Improving the engineering knowledge from Crossrail data – Kempton Court case study

by

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I hereby declare that, except where specifically indicated, the work submitted herein is my own original work.

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Technical abstract

In highly populated areas, such as London, with existing tunnels and deep foundations constructed during different periods ranging from few hundreds of years ago to modern construction techniques, which constantly being modified, geotechnical engineers more often face the challenge of constructing tunnels close beneath structures' foundations. The tunnelling works affect the ground in these areas, which deflections affect the foundation and then the structure itself. Therefore, it is vital not only to design structures to be able to withstand the effects of tunnelling beneath, but also to engineer tunnels and plan tunnelling works to avoid extensive movements and damage to structures.

The aim of this report is to describe and analyse ground movements of Kempton Court, 2 Durward Street located in the zone of influence of Whitechapel Crossrail Station. The Kempton Court building consists of two structures – Building A and Building B. The building is 4 storey masonry structure lying on pile foundations. The elevations of the Building A from Brady Street was found to be most affected by tunnelling works from western parts of Eastbound and Westbound Crossrail tunnels being constructed from October 2012 till July 2013 using sprayed concrete lining (SCL) methods.

The data collected from real time capturing software on tunnel construction progress and records from monitoring sensors placed in the area of underground works and on the structure was extracted for both greenfield and structural array cross sections parallel Brady street elevation - predicated critical settlement trough location. Using the information obtained from literature review on surface settlements and volume loss theory, for each monitoring array line the settlements were found for pilot and enlargement of pilot tunnelling works for Eastbound and Westbound tunnels, then Gaussian distribution curves fitted to final stages of tunnel section progress.

The results showed that greenfield settlements produced better fit of Gaussian curve compared to structural monitoring sensor array results. Also, structural surface settlement response were of similar profile to greenfield response. The structural settlements were also compared to the finite element model response produced from greenfield results provided by Arup, it was found that 2D FE model produced similar settlement response for the structure observed.

The results of surface settlement volume loss calculations produced similar maximum settlement, trough width parameters between greenfield and structure, which showed structure to behave flexibly.

Possibly to improve the analysis and to aid as a comparison to the results obtained, more monitoring sensor sections could have been analysed, especially taking into account the reflection of compensation grouting taking place in the south-east in the settlement results of Westbound tunnel.

Introduction

Kempton Court and Crossrail works information

Kempton Court (2, Durward Street, London) building is located in the area of Whitechapel Crossrail Station construction. Figure 1 shows relative location of the underground tunnel in buildings area.

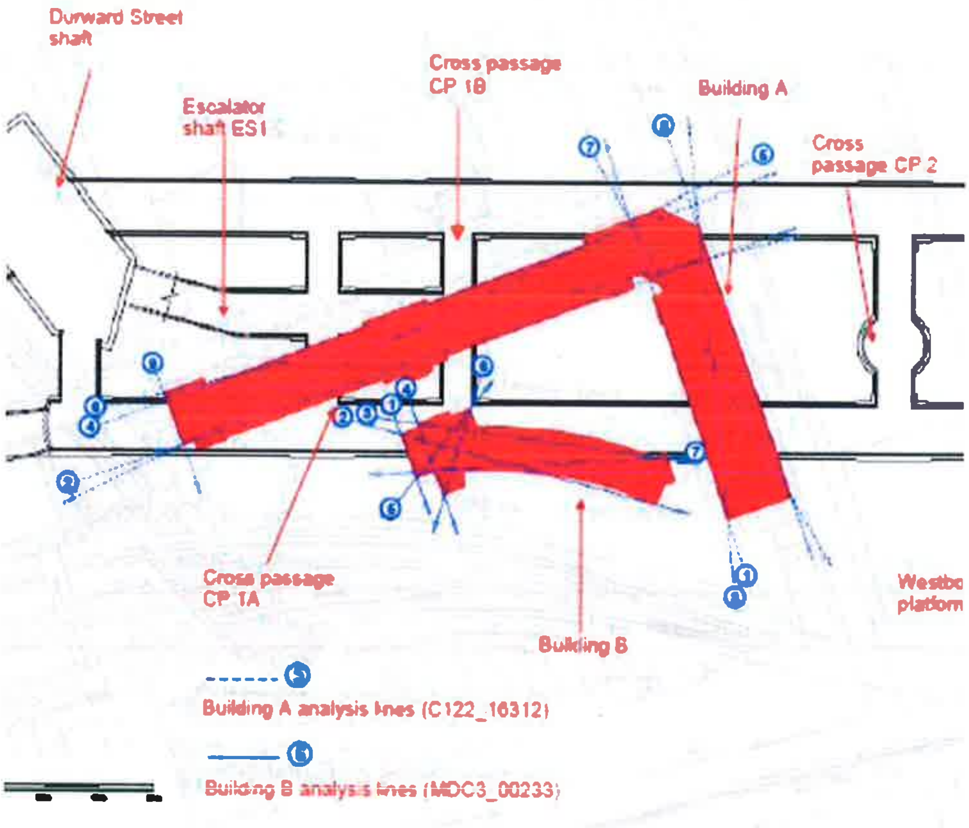


Figure 1. Kempton Court Building A and Building B location relative to tunnel plan [1]

Tunnel construction started back in 2012 and data on tunnelling progress has been received in autumn of 2013.

Construction of Crossrail in Whitechapel station area began from shafts CS1, CP2S and CP2N. Pilot tunnels started from shafts both in west and east directions of Eastbound and Westbound tunnels. The latest was done construction of CHRS.

Tunnels were constructed using open face SCL method. The tunnels cross-sections vary in diameter and vary in shape from circular to oval. For analysis the average diameters of 6.26 m and 10.74 m respectively will be taken for pilot and enlarged pilot tunnels. Relative locations are 87.63 mATD and 87.78 mATD for pilot and enlarged pilot tunnels respectively. The ground level was found to be at 111.9 mATD.

Structural details

Figure 2. General view of Building A and Building B looking East [2]

Kempton Court, build in 1995, consist of two structures, referred in Crossrail documentation as Building A and Building B. Each building has four storeys and piled foundations, pile length is ranging between 11.1 to 19.9 m. Figure 2 shows the photo of its two building looking East.

The ground floor is supported by 150 mm pre-cast concrete units spanning onto the deep reinforced ground beams of 500 mm x 600 mm. The first two floors are constructed from timber, except the shops on Brady Street with 150 mm pre-cast concrete units spanning steel beams and load bearing masonry. External walls are cavity construction with thick lightweight block inner leaf and brick outer leaves. The roof is made of timber trussed rafter.

Monitoring data

To measure the movement of ground and building's structure monitoring systems were installed during the different periods of year of 2012. Three types of monitoring sensors were installed: BRE levelling studs, domed metal studs, automatic 3D prism targets on the building.

The focus in this report will be given to western Eastbound and Westbound tunnels. Unfortunately, no monitoring data available after the 1st of June, hence full analysis of the effect from enlargement of Eastbound pilot tunnel could not be presented.

Theory

Surface settlement

The shape of surface settlement trough that develops during tunnelling works is defined by Gaussian distribution, as shown on figure 3 below. The settlement in clays, S is defined as

$$S = S_{max}\, e^{(-x^2/2i^2)},$$

where S_{max} is the maximum settlement, which occurs above the tunnel centreline. The *i* value represents width of settlement profile, i.e. the distance from the tunnel centre to the point of inflexion of the trough (shown on figure 3). The total distance from the tunnel centreline to trough edge is found to be about 2.5*i*.

O'Reilley and New produced the relationship between depth of tunnel axis below ground and *i* for UK tunnels in clays. The fitted linear relationship was presented to be

$$i = 0.43z_0 + 1.1$$

In this report, as in many works in this area, linear relationship of

$$i = K\, z_0$$

will be used to simplify the analysis.

The volume loss (or ground loss) is the ratio of ground lost in the tunnels area of influence and defined as

$$V_{L=}\frac{4V_S}{\pi D^2}$$

where D is excavated diameter and V_S represents the volume of transverse settlement trough per metre length of tunnel, obtained by integrating the settlement equation:

$$V_{S=}\left(\sqrt{2\pi}\right)\, i\, S_{max}$$

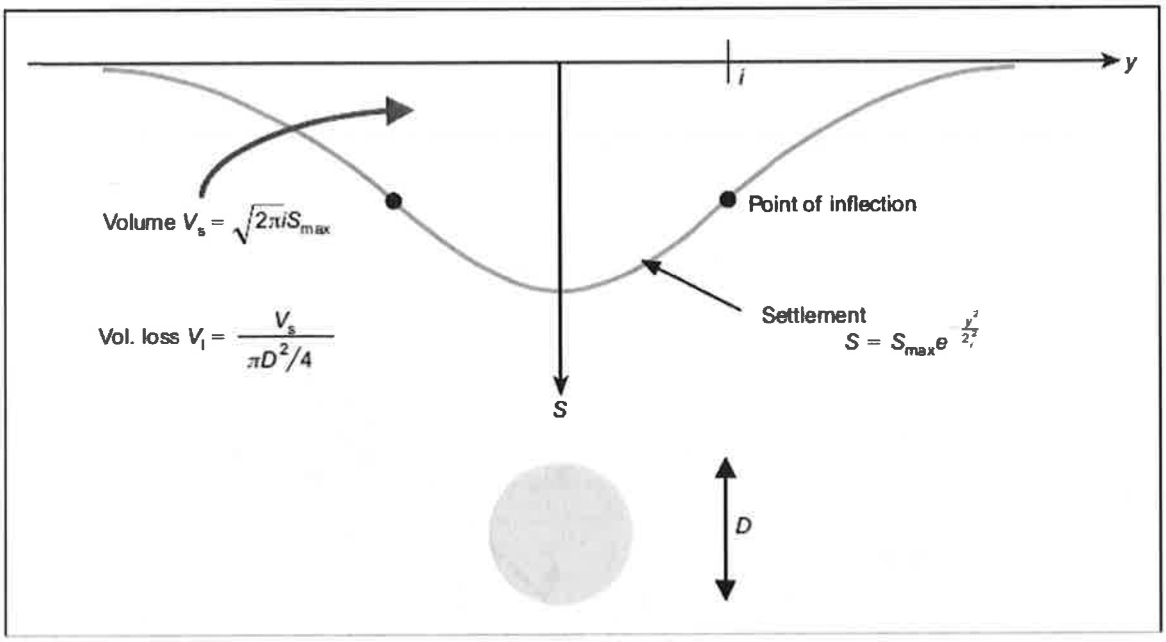


Figure 3. Definition of volume loss [3]

Subsurface settlement

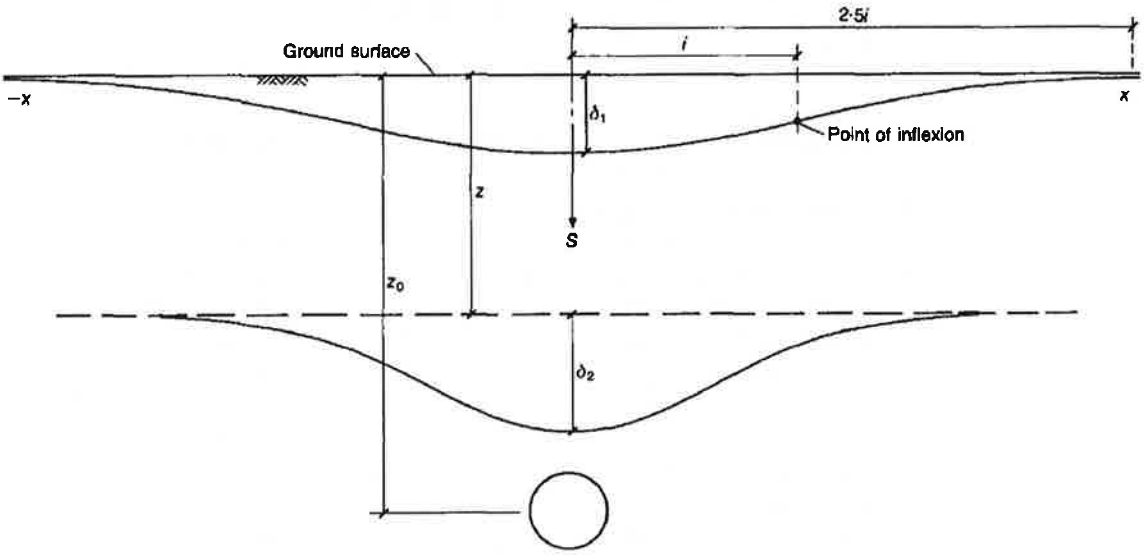


Figure 4. Subsurface settlement profile relative to surface [4]

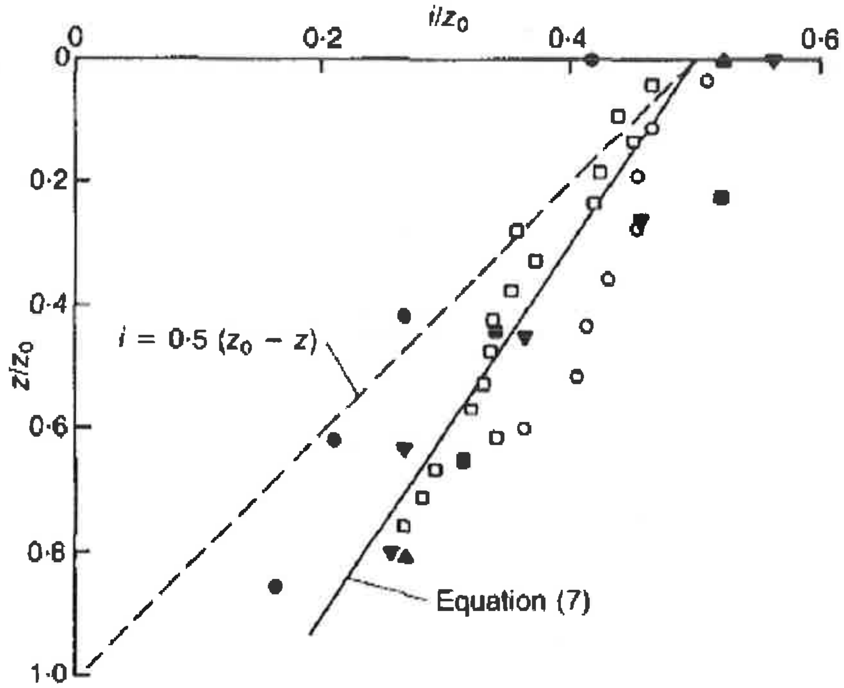
Figure 4 show the subsurface settlement profile relative to surface, which also can be characterised by Gaussian distribution, however, the research shown that K parameter increases with depth, which needs to accounted when approximating subsurface settlements.

Substituting tunnel depth correction for subsurface K parameter estimate, the value of trough width *i* can be expressed as:

$$i = K\,(z_0 - z)$$

where z is a pile depth level.

Figure 5 below shows variation of subsurface settlement trough width parameter with depth for tunnels in clays, obtained from various field measurements.



	Location	Soil type	D: m	z_0: m	Reference
●	Green Park	London Clay	4·1	29	Attewell & Farmer (1974)
▲	Regent's Park (northbound)	London Clay	4·1	20	Barratt & Tyler (1976)
▼	Regent's Park (southbound)	London Clay	4·1	34	Barratt & Tyler (1976)
■	Willington Quay	Soft clay	4·3	13.5	Glossop (1978)
○	Centrifuge* model 2DP	Soft clay	0·06	0·13	Mair (1979)
□	Centrifuge* model 2DV	Soft clay	0·06	0·22	Mair (1979)

*Models tested at 75g: equivalent full-scale D = 4·5 m, z_0 = 9·8 m (2DP), 16·5 m (2DV)

Figure 5. Variation of subsurface settlement trough width parameter with depth for tunnels in clays [5]

The field measurements show that previously used factor of 0.5 does not give good representative of trough width parameter, hence new relationship was obtained by finding the best fit line (shown as Equation 7 on the figure) for field measurements giving

$$\frac{i}{z_0} = 0.175 + 0{,}325(1 - \frac{z}{z_0})$$

Substituting this to the previous relationship, K value for subsurface settlements will be:

$$K = \frac{0.175 + 0{,}325(1 - \frac{z}{z_0})}{1 - \frac{z}{z_0}}$$

Using this new K parameter more realistic width of subsurface settlements can be obtained, then to be used for more reliable comparison with structural settlements found from real-time measurements.

Hence, using theoretical relationships outlined above, the following procedure of investigating settlements due to Crossrail tunnelling works and its corresponding volume loss to be followed:

1. Critical settlement trough location was found
2. Greenfield and structural cross sections to be investigated were chosen
3. Tunnelling works constructions progress was analysed
4. Periods for analysis for settlements due to Eastbound and Westbound pilot and pilot enlargement tunnels were found
5. Plots of Settlement vs perpendicular distance with selected tunnel centreline intersection were plotted
6. Gaussian distribution curves were fitted to the settlement profiles to calculate volume loss, maximum settlement and its K parameters.

Methodology

Settlement analysis

For settlement analysis the most critical region, where western Eastbound and Westbound tunnels were constructed, of greenfield area of Brady Street behind building B and part of the structure parallel to Brady Street were chosen, giving in total three monitoring sensor arrays. One long array of precise levelling points for greenfield and two arrays of BRE sockets on Building B for structure (figure 6).

The readings for analysis were provided by Crossrail representative M.Alhaddad in the form of spreadsheets (construction progress map) and monitoring data files broken down to several periods and classified by sensor type.

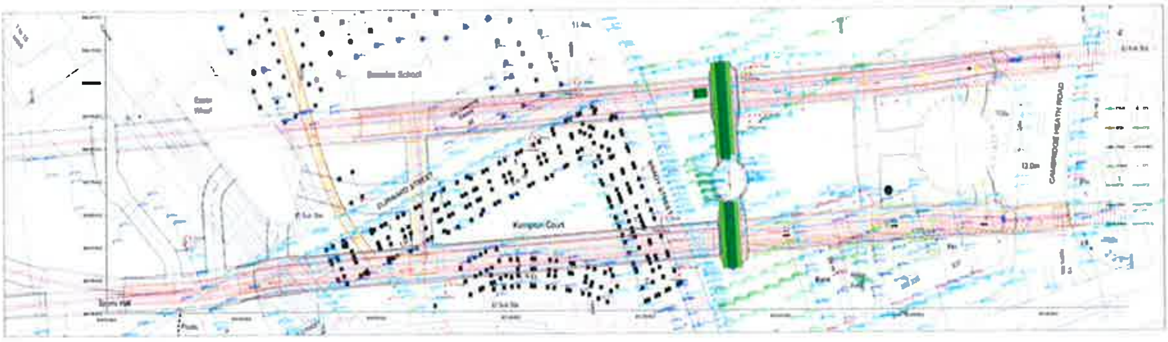
Figure 6. Settlement monitoring arrays (red – greenfield LP, blue – structural BRE)

Construction progress images were plotted (see figure 7 below) to serve as an aid to visualise construction progress and its effect on different stages of construction. As was noted before, we are interested in west parts of Eastbound and Westbound tunnels. Hence, the called Gantt chart, shown on figure 8, was created to summarise the overlapping periods in tunnel construction to aid for analysis.

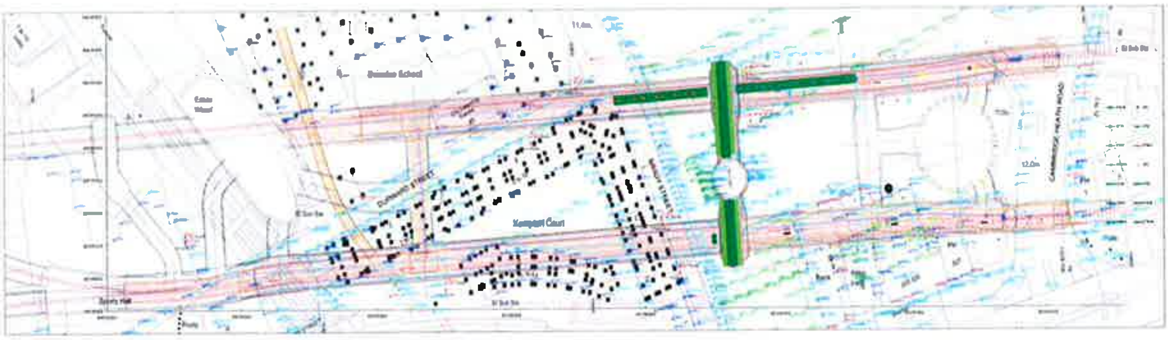
Construction of Eastbound pilot tunnel (PTE) was done in two stages: starting from 19th October 2012, PTE works pause from 18th November 2012 to 25th January 2013, and PTE works end on 19th February 2013.

Construction of Westbound pilot tunnel (PTW) started on the 13th of November 2012, and lasted till 22d January of 2013, switching back to Eastbound works and continuing pilot works from 6th February 2013 to 6th March 2013.

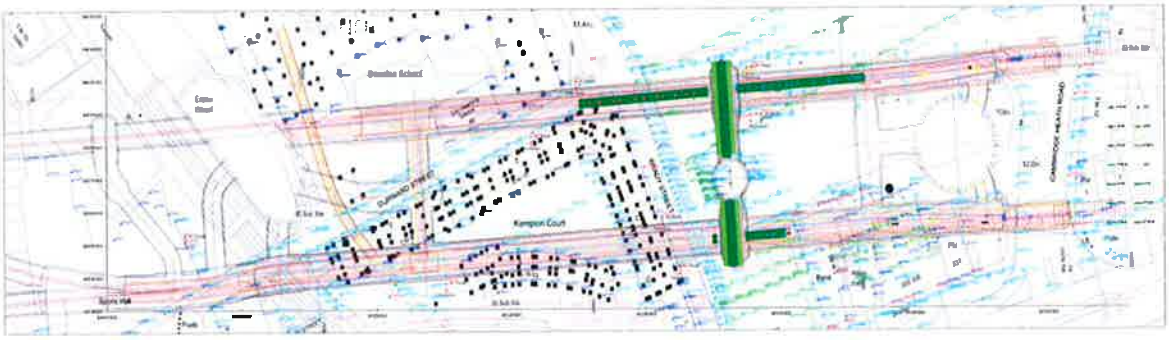
From the 27th of March 2013 till 13th of July 2013 lasted enlargement of Westbound pilot tunnel (ETW). On the 25th of May works launched on enlargement of Eastbound pilot tunnel (ETE) ending on 24th July 2013.



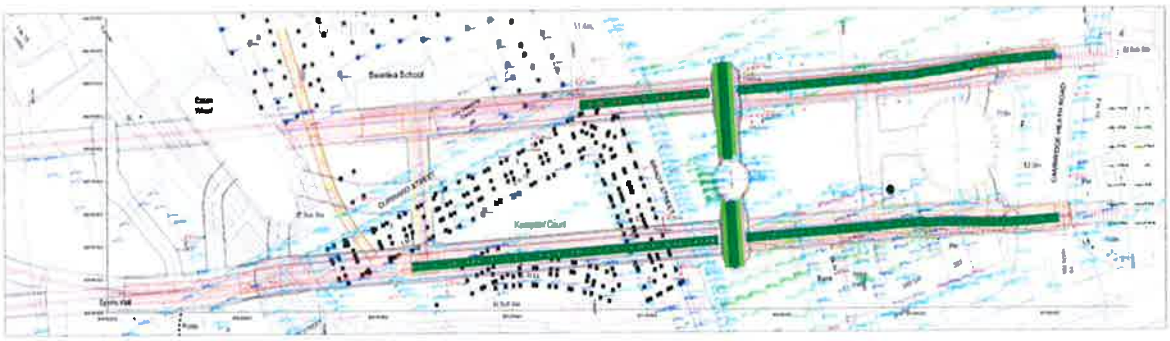
(a) Construction progress on the 19/10/2012



(b) Construction progress on the 13/11/2012



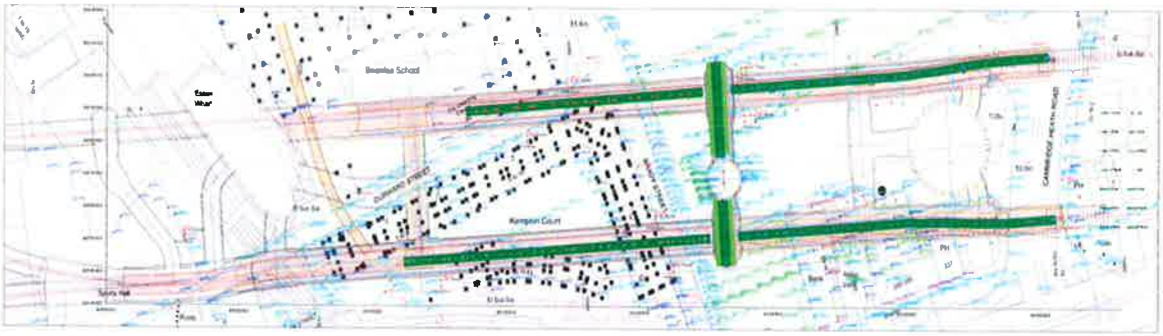
(c) Construction progress on the 18/11/2012



(d) Construction progress on the 22/01/2013

Figure 7. Construction progress for Eastbound and Westbound tunnels

(e) Construction progress on the 25/01/2013



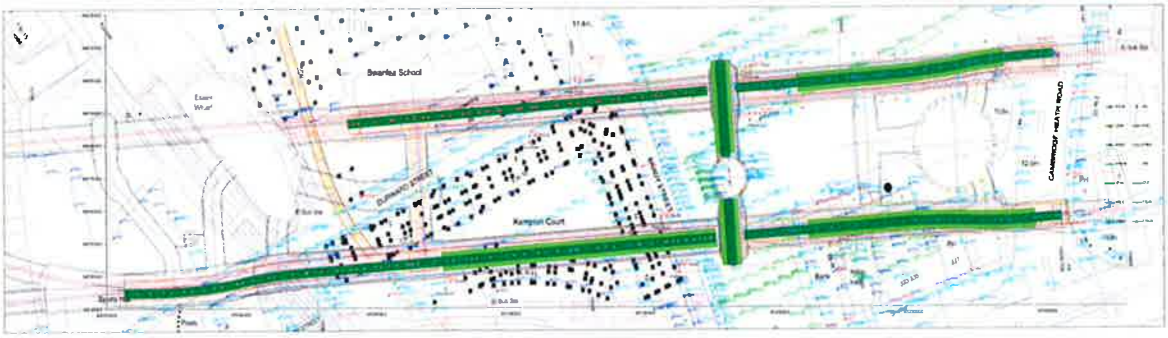
(f) Construction progress on the 06/02/2013

(g) Construction progress on the 19/02/2013

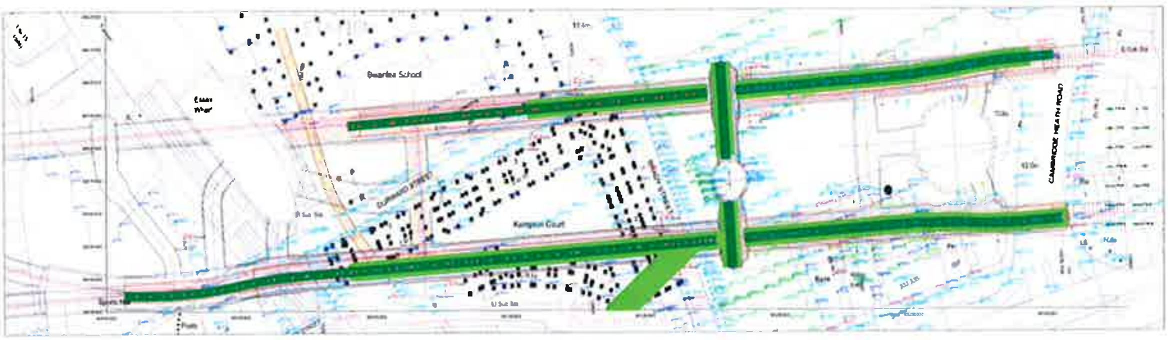
(h) Construction progress on the 06/03/2013

Figure 7. (cont.) Construction progress for Eastbound and Westbound tunnels

(i) Construction progress on the 27/03/2013



(j) Construction progress on the 25/05/2013



(k) Construction progress on the 01/07/2013

Figure 7. cont. Construction progress for Eastbound and Westbound tunnels [6]

Figure 8. Construction progress Gantt chart

Noting the overlapping periods found from Figures 7 and 8 for construction of Eastbound and Westbound tunnels sections in the area of interest, it was crucial to isolate settlements due to section being considered and avoid counting deflection twice.

Considering settlements from the start of construction from Eastbound pilot tunnel (PTE), monitoring sensor deflections were baselined on that date (18th October 2012) and settlement values were calculated. As PTE works continued after Westbound pilot tunnel construction pausing on 22th January 2013, corresponding deflections were baselined on this date and settlement were produced by adding those to values on 18th November 2012.

Although, Westbound pilot tunnel (PTW) construction launched on 13th November 2012, the baseline for PTW start taken to be immediately after PTE pauses to allow for PTE take place. No settlements were considered after PTW works were put on hold (22d January 2013), because for all three sections analysed, the construction progressed sufficiently far (more than 10 tunnel diameters) to produce significant changes in settlement values.

For Westbound pilot enlargement tunnel (ETW) its entire construction period was baselined on 27th March 2013, with no corrections made due to Eastbound pilot enlargement tunnel (ETE) works launch, since on the 25th May ETW progressed more than 10 tunnel diameters away for all three monitoring arrays analysed. ETW tunnel only settlements were produced along ETW and PTW combined effect settlements by adding recorded PTW settlements to enlargement only values.

As sensor monitoring data was provided with no records after 1st June 2013 taken, no Eastbound pilot enlargement tunnel (ETE) settlement vs distance from array tunnel intersection were produced and no analysis on ETE was done.

Results

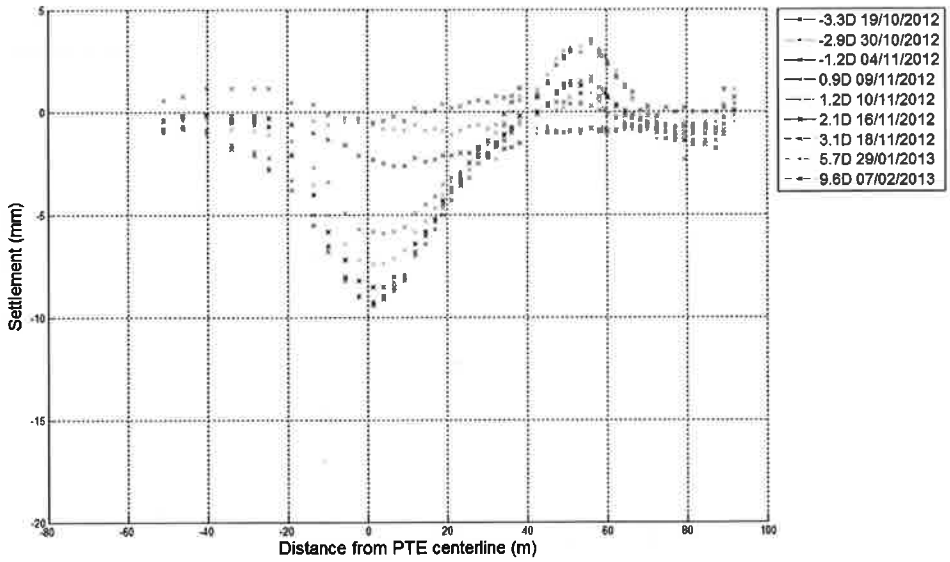
Greenfield tunnelling analysis

For greenfield analysis 53 precise levelling points creating long array located parallel to Brady street were selected, referred as Greenfield Brady Street array.

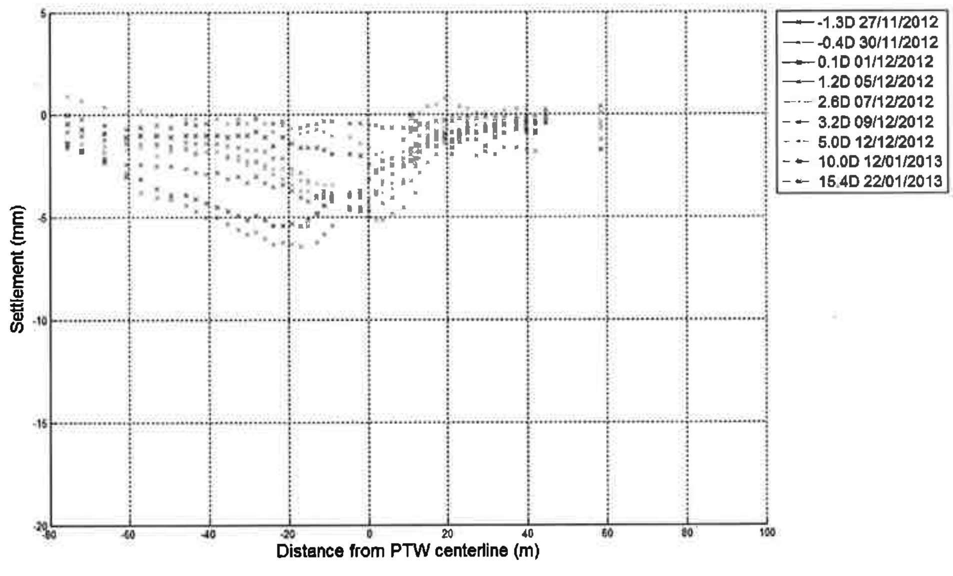
To produce cross section plots, those 53 precise levelling points individual locations were plotted against Eastbound and Westbound tunnel centreline construction locations, then those individual locations were projected to create straight array line crossing tunnel centrelines to produce best projected locations. Intersections of greenfield array produced with PTE, PTW, ETE and ETW centrelines were found, those intersections shown on settlement plots as x-coordinate 0 point for Eastbound and Westbound tunnel section construction. Hence, relative distances away from tunnel centreline intersections were produced for all 53 monitoring sensors. Using intersections of tunnel centreline with array and construction progress records for pilots and their enlargements corresponding distances were found for available dates of tunnel construction and monitoring sensor records.

Figure 9 and Figure 10 show settlements found due to Eastbound and Westbound pilot and enlargement of pilot tunnel constructions

It was observed from the greenfield section plots that area above Westbound tunnel show heaving, i.e. positive settlements, which most can be seen from group of monitoring sensors at around +35 m away from the Eastbound tunnel centreline shown on Figure 9 (a). This effect was explained by compensation grouting taking place in the zone above Westbound tunnel.

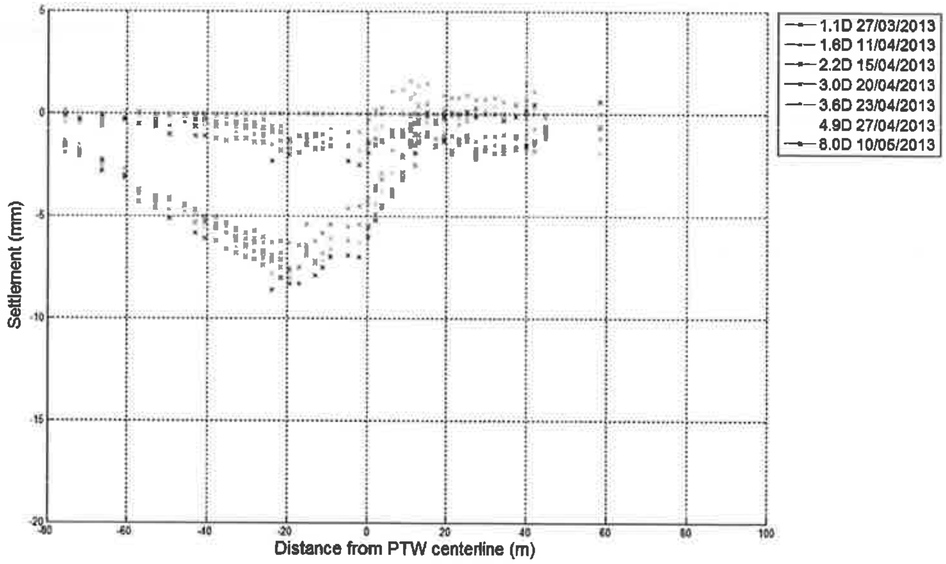


(a) PTE pilot only tunnel settlement

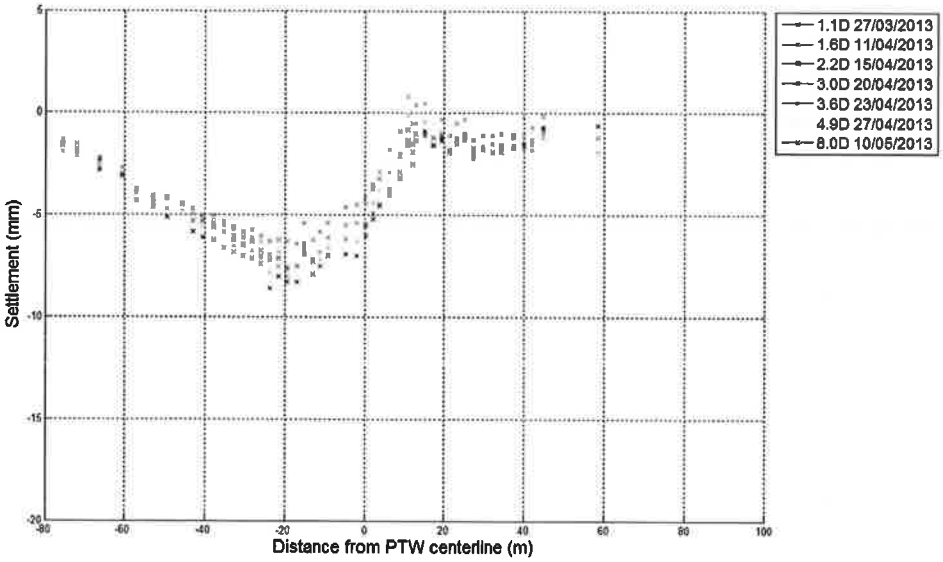


(b) PTW Pilot only tunnel settlement

Figure 9. Greenfield Brady Street array pilot settlements



(a) ETW Enlargement only tunnel settlement



(b) PTW Pilot and Enlargement combined settlement

Figure 10. Greenfield Brady Street array enlargement settlements

Greenfield volume loss

Using the settlement data from the Brady street array calculated above, for each tunnel sections at the last settlement stages Gaussian curve was fitted using Volume loss theory discussed earlier. For this analysis, to the available settlement data, which included relative distance away from tunnel intersection, z-location of the monitoring points, tunnel depth and average diameter, initial (approximate) parameters of location array, settlement trough and maximum settlement were defined. Hence, the Gaussian trough curve was fitted, then calculating corresponding volume loss.

As part of greenfield array deflections were affected by compensation grouting taking place, calculations of volume loss for Westbound section can be less reliable compared for Eastbound pilot results.

Table 1 summarised results of volume loss analysis for greenfield Brady street array.

Tunnel	K value	Smax (mm)	Vloss (%)
PTE (pilot only)	0.64	10.9	1.30
PTW (pilot only)	0.70	10.8	1.30
ETW (enlargement only)	0.45	19.8	0.80
ETW (combined effect)	0.51	30.1	0.94

Table 1. Greenfield Brady Street array gaussian analysis results

Structural tunnelling analysis

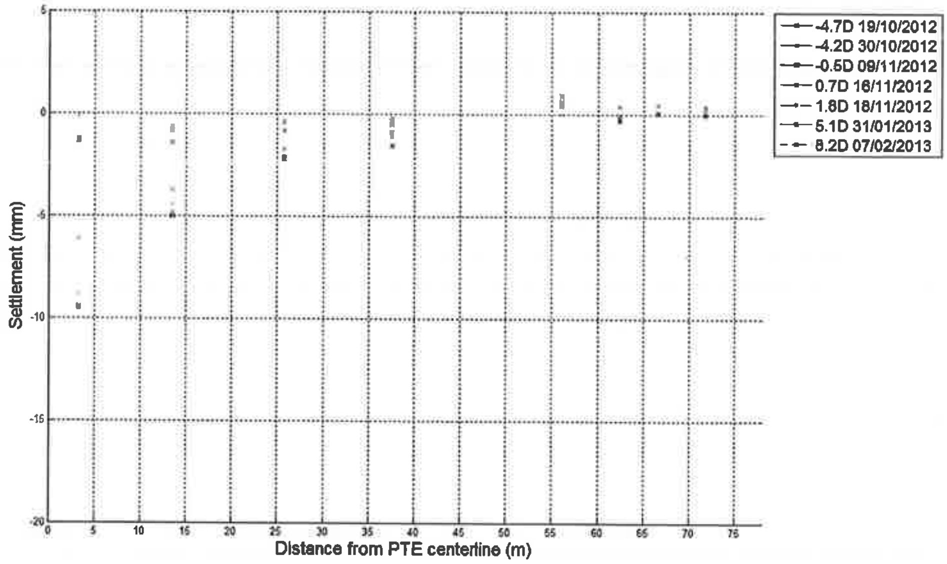
Two arrays of BRE sockets located on two sides of the structure parallel to Brady street, referred as Structural BRE Front array and Structural BRE Back array were selected for structural settlement analysis. BRE Front has 8 individual monitoring sensor locations and BRE Back array uses 6 individual monitoring sensor locations located on 2 levels of the structure.

Similarly to greenfield points, structural arrays were plotted to return their projected locations on arrays, projected locations were found having about than 0.0001% variation with their true locations indicating that point were placed on straight line along the wall.

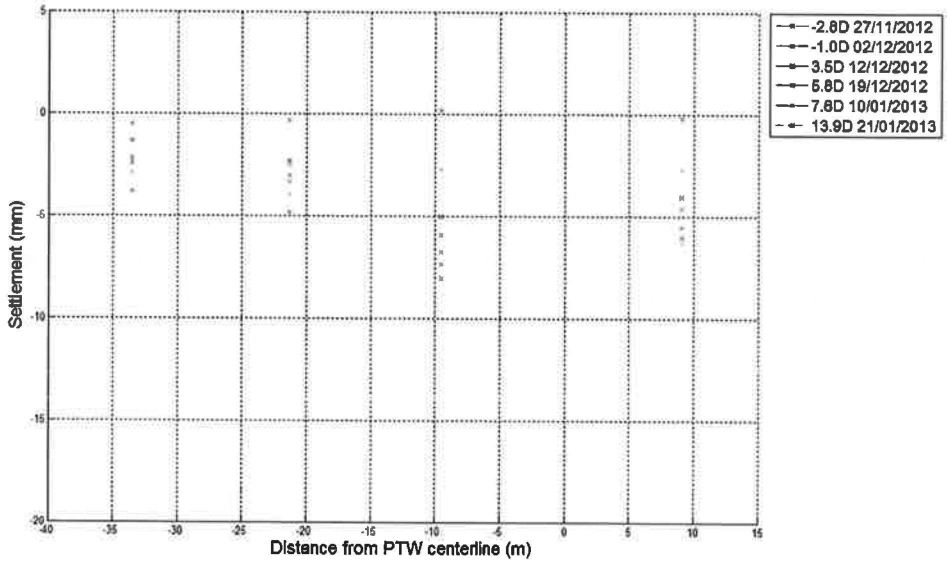
Intersections with PTE, PTW, ETE and ETW centrelines were found, those intersections shown on settlement plots as x-coordinate 0 point for Eastbound and Westbound tunnel section construction. The relative distances away from tunnel centreline intersections were produced for readings.

Figures 11, 12 and Figures 13, 14 show settlements found due to Eastbound and Westbound pilot and enlargement of pilot tunnel constructions for BRE Front and BRE Back arrays respectively. For these BRE sockets measurements were taken on less frequent basis, so as seen on settlement plots, for each location away from tunnel centreline there is a single readings taken on a particular date (distance in diameters of tunnelling works).

Structural BRE Front array extends to the area of influence of compensation grouting zone near Westbound tunnel region, which can be observed with positive settlements on plots.

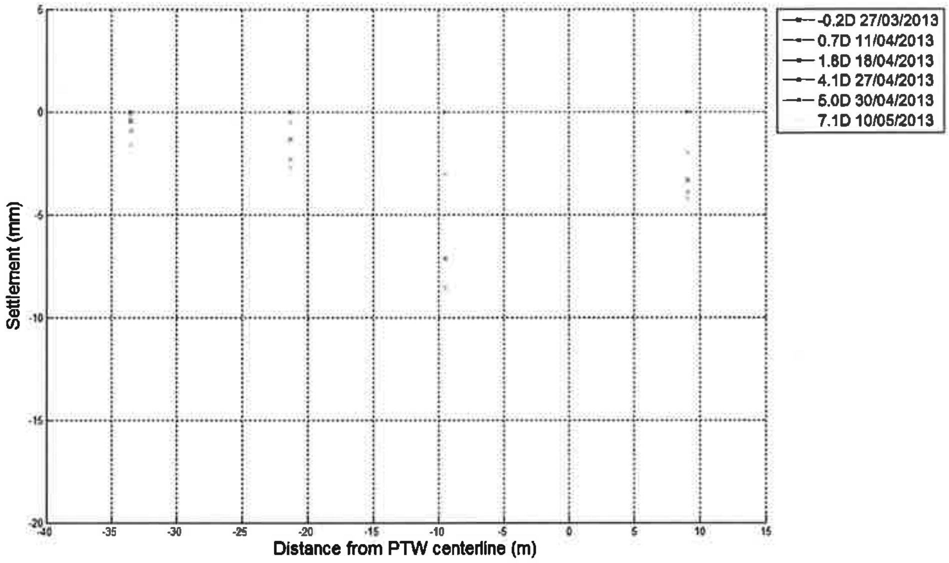


(a) PTE Pilot only tunnel settlement

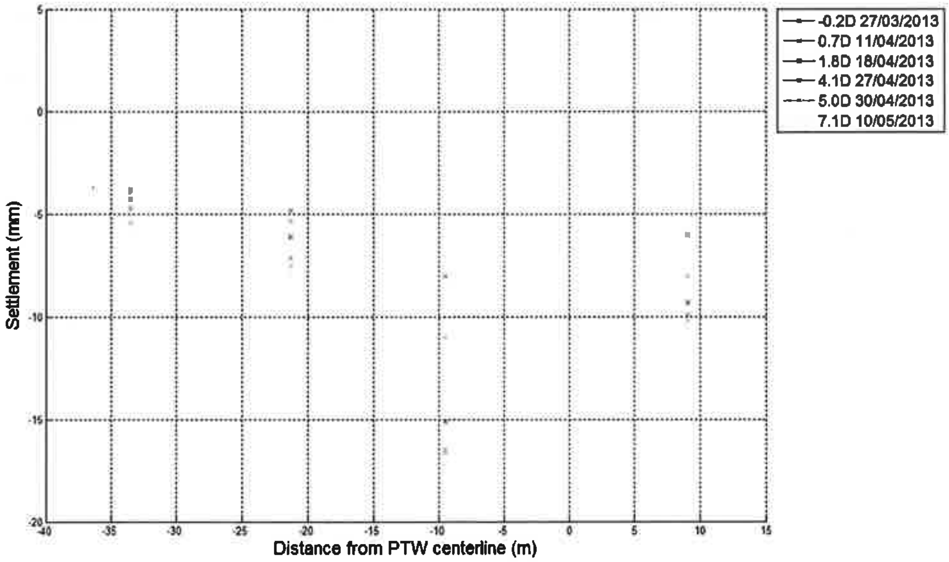


(b) PTW Pilot only tunnel settlement

Figure 11. Structural BRE Front array pilot settlements

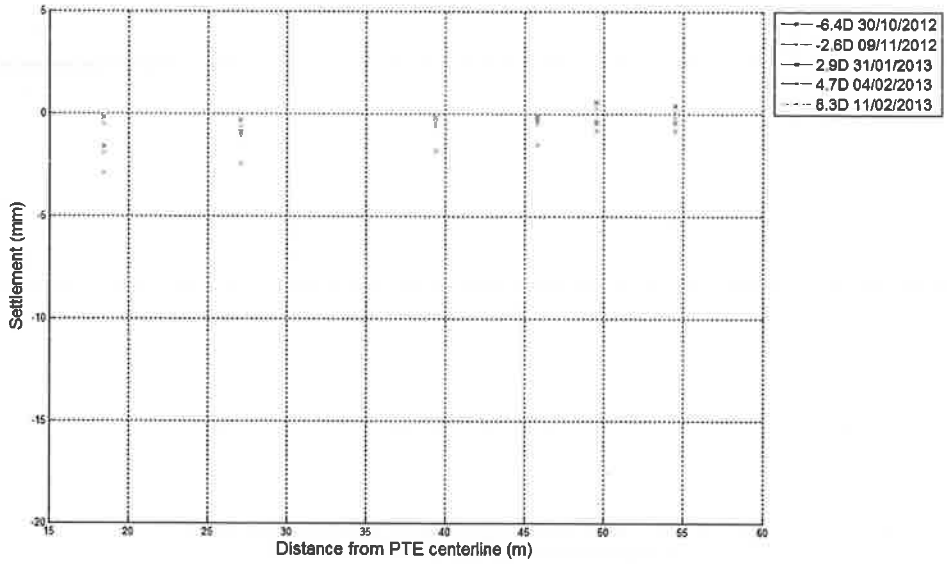


(a) ETW Enlargement only tunnel settlement

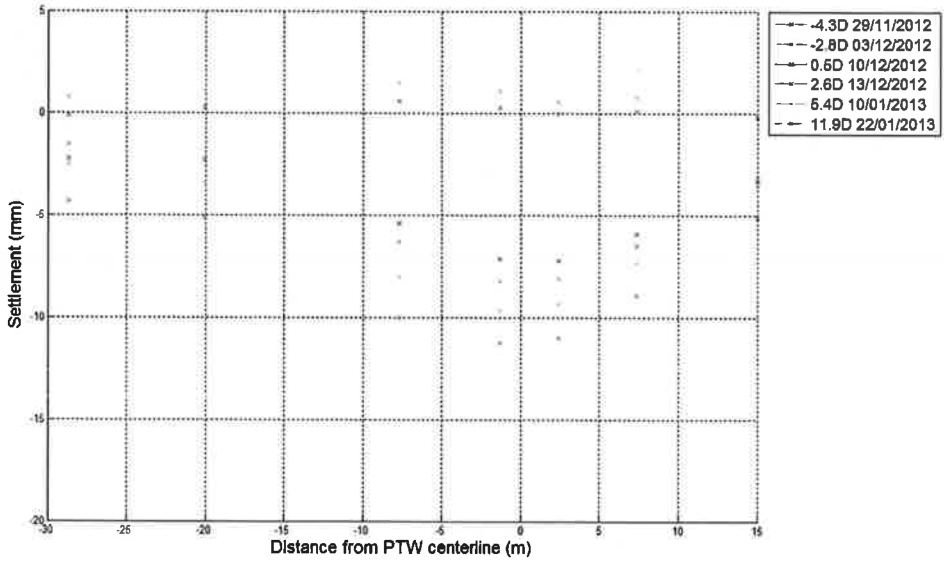


(b) ETW Pilot and Enlargement combined settlement

Figure 12. Structural BRE Front array enlargement settlements

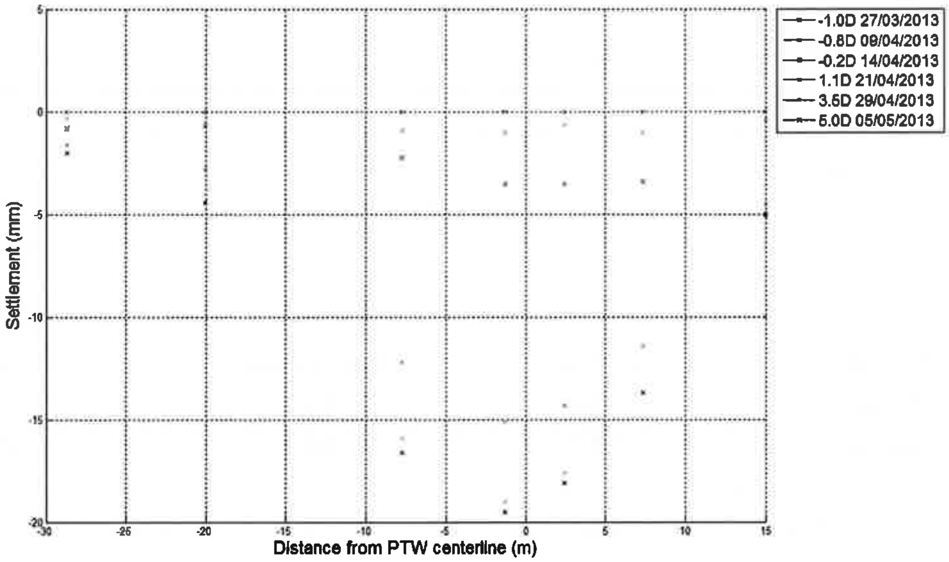


(a) PTE Pilot only tunnel settlement

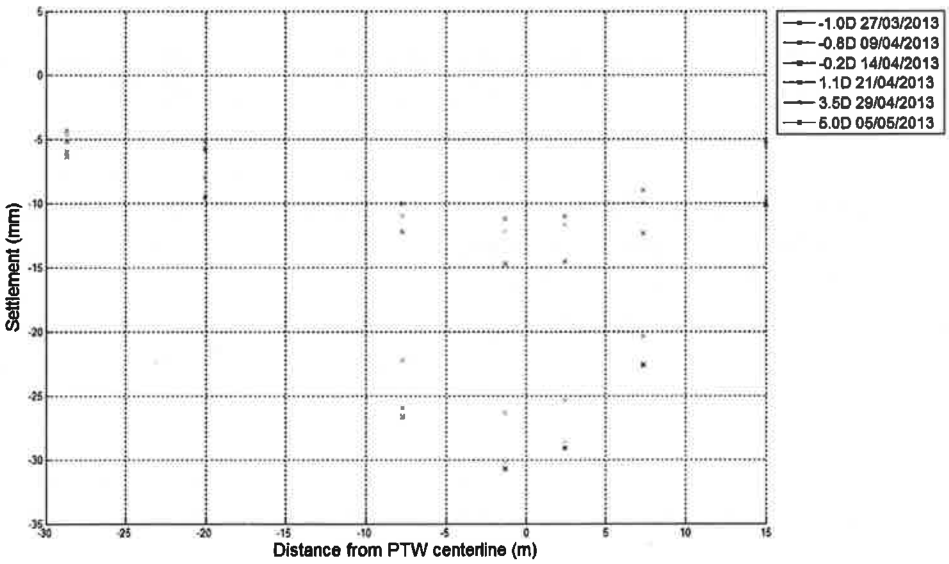


(b) PTW Pilot only tunnel settlement

Figure 13. Structural BRE Back array pilot settlements



(a) ETW Enlargement only tunnel settlement



(b) ETW Pilot and Enlargement combined settlement

Figure 14. Structural BRE Back array enlargement settlements

Structural volume loss

Following the procedure for greenfield volume loss analysis, Gaussian curves were fitted to two arrays structural settlement profiles. Both Structural BRE Front and Back arrays were sufficiently far away from Eastbound tunnel centreline intersections, hence, no analysis was done for Eastbound pilot and enlargement of pilot tunnel sections. The results obtained for BRE Front and BRE Back array curve fitting agreed.

Table 2 summarised results of volume loss analysis for Structural BRE Front and Back arrays.

Tunnel	K value	Smax (mm)	Vloss (%)
PTW (pilot only)	0.70	11.5	1.35
ETW (enlargement only)	0.40	19.3	0.80
ETW (combined effect)	0.46	30.5	0.97

Table 2. Structural BRE arrays gaussian analysis results

Discussion of results

Greenfield volume loss values for Eastbound and Westbound pilot tunnels are found to be consistent, small variation can be explained by existing section affected by compensation grouting, however since no other arrays were analysed for greenfield, no comparison results to be presented. Initially, possibility of analysis one more greenfield array located behind Structural BRE Back array was considered, however as in case of structural array, sufficiently far location from Eastbound centreline intersection of the edge points of this array, it was decided to use Brady street array for all Gaussian fitting.

As was noted earlier, for the last stage of construction, monitoring sensor records last data available was found to be before the end of Westbound enlargement of pilot completion, hence there is possibility of obtaining higher value of corresponding volume loss.

The results of structural settlements were found to be similar to earlier obtained greenfield results, showing 10% or less variation in Smax. Again, there is concern on arrays being analysed being 'short'.

Looking at Figures 11-14 for structural settlements, and comparing to parallel array responses at each stage of construction outlined, it is seen that no Structural BRE Front and Back array results behave in very similar manner, indicating no twisting of the building along this part of the structure. Array show progressive settlement from -10 m away from Westbound tunnel centreline intersection for PTW and ETW graphs.

Greenfield and Structural response comparison

To compare greenfield against structural response Brady street array to be compared with BRE Front array. From plots of pilot and enlargement tunnel section on Figures 9-10 and

11-12 can be analysed more thoroughly. It can be seen, that structural settlement lines practically repeat the behaviour of greenfield response. There are some variations at the end of the building, which can be best observed on Figure 11, especially for PTE developments settlements. Hence, it can be concluded that structure does not behave in rigid manner.

FE results comparison

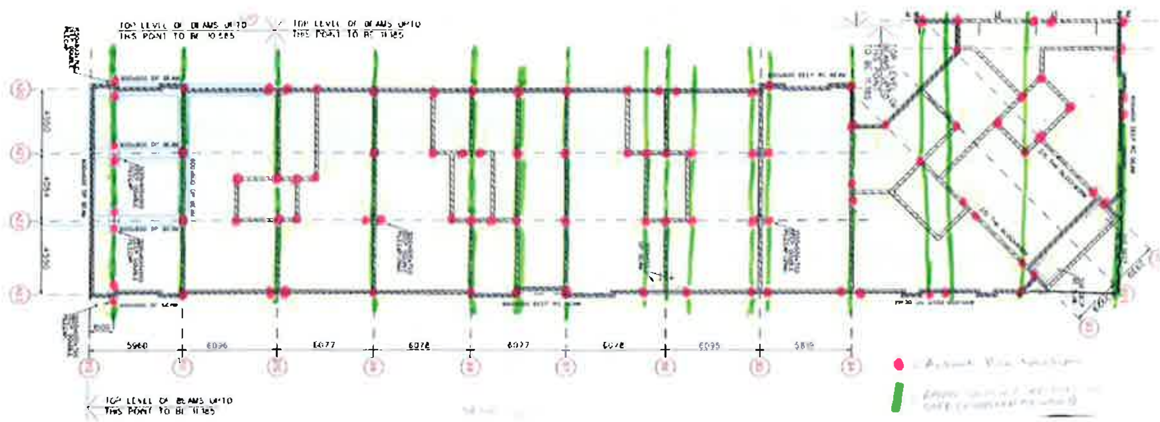


Figure 15. Brady Street elevation Building A pile plan [7]

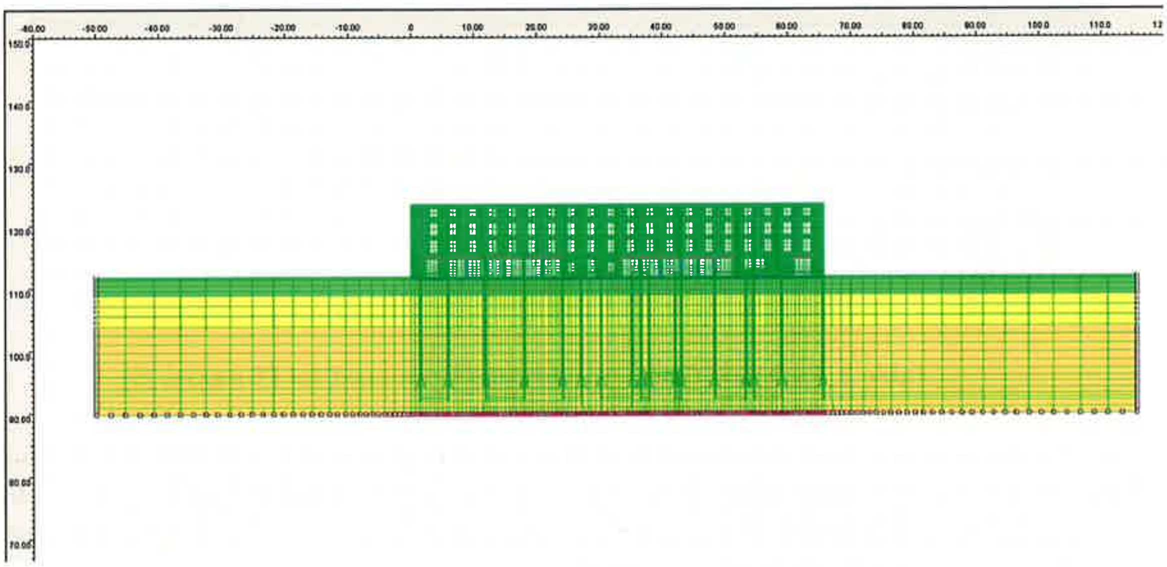


Figure 16. Brady Street elevation FE model [8]

Finite element (FE) analysis was developed by Arup to study Brady street elevation building A. Figure 15 show the plan of part of the Building A to be used for FE analysis, with actual pile location and approximate pile locations for modelling. The Oasys finite element program SAFE was used to create the model, shown on Figure 16, showing structure and ground around its foundations. The model was created with 2 groups of nodes – far field 200 m away from the building left edge (Brady street elevation) and ground nodes, with vertical and horizontal displacements applied for each greenfield and producing corresponding residual loads on the structure.

As can be seen from model in Figure 16, mesh contains solid strata and gaps of 'window strata', for windows and masonry. Although Building A is in fact L-shaped in plan, the part of the façade perpendicular to Brady Street elevation was ignored due to constraints of two dimensions of SAFE Oasys.

The model elements can be categorised to structural elements (building elements) and ground elements. Real ground conditions were used to produce better representation of soil structure giving 3 sets of conditions for ground elements. Table 3 summarises conditions used for made ground, river terrace deposits and London clay layers.

	Made Ground	**River Terrace Deposits**	**London Clay A3**
RL Top (mATD)	112	109	104
Unit Weight (kN/m3)	19	20	20
K0	0.5	0.5	1.1
E'v Top (MPa)	10	25	18
E'v Base (MPa)	10	25	51
V'	0.2	0.25	0.2
c' (kPa)	0	0	5
Phi' (Deg)	25	40	25
cu Top (kPa)	-	-	104
cu Base (kPa)	-	-	197
PWP Top (kPa)	0	0	50
PWP Base (kPa)	0	50	120

Table 3. Kempton Court ground conditions used for FE model [9]

The finite element analysis results done by Arup engineers using displacement inputs from settlement from Oasys XDisp greenfield ground movements being applied to the nodes produced plots of modified displacements for Brady street area. Figure 15 shows exaggerated deformations due settlements along elevation.

It must be noted that the model for SAFE was constructed from the façade facing on Figures 16 and 17 is the view on the building from Brady street, while our settlement vs distance away from the intersection of tunnel centreline graphs produced on Figures 9-14, show the mirrored results of FE outputs produced in this particular model.

Comparing settlement response of Figures 11-14 for Structural BRE Front and Back arrays with Figure 17 exaggerated response, it can be seen that the profiles of settlement response produced follow pattern from figure 17.

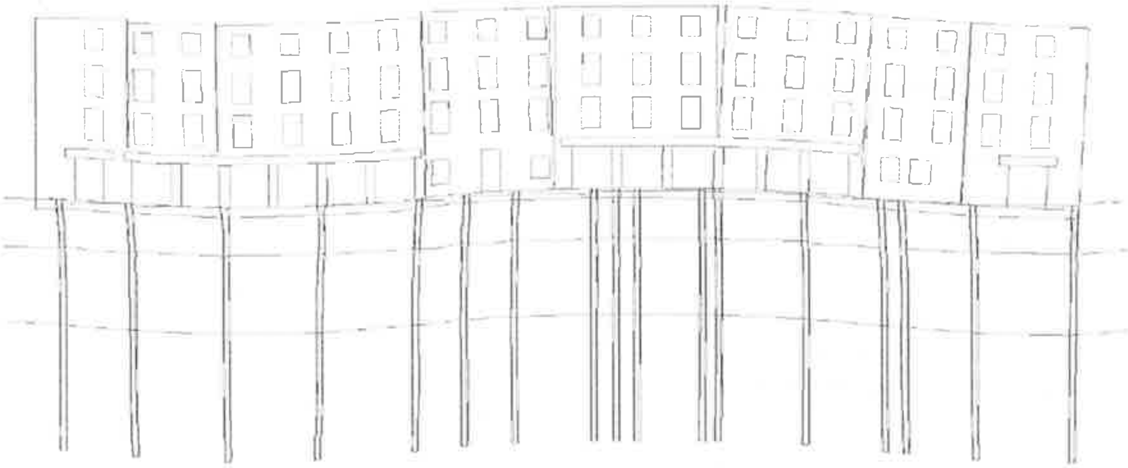


Figure 17. Exaggerated deformation plot along Brady street elevation [10]

Conclusions

Surface settlements of greenfield produced good approximation of Gaussian fit.

The Greenfield settlements were compared to structural settlements produced parallel from different monitoring sensor points and found to have similar profiles.

The settlements of the structure were of similar magnitude to greenfield.

The behaviour of structure was not rigid, the most contribution to settlements observed were found in south-east area from tunnelling works of Westbound tunnel.

The structural settlements were compared to the finite element model response produced from greenfield results, it was found that 2D FE model produced similar settlement response for the structure observed.

Notes on images

[1] Image obtained from ref no. 4
[2] Image obtained from ref no. 4
[3] Images obtained from ref no. 3
[4] Image obtained from ref no. 1
[5] Image obtained from ref no. 1
[6] Images obtained from ref no. 6
[7] Image obtained from ref no. 7
[8] Image obtained from ref no. 8
[9] Image obtained from ref no.7
[10] Image obtained from ref no. 8

References

1. Mair, R.J., Taylor, R.N. & Bracegirde, A. (1993). Subsurface settlement profiles above tunnel and clays. Geotechnique 43, No.2, 315-320.
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3. Dimmock, P.S., Mair, R.J. (2007). Volume loss experienced on open-face London Clay tunnels. Proceedings of the Institution of Civil Engineers. Geotechnical engineering 160, Issue GEI, 3-11.
4. Phase 3 Report Kempton Court, 2 Durward Street. Document ref C122-OVE-Z-RAN-CRG01-00651 Rev 2.0, Crossrail.
5. Whitechapel Construction Process_A_18-October-2013_v1. Excel model by Mehdi Alhaddad, Crossrail.
6. Kempton Court monitoring data files. Files from Mehdi Alhaddad, Crossrail.
7. Kempton Court SAFE modelling presentation. Files from Anton Pilai, Arup.
8. Kempton Court SAFE finite element model. Files from Anton Pilai, Arup.

Appendix A. Risk assessment retrospective

The project at the beginning of work was described as very low risk project. At this final stage of the project, it can be confirmed that although project work mainly associated with computer (student laptop) use, no risks outlined at the risk assessment form (electrocution from hardware faults, contact with water) were faced during period of 9 month of working on the project.