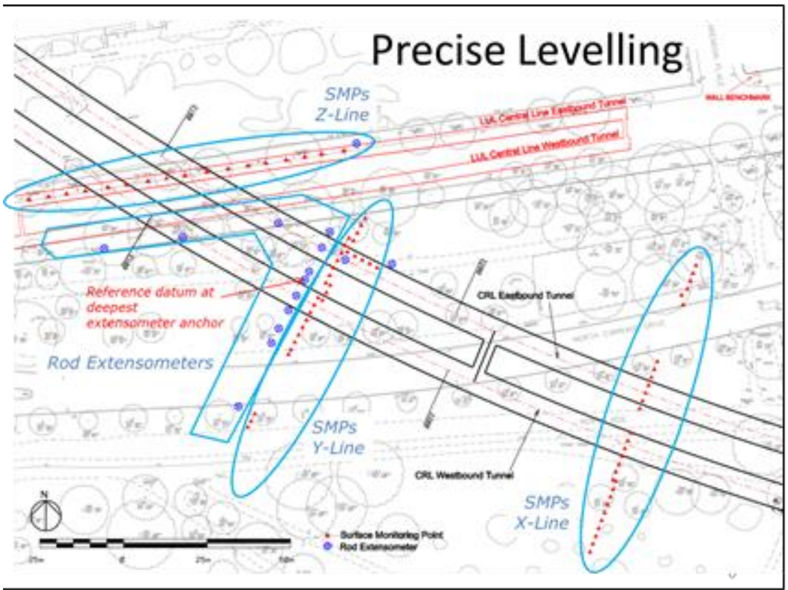


Fig. 7 Situation plan of the Precise Levelling Points installed

The sections employed for the comparison between the real settlements measurements and the settlement results obtained with the numerical models to be described in the following paragraph are sections of surface monitoring points Y-Line and X-Line. Their locations are depicted in the layout of figure 7. The following Figure 8 shows the transverse settlement trough registered during the construction of the Westbound tunnel at section X-Line. Settlements were measured for different distances of the TBM head from the control section. Negative distances indicate that the TBM head has not yet reached the control section whereas positive distances indicate that the TBM head has already gone past the control section. The figure shows how settlement increase as the TBM advances towards the control section and goes past it.

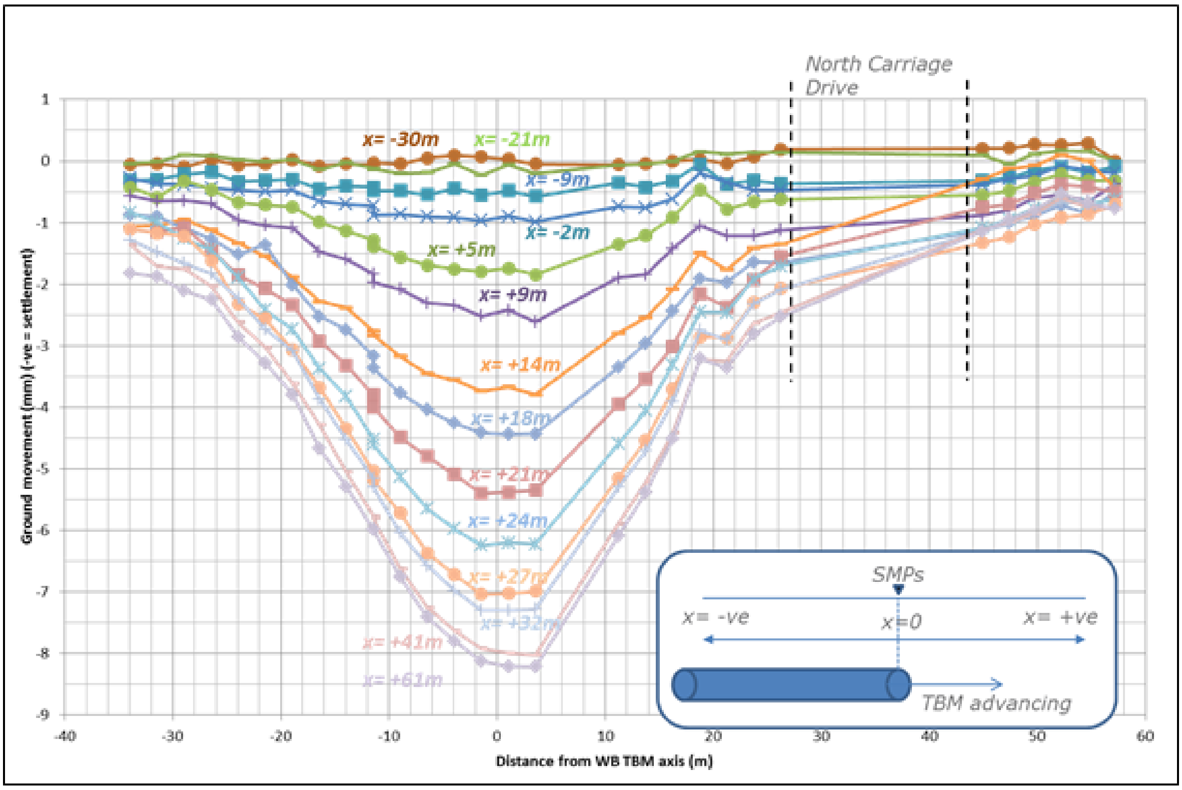


Fig. 8 Settlements measured due to construction of Westbound (WB) in section X-line (refer to Figure 7 for location). Note: X = -30 m means the TBM is approaching the instrument array but is 30 m away.

The following Figure 9 shows the longitudinal settlements recorded during the construction of the Westbound tunnel at section Y-Line and section X-Line, as the EPB machine excavated below each section. Settlements were registered at the tunnel's centerline for different distances of the TBM head from the control sections. The figure shows how settlement progressively increases as the TBM advances towards the control sections and goes past them.

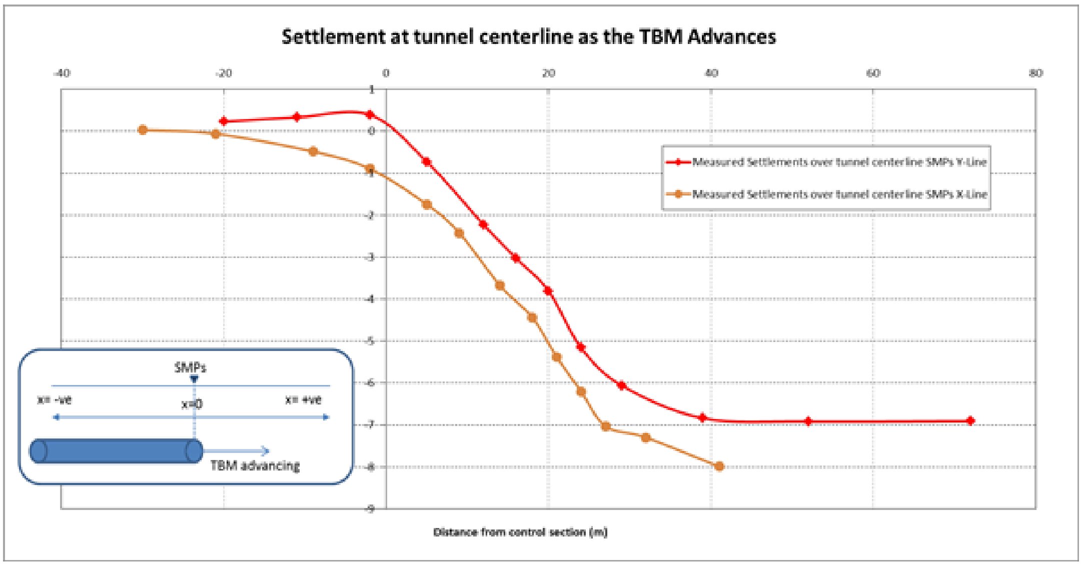


Fig. 9 Longitudinal settlements in mm measured due to construction of Westbound (WB) tunnel in sections X-line and Y-line

Finally the following Figure 10 shows a superimposition of the settlements registered at the other greenfield control sections existing in Hyde Park. All settlements correspond to "long term" settlements, that is, final settlements measured when the TBM is far away from the different control sections.

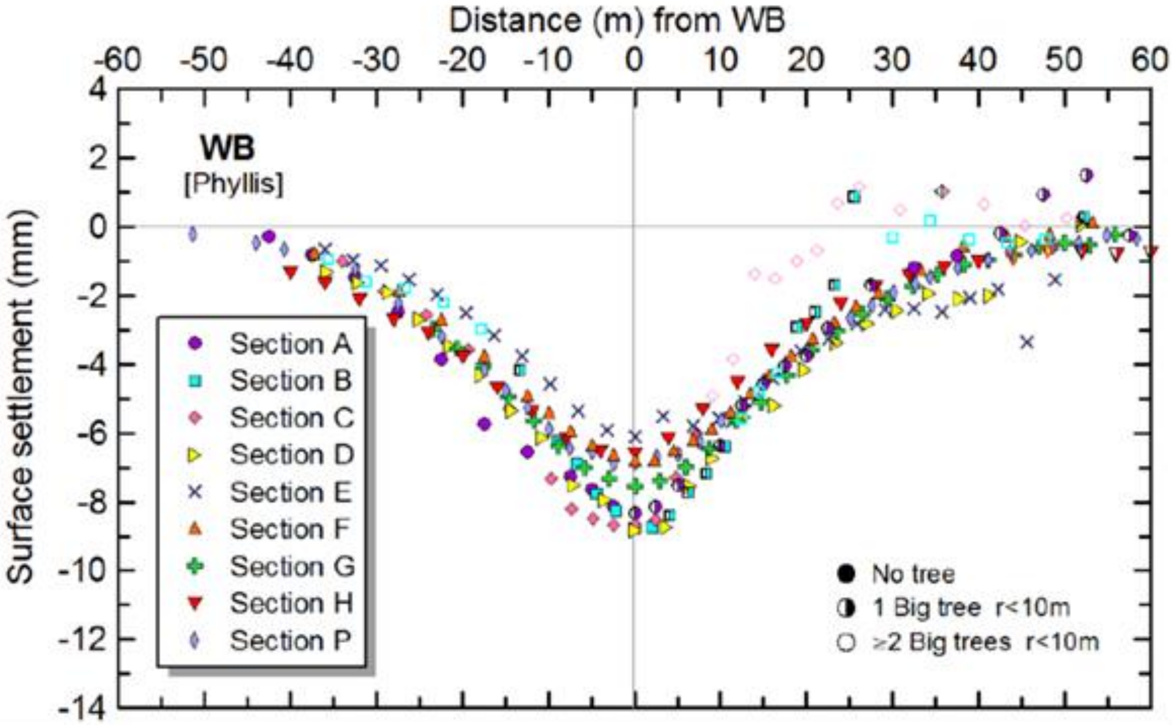


Fig. 10 Transverse settlement troughs for 9 greenfield control sections, corresponding to the Westbound TBM (WB) tunnel

4 Description of the numerical models

This paragraph presents a comparison between the results obtained with the Plaxis 3D and FLAC3D models performed with a standard Mohr-Coulomb model and those obtained with FLAC3D models with a Small Strain constitutive model using an Upper and Lower Bound modulus decay curves. All these results are then compared with real on site measurements of tunnelling-induced settlements registered during the construction of the Westbound Tunnel of Crossrail in its stretch below Hyde Park.

The comparison between real measurements and the results obtained in the numerical models indicates that a better adjustment of the real settlement troughs is obtained by using a Small Strain constitutive model.

Following Peck (1969), volume losses caused by tunneling, VL, are usually interpreted empirically assuming a Gaussian distribution for the transversal surface settlement trough where the centerline settlement, and inflection point, xi, are fitted to measured data (e.g., Mair et al. 1993). For undrained construction of tunnels in low permeability clays, the displaced volume at the ground surface, Vs = VL is then equated with the volume loss.

The FLAC3D model assumes symmetry and represents a half section of the circular tunnel. The model has a rigid boundary at the base (node displacements blocked in all directions) and node displacements in the lateral boundaries are only blocked in the normal direction of the plane of the lateral boundary. As depicted in the following Figure 11, the EPB machine is modelled introducing the accurate geometry of the cutting wheel, shield and lining ring corresponding to the TBM employed.

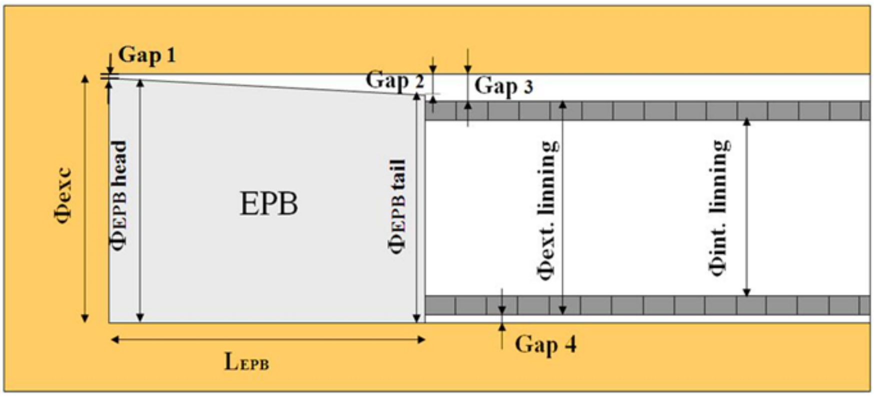


Fig. 11 Schematic representation of the TBM in the numerical model. Dimensions shown are: Φexc=7100 mm, ΦEPB head=7080 mm, ΦEPB tail=7050 mm, Φext lining=6800 mm, Φint lining=6200 mm, LEPB=12000 mm, Gap1=20 mm, Gap2=50 mm, Gap3=250 mm, Gap4=50 mm.

The face pressure applied by the TBM head is modelled as a normal pressure applied against the face of the elements of the mesh that constitute the face of the tunnel. The face pressure distribution is trapezoidal, with a minimum value at the crown of 180 kPa that increases gradually towards the tunnel invert according to the following equation: $\sigma(z) = 180 + 15 \cdot z$, where "z" is the vertical distance of each point of the tunnel face from the tunnel crown.

The analysis sequence followed consists of the following stages:

1. Initial Stage: Determination of the initial stress state of the different soil formations prior to tunnel excavation. A geostatic initial stress state using the earth pressure coefficient at rest (k0) assigned to each soil type. The initial hydrostatic pore pressure distribution is also determined in this stage. After equilibrium is reached, displacements are reset to zero.
2. Sequential excavation of the tunnel: The tunnel excavation is modelled following a total of 67 phases, each corresponding to a ring length of 1,5 m, i.e considering a stretch of 100 meters of tunnel (100/1.5 ≈ 67).

The measured longitudinal settlement troughs presented in Figure 9 have been used for the calibration of different numerical models in order to accurately reproduce with calculations the field data. Figure 12 shows the modulus decay laws adopted for the London Clay material and results of the comparison for the tunnel centerline settlements. As the London Clay is a fissured material there are two bounds to the deformation parameters: an upper bound given by the parameters for the intact clay, that is, without fissures; and a lower bound given by the behavior of the fissure. The deformation moduli that apply to a particular volume of clay will lie between these two bounds and will be determined by the spacing, extent and orientation of the fissures, by the direction of shearing, and by the kinematic constraints—that is, whether potential shear surfaces can seek out the lower-strength fissures. The preferred orientation of the fissures in London Clay means that fissures are more likely to be influential for certain directions of loading. In its simplest form this is shown in the left part of Figure 12, where two modulus decay bounds are proposed by Hight et al. (2002).

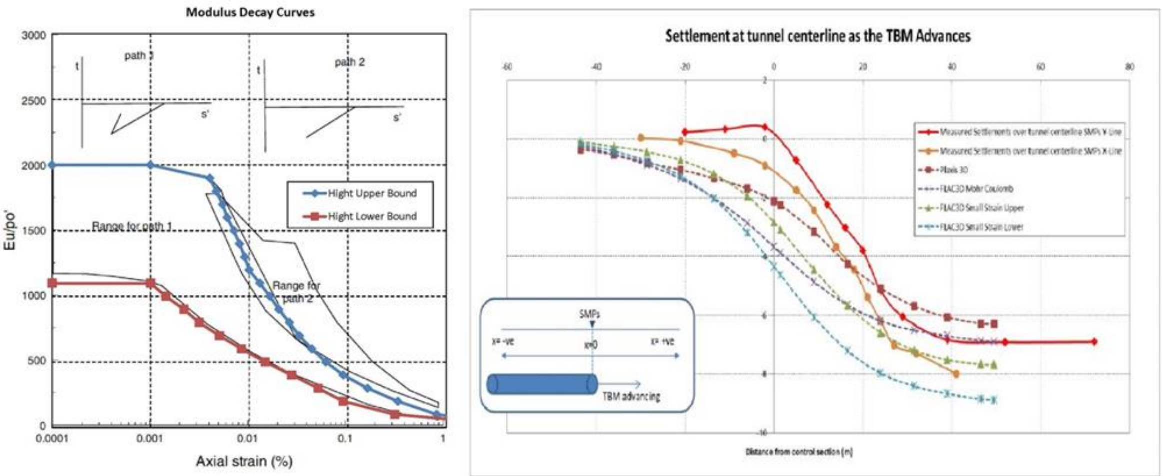


Fig. 12 a) Modulus decay curves adopted for the numerical models, modified from Hight et al. (2002). b) Comparison between real settlements in mm and numerical results (longitudinal trough)

From the preceding Figure 12, it can be seen that all calculations overestimate settlements when the TBM head has not yet reached the control section or is at the control section (x = 0 m). Settlements predicted by the numerical models resemble those measured on site when the TBM has gone past the control sections (from x ≈ 25 m onwards). However, the FLAC3D simulation performed with the Small Strain constitutive law using Hight's Upper Bound decay curve is the model that best adjusts the settlement troughs measured on site, especially the final settlements.

The following figures 13 and 14 present the comparison of the settlements measured on site with the settlements obtained with the numerical models. For comparison with the transverse settlements troughs measured in section SMPs X-Line, the settlements obtained when the TBM head is at the control section (Phase 34) have been compared with the settlements measured on site when the TBM head is 24 meters away from the control section.

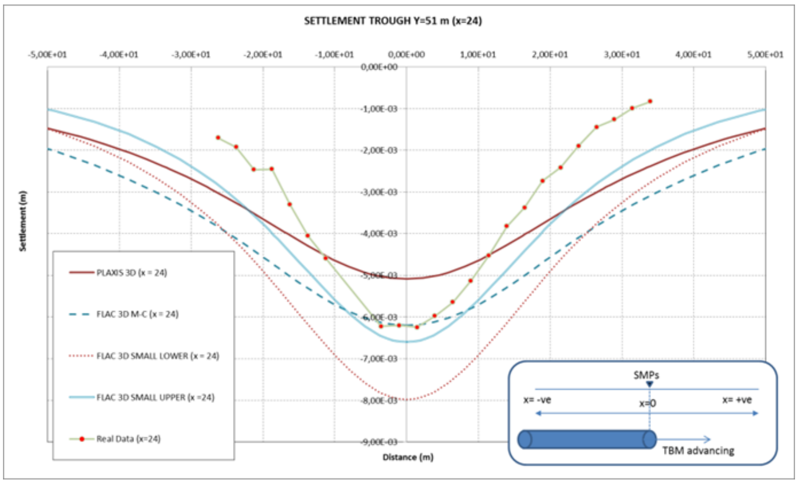


Fig. 13 Comparison between real settlements (mm) and numerical results for TBM face 24m past the Control section

Finally, the settlements obtained when the TBM head is 49 m past the control section (phase 67) have been compared to the settlements measured on site in the X-line, as previously shown in Figure 8. Again, the best fit is obtained using the Hight´s Upper Bound modulus decay curve.

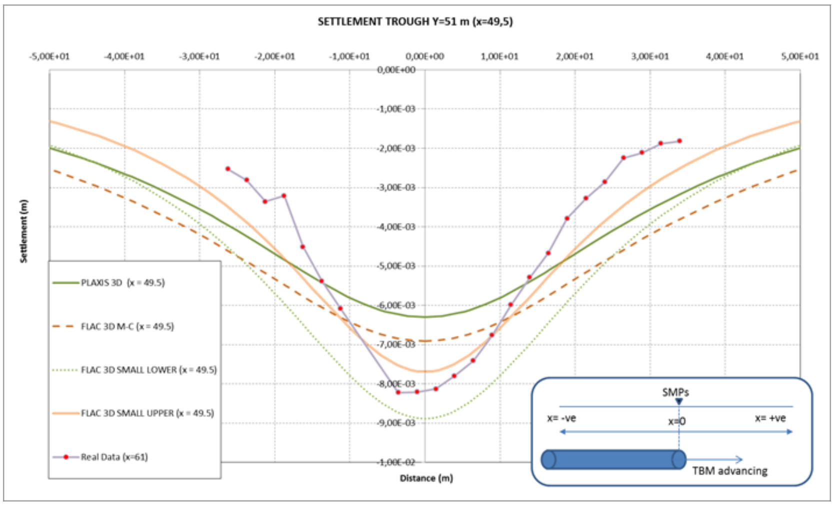


Fig. 14 Comparison between real settlements (mm) and numerical results for TBM face 49 m past the Control section

5 Conclusions

The construction of Crossrail C300 has provided an interesting experience of the performance of EPB TBM in London Clay. It has shown that a careful control of the different operational parameters of the machine, particularly the face pressure and the grout pressure, results in settlements being kept within the limits established during design. On the other hand, the back-fitted numerical models adjusted to simulate relevant details of the TBM operation and ground behaviour have also shown excellent agreement with the measured close-to-face and far-field deformations and hence, provide important insight for evaluating the EPB performance using numerical predictions from comprehensive 3D numerical models. There's an evident interest of such analysis for its application in future tunnelling works, not only in London Clay, but also in other geological environments provided there are accurate enough data on the ground deformation behaviour. This paper has shown the usefulness of such an integrated approach of data acquisition and interpretation through numerical models previously calibrated to give a comprehensive tool for the settlement control of TBM operation.

6 Acknowledgement

The author is grateful to the engineers from the BAM-Ferrovial-Kier Joint Venture who provided tremendous help in gathering data from the C300 project. This research was supported by Ferrovial-Agroman through the Ferrovial-MIT program.

References

Hight, D.W., McMillan, F., Powell, J.J.M., Jardine, R.J., Allenou, C.P. 20003. Some characteristics of London Clay. *Characterisation and Engineering Properties of Natural Soils* – Tan et al. (eds.)
© 2003 Swets & Zeitlinger, Lisse, ISBN 90 5809 537 1

Ieronymaki, E.S., Whittle, A.J. and Simic, D. 2014. Ground movements in Hyde Park caused by the Crossrail tunnel construction. Submitted for publication.

Mair, R.J., Taylor, R.N., Burland, J.B. (1996). Prediction of ground movements and assessment of risk of building damage due to bored tunnelling. *Proc Int. Symp. on Geotechnical Aspects of*

Underground Construction in Soft Ground. Mair, R.J. y Taylor, R.N. (eds.). Balkema, pp. 713-718. Rotterdam.

Peck, R.B. 1969. Deep Excavations and Tunnels in Soft Ground. *Active Geotechnics: Proceedings.* 7th International Conference on Soil Mechanics and Foundation Engineering (State of the art Volume), 225-290.

Standing, J.R. and Burland, J.B. 2006. Unexpected tunnelling volume losses in the Westminster area, London, *Géotechnique.* 56(1), 11-26.