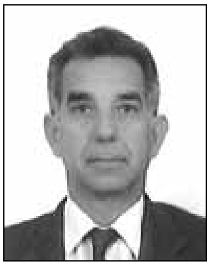
Settlement control: assuming the challenge of underground construction in London

El control de asientos: asumiendo el reto de la construcción subterránea en Londres



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Resumen
Los proyectos de túneles urbanos suelen incorporar riesgos asociados con los movimientos del terreno producidos por la excavación y sus efectos en edificios e instalaciones próximos. Los proyectos imponen límites estrictos en los movimientos permitidos (a veces medido como pérdida de terreno), y analizan el comportamiento a través de seguimiento en zonas y estructuras puntuales en la trayectoria del túnel. Los constructores también suelen evaluar y refinar sus sistemas de control durante la excavación para cumplir con estas limitaciones críticas del diseño. Las mediciones en campo libre de los movimientos en superficie y subsuperficie proporcionan datos fundamentales para la evaluación del rendimiento de distintos métodos de construcción de túneles y sirven para desarrollar métodos de predicción más fiables. En este artículo se expone la construcción realizada recientemente para Crossrail de dos túneles paralelos debajo de Hyde Park ejecutado por tuneladoras EPB, en donde se hace un análisis del rendimiento de las dos tuneladoras a través de soluciones analíticas y numéricas empleando parámetros ajustados a los datos de campo. El éxito de dicha evaluación queda demostrada por la concordancia entre el modelo de predicción y los datos de asentamiento reales.

Palabras clave
Proyectos de túneles urbanos, control de asentamientos, modelo de predicción

Abstract
Urban tunnelling projects inevitably involve risks associated with construction-induced ground movements and their effects on overlying buildings and facilities. Projects impose stringent limits on allowable ground movements (sometimes measured as volume loss), and evaluate performance through careful monitoring at selected sections and structures along the tunnel alignment. In addition, tunnel contractors often evaluate and refine their control systems during construction in order to meet these critical design constraints. Measurements of surface and sub-surface ground movements at free-field sites provide essential data for evaluating the performance of different tunnel construction methods and developing more reliable methods of prediction. This paper describes the recent EPB construction of twin tunnels for Crossrail beneath Hyde Park in which the performance of the two TBMs is analyzed through analytical and numerical solutions 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.

Keywords
Urban tunnelling projects, settlement control, model prediction

1. Introduction

Crossrail Ltd (CRL) was established in 2001 to promote and develop vital links to meet the needs of people and businesses throughout the South East, and to ensure that London continues in its role as the Europe's leading financial and business centre.

It was a 50/50 joint venture company between Transport for London and the Depart-ment for Transportation. On 5th December 2008 it became a fully owned subsidiary of TfL. CRL represents a real commitment to the development of new services to tackle the lack of capacity and congestion on the existing network. 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 (see figure 1):

C300: bore of two 6.2km tunnel drives between Royal Oak and Farringdon: Twin 7.1m 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

This paper will address the EPB construction works which started from Royal Oak por-tal, next to Paddington station, to Farringdon station with 2 EPB machines.

The site locations for the EPB tunnelling works are:

Royal Oak Portal – See Figure 2, main site for TBM, spoil transported away by train.

Figure 3 shows the longitudinal alignement, excavated mostly in London Clay.

Bond Street Station – 5 grout shafts / SCL works at 2 sites (see Figure 4).

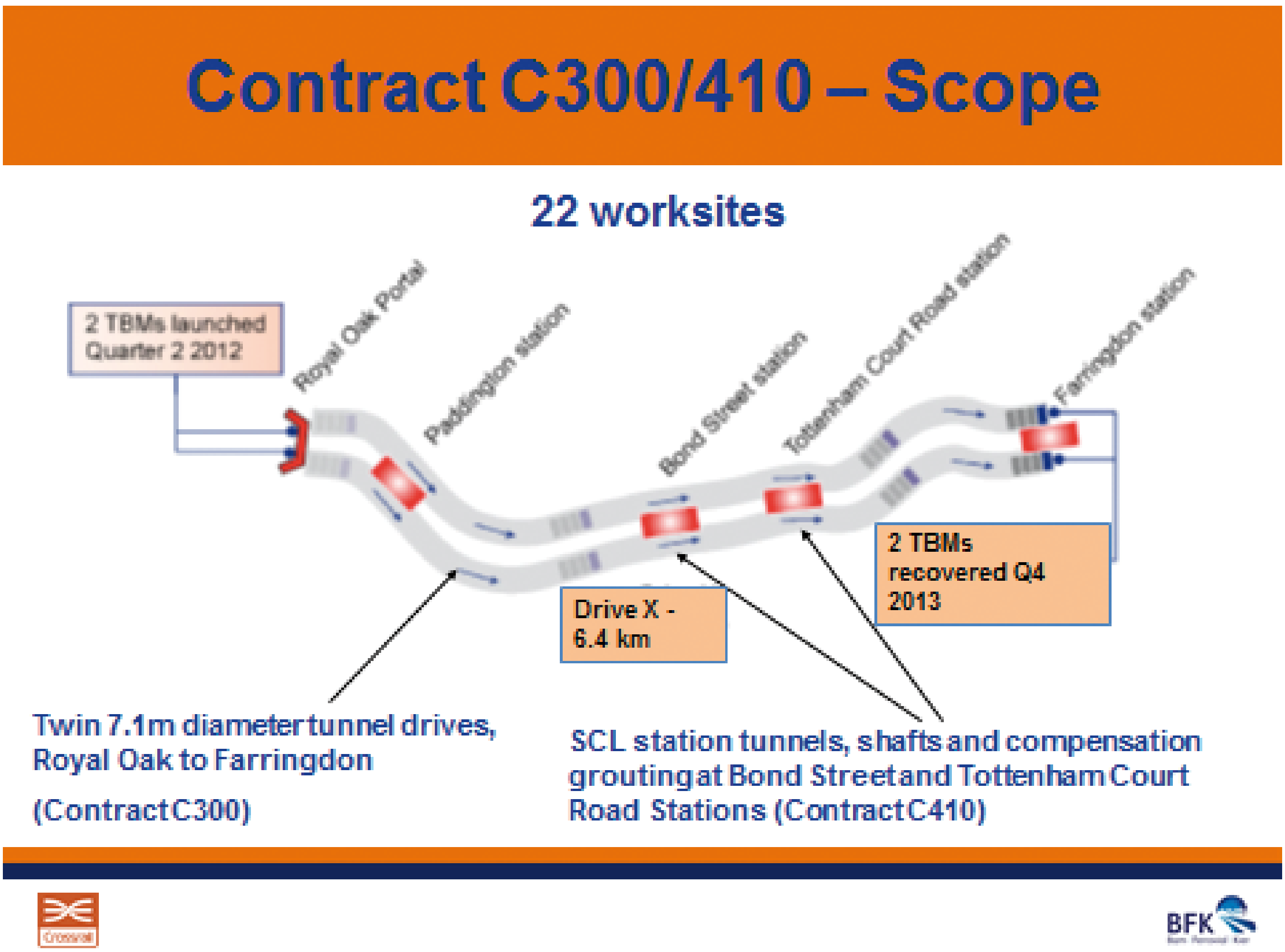


Fig. 1. Crossrail C300 and C410

Fig. 2. Royal Oak portal. Main tunnel site

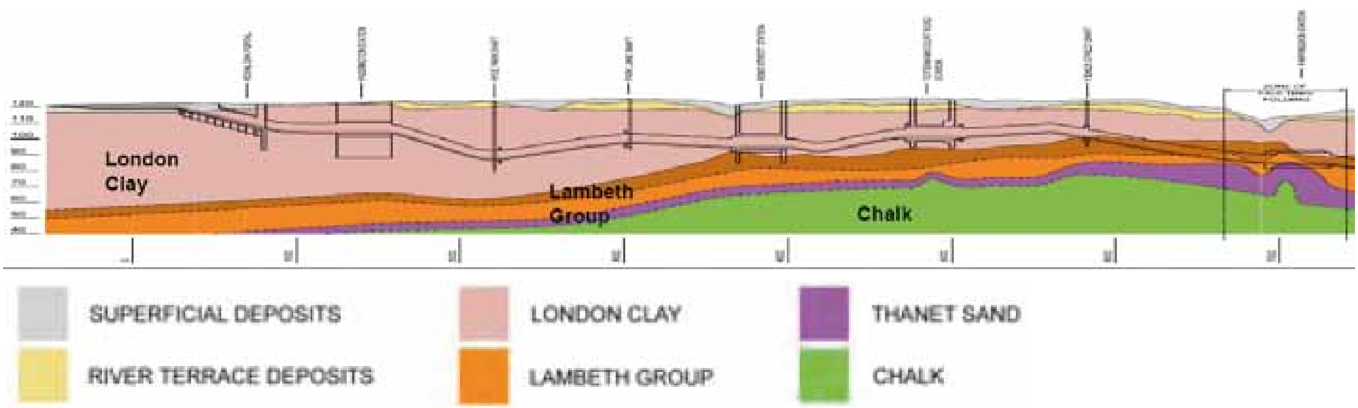


Fig. 3. Geology: most tunnelling is through London Clay

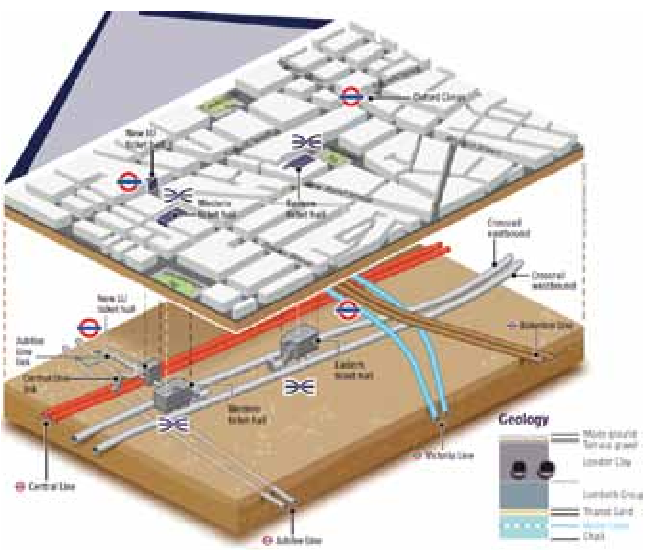


Fig. 4. Bond street station

Tottenham Court Road Station – 7 grout shafts / SCL works at 2 sites

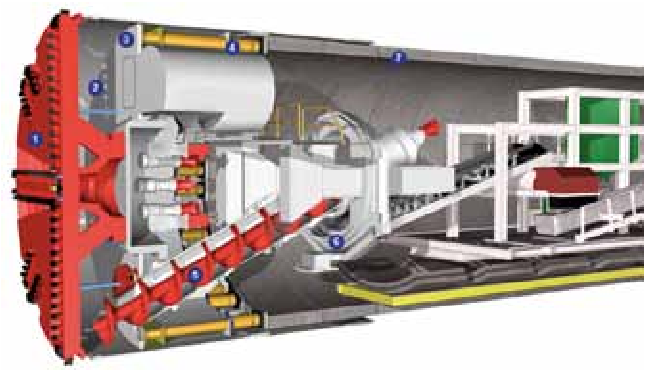
2. Operational control of the EPB excavation

Integrated team & systems for Monitoring ground movements has been in place during all tunnelling works. A particular strategy was devised to reduce the settlement impact through the control of EPB operational parameters.

As shown in Figure 5, action was taken in the cutting wheel, muck chamber, face pressure and jacking force.

Figures 6 to 7 show different examples of the real time monitoring that was carried out of some important operational parameters, such as:

- *Face pressure*
- *Grout pressure and volume*



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

Fig. 5. Strategies to reduce settlement through the control of TBM parameters

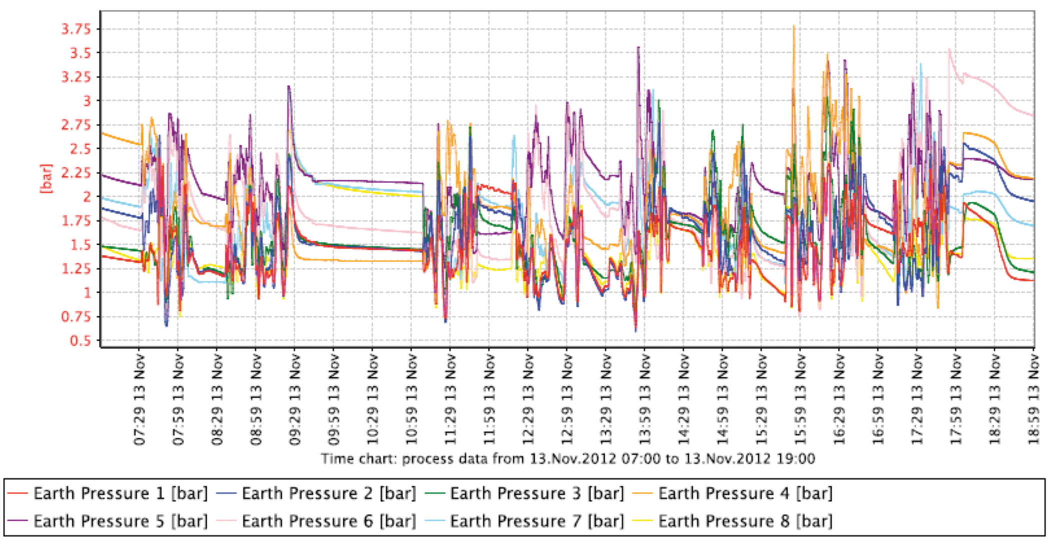


Fig. 6. Face pressure

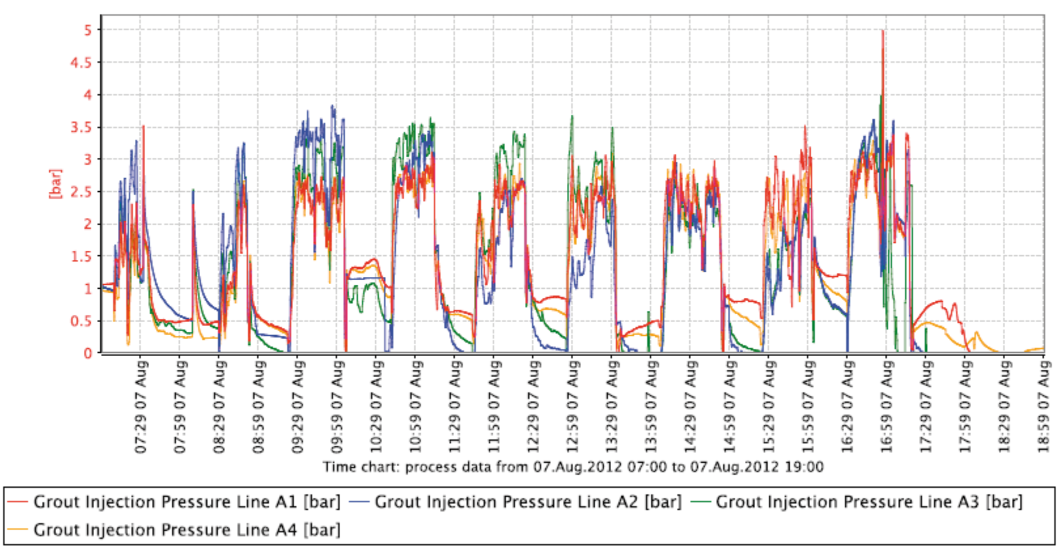


Fig. 7. Grout pressure

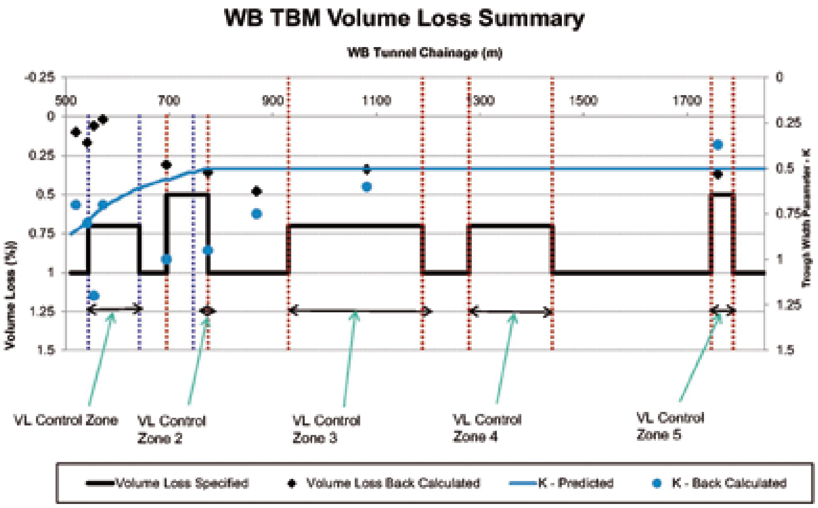


Fig. 8. Volume losses measured during TBM 1 operation

- *Propulsion Force of jacks and rate of advance*
- *Belt weights*
- *Cutter torque*
- *Foam injection quantities*
- *Belt scales*
- *EPB crown pressure*

Such integrated approach delivered confidence that we can accurately monitor and control the ground movements. This is summarized in Figure 8, where the specified and measured settlements are successfully compared, as all measured volume-losses fall below the specified values.

3. Instrumented site –Hyde Park

Crossrail contract C300 involved construction of twin tunnels, with inside diameter, 6.2m, running from Royal Oak portal eastwards to Farrington station. These were con-structed using Earth Pressure Balance (EPB) Tunnel Boring Machines (TBM) with max-imum 7.1m diameter cutterhead and 0.30m precast concrete lining segments forming a 6.8m outer diameter lining system. Tunnel-induced ground movements were careful-ly 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 sec-tion. This paper focuses 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 = 33.6m below ground level and was advancing at a rate of 3.5m/hr with an average face pressure, pf = 175kPa (pf/v0 = 0.54) and a grout pressure that de-creased between pg= 170-90kPa 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 58m 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 is shown in the following figures 9 and 10. As can be seen the situation is typically green-field.

The sections employed for the comparison between the real settlements measure-ments 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 10. The following Figure 11 shows the transverse settlements trough registered during the construction of the West-bound tunnel at section X-Line.

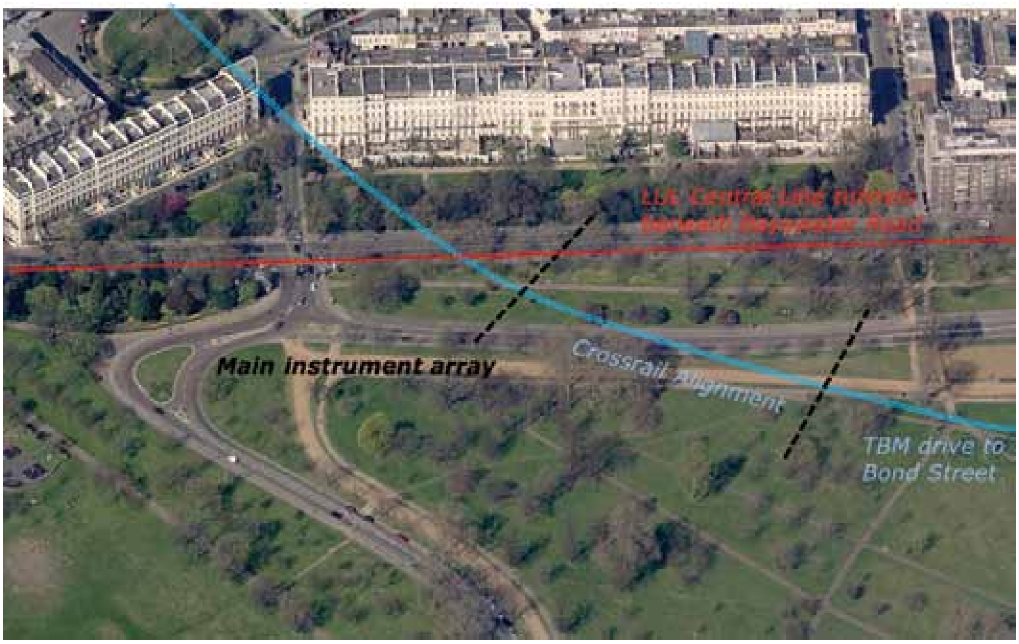


Fig. 9. Location of instrumented sections monitored in Hyde Park area

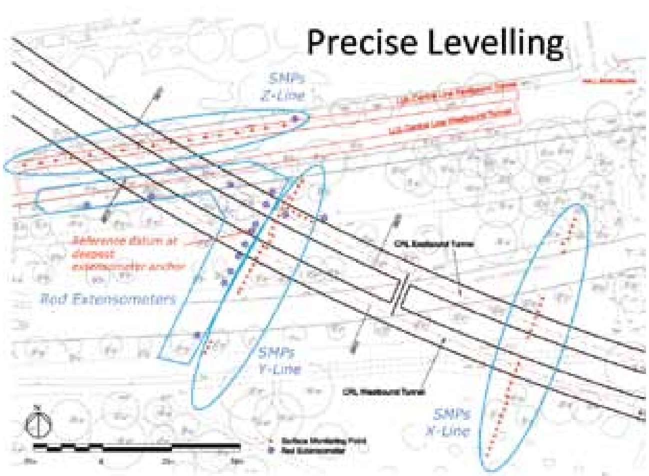


Fig. 10. Situation plan of the Precise Levelling Points installed

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.

The following Figure 12 shows the settlements recorded during the construction of the Westbound tunnel at section Y-Line and section X-Line. Settlements were regis-tered at the tunnel's centerline for different distances of the TBM head from the con-trol sections. The figure shows how settlement increase as the TBM advances towards the control sections and goes past them.

Finally the following Figure 13 shows a superimposition of the settlements registered at the different control sections. All settlements correspond to "long term" settlements, that is, final settlements measured when the TBM is far away from the different con-trol sections.

4. Description of the FLAC 3D numerical model

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 ob-tained with FLAC3D models with a Small Strain constitutive

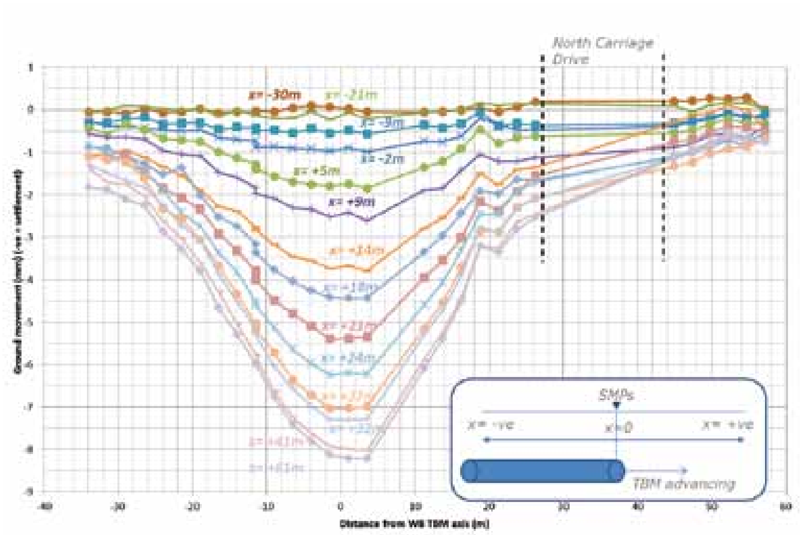


Fig. 11. Settlements measured due to construction of Westbound (WB) in section X-line

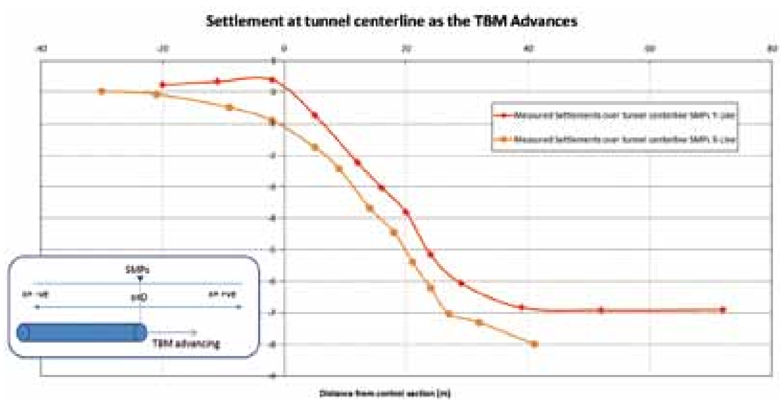


Fig. 12. Settlements in mm measured due to construction of Westbound in section X-line

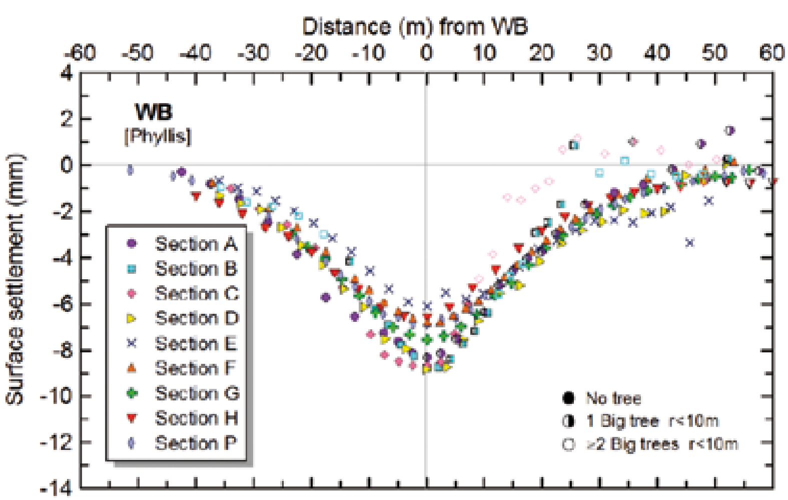


Fig. 13. Measured settlements by conventional levelling, represented from the Westbound TBM (WB) axis

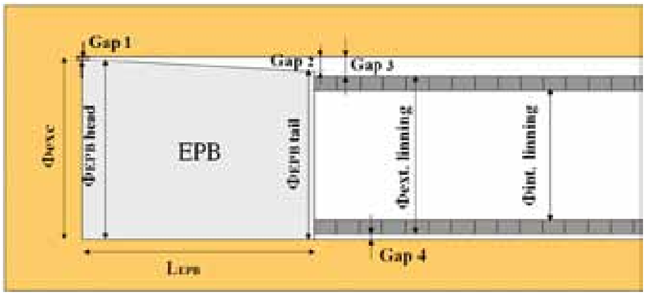


Fig. 14. Dimensions of the FLAC3D model

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 construc-tion 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 Fig-ure 14, the EPB machine is modelled introducing the accurate geometry of the cutting wheel, shield and lining ring.

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 kN/m^2 that increases gradually towards the tunnel invert with a gradient of 15 kN/m^2 according to the following equation:

$$\sigma(z) = 180 + 15 \cdot z$$

where "z" is the vertical distance of a certain 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 for-mations prior to tunnel excavation. Gravity loading is considered for vertical stresses and horizontal stresses are determined according to the earth pres-sure 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 and plastic (yielded) zones are reset to zero.

2) Sequential excavation of the tunnel: The tunnel excavation is modelled follow-ing a total of 67 Phases (Stages) that are considered to excavate the 100 me-ter long tunnel (100/1.5 ≈ 67).

Data reflected in Figure 12 have been used for the calibration of different numerical models in order to accurately reproduce with calculations the field data. This analysis is beyond the scope of this paper, only a mention will be made in the following Figure 15

From the preceding Figure 15, it can be seen that all calculations overestimate settle-ments 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). The FLAC3D model performed with the Small Strain constitutive model (Up-per Bound) is the model that better adjusts the settlement troughs measured on site, especially the final settlements.

The surface settlement and horizontal displacement troughs and the volume loss (area enclosed by the settlement trough divided by the excavated area of the tunnel and expresses as a percentage) have been determined for several cross sections.

The following figures 16 and 17 present the comparison of the settlements measured on site with the settlements obtained with the numerical models. For comparison with

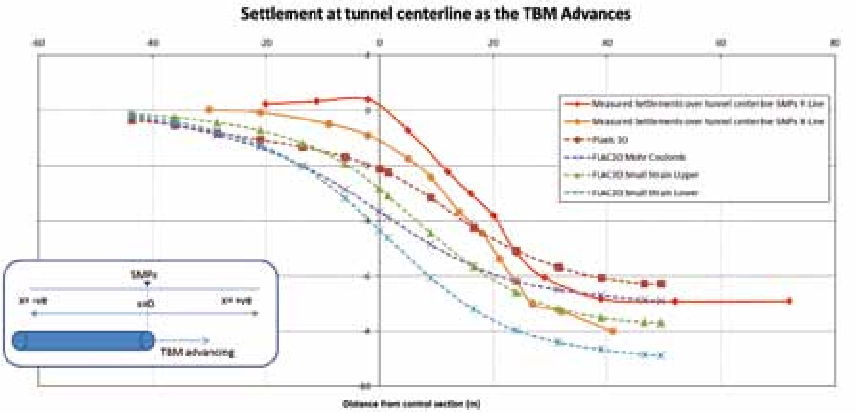


Fig. 15. Comparison between real settlements in mm and numerical results (longitudinal trough)

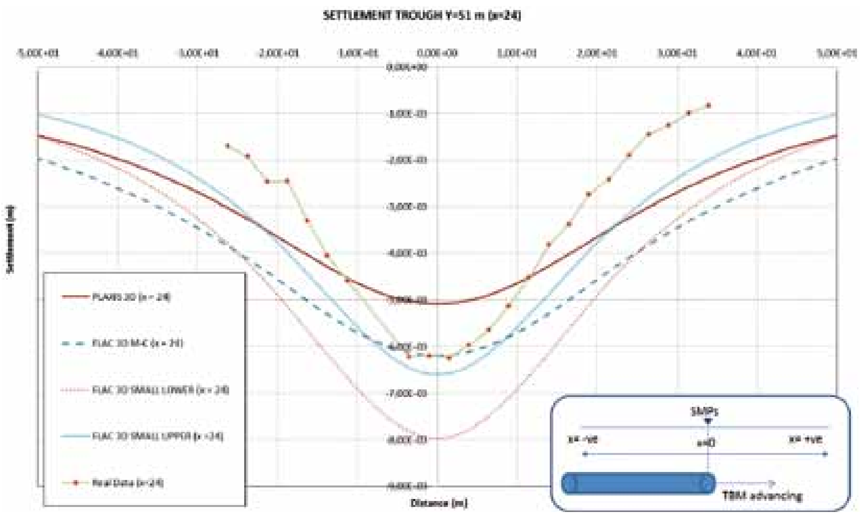


Fig. 16. Comparison between real settlements (mm) and numerical results (phase 50). Face 24m past the Control section

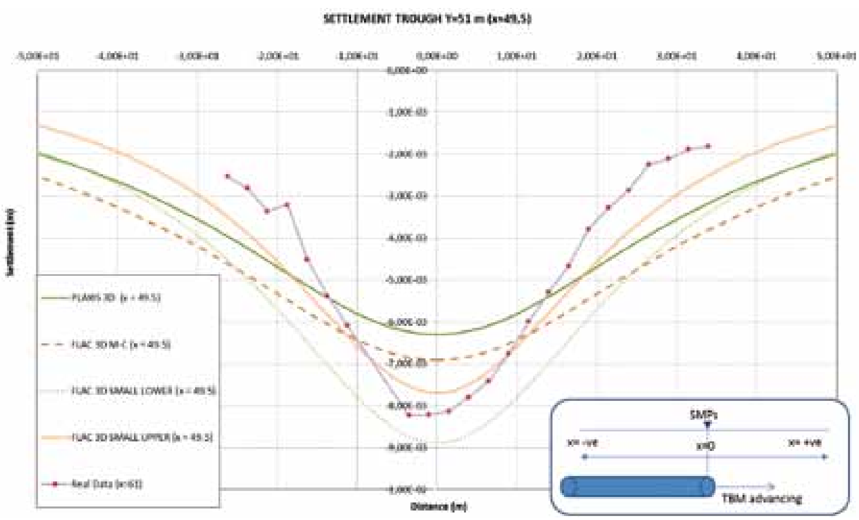


Fig. 17. Comparison between real settlements (mm) and numerical results (phase 67). Face 49m past the Control section

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. Finally, the settlements obtained when the TBM head is 49m past the control section (Phase 67) have been compared to the settlements measured on site in the X-line, as previously shown in Figure 11.

5. Conclusions

The construction of Crossrail C300 has provided an interesting experience of the per-formance of EPB TBM in London Clay. It has shown that a careful control of the differ-ent operational parameters of the machine, particularly the face pressure and the grout pressure, results in settlements being kept within very tight limits The back-fitted numerical solutions 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 finite difference models. There's an evident interest of such analysis for its application in fu-ture tunnelling works in London Clay.

From the preceding analysis, the following conclusions can be derived:

1-For Phase 34 (x =0, TBM head at control section), all settlement troughs obtained with the different models are significantly different from the settlement trough measured on site. The settlement troughs that best adjust are the one obtained with Plaxis 3D and the one obtained with FLAC3D using the Small Strain constitutive model with the Upper Bound decay curve.

2-For Phase 50 (x =24m, TBM head at +24 m from the control section), the settle-ment troughs that best adjust are the ones obtained with FLAC3D using the standard

Mohr Coulomb model and the Small Strain constitutive model with the Upper Bound decay curve. The FLAC3D model using the Mohr Coulomb law better adjusts the maximum displacement, but settlements at greater distances from the tunnel's centerline are greater than those measured on site. The maximum settlement provided by the Small Strain constitutive model with the Upper Bound decay curve is slightly greater than the maximum settlement measured, but settlements at greater distances from the tunnel's centerline adjust better to those measured.

3-For Phase 67 (x =49, TBM head at +49 m from the control section), it is clear that the settlement trough that best adjusts the settlements measured is the trough ob-tained with the FLAC3D model using the Small Strain constitutive model with the Up-per Bound Decay Curve.

6. Acknowledgement

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