Cast Iron Tunnel Assessment by the Influence of Crossrail Tunnelling

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

The Crossrail western tunnel drive, drive X, comprising twin tunnels with inner diameters of 6.8m, passed beneath 3 existing cast-iron lined railways. The construction of the Drive X tunnels caused ground imparts movements influencing the existing surface or sub surface structures such as London Underground (LU) tunnels. To maintain safe and comfortable running of trains, the structure and track have a limited tolerance to movements. There was extensive monitoring within the existing cast-iron tunnels, mainly in the form of (a) electro-level level beams installed above knee level; (b) Basset Convergence Systems or similar at the point the Crossrail tunnel alignment crosses the existing tunnel; (c) 3 point retro-reflective targets installed at 10m centres; and (d) precise levelling carried out at 2m centres.

The results presented in this report are derived from some of the monitoring performed by Crossrail of the structure and track when Crossrail construction work was in the zone of influencing existing tunnels. The tunnels mainly examined are those of the LU/08 Victoria Line from Oxford Circus to Green park and LU/09 Bakerloo Line from Oxford Circus to Regent Street. As the region of influence for Victoria&Bakerloo Lines due to the construction of the Crossrail Line (CRL) Westbound (WB) and Eastbound (EB) are at the same site, which is at the south of Oxford Circus as shown in Section 3.1 Location of Work, it makes sense to investigate the behaviour of the cast-iron lining tunnel responses of those two existing lines together. Longitudinal settlement profiles from different monitoring systems along the track/tunnel of each existing tunnel of Victoria&Bakerloo line have been plotted and compared with the prediction as well as with each other.

- ❖Theories about the prediction of settlement profiles, distortion and rotation of the existing tunnels have been understood and investigated in the content of the project. The 2D settlement profiles for Victoria & Bakerloo Lines follow well with the empirical Gaussian distribution where the percentage difference in maximum settlement between the actual settlement profiles and the predicted ones are only 0.38% to 0.9%.
- ❖The final degree of rotation of each existing tunnel have been calculated and proven to lie in the correct region where the new tunnelling works were leaving the zone of influence of the existing tunnels, which is less than 0.5 degrees.
- ❖ Historical case about the effect of Jubilee Line Extension on the existing tunnels have been studies and similar analysis have been done based on this project. It shows that the results of the shapes of the settlement troughs from Victoria and Bakerloo Lines in this project follow the theories well: the larger the separation, the closer the new tunnel to the existing tunnel, the more distinct settlement toughs. Victoria Northbound has the

most distinct settlement troughs which follow the most closely with the predicted Gaussian distribution because the spacing between the Crossrail tunnel axes beneath it is the largest and the depth of the Crossrail tunnels is the smallest. In contrast, Victoria Southbound has the most merged settlement troughs because the spacing between the Crossrail tunnel axes beneath is is the smallest and the depth of the Crossrail tunnel is the largest.

- ❖Maximum settlement of up to about 14.8 mm for the two tunnels of Victoria Line and about 10.2mm for the two tunnels of Bakerloo Line were measured. These values are within the safe levels of trigger values set by Crossrail, showing a careful control of volume loss.
- ❖ Back-analysis determined volume losses and those movements encountered during the Crossrail works upon the existing tunnel assets were well within design criterion, with earth pressure balance (EPB) tunnelling volume losses between 0.31% and 0.6%, lower than the value used for prediction of the settlement profiles which is 0.7%.
- ❖ Using data from manual track shoe monitoring within the existing tunnels, investigations have been conducted into cant and track twist during the crossing. All the track cant and twist are very small and well below the trigger levels set by the Crossrail.
- ❖ Comparisons and relationships between tunnel and and track movements have been established. It shows that there is a strong and positive relationship between the results from Electro-level beams (automated monitoring system) and track-shoe monitoring systems (manual monitoring system), with a correlation coefficient larger than 0.9 for all the cases considered and electro-level beam monitoring proved to provide better accuracy and reliability.

1. Introduction

1.1 Background

During the construction of one of the underground sections (Crossrail Contract C300) of the Crossrail project, there are 12 interfaces with existing operational National Rail (NR) and London Underground Ltd (LUL) railway lines where new tunnelling works pass below or above existing railway assets. The C300 contract comprises twin bored tunnels 6.8m internal diameter(ID) traversing a length of 6.4km under the City of London from Royal Oak Portal in the west, through to the east end of Farringdon Station. Of the 12 rail interfaces, 7 of the existing tunnel structures are made up of cast iron segmental linings. This project will focus on 3 of these 7 interfaces where the new tunnelling works of C300 pass within close proximity (less than 1 diameter) of the existing tunnels.

The study discussed within this project is about the effect of Crossrail construction on cast-iron lined running tunnels. The induced ground movement by the construction works associated with the new Crossrail projects within LUL running rails, tunnels and structures are investigated in this project. The interfaces designated in this report is LU/08 Victoria Line from Oxford Circus to Green Park and LU/09 Bakerloo Line Oxford Circus to Regent Street by interpreting data and analyzing the interfaces. In Section.3 for the locations of the Crossrail tunnelling work, Fig.3.1(a) shows a plan of the Central London region for the Crossrail tunnelling work and the existing structures. Fig. 3.1.1(a) and Fig.3.1.2(a) show the regions of influence of Victoria & Bakerloo Lines respectively which are designated in this project.

1.2 Motivation and Objectives

Network Rail (NR) and London Underground Limited (LUL) impose restrictions and conditions on third parties whose intent is to conduct works in close proximity to their assets, in order to show that the safety and operation of the railway is not compromised, directly or indirectly. A common practice for deep and sub-surface railways is assigning the third party to perform routine monitoring on structure and track. Track shoe monitoring is used to determine differential vertical level changes in each of the running rails, both relative to each other and to a prescribed longitudinal interval in order to calculate cant and twist respectively. These calculated values are used to determine the movement of the train body laterally (kinematic envelope) and to check a safe clearance is maintained between the train and structure. Ride quality is also assessed using these results. Both clearances and ride quality number must be maintained within set levels.

One of the main problems for conducting track monitoring is access. The normal method of recording track levels uses precise levelling method with specifically designed staff shoe that measures the level from a specific, repeatable position upon the head of the rail track. This requires 2 operators to work together, measure in remote locations far from the nearest point of access. For safety reasons, no work is permitted within subsurface of deep level railways during operating hours, hence operation must be either suspended or the work conducted in the engineering hours during the night. This is time consuming and expensive, where results can generally only be practically obtained sporadically and not ideal from a data interpretation perspective. On the other hand, structural monitoring can use automated systems to record movements at predefined intervals without an operator, either directly using prisms/targets or indirectly from inclination data, for automatic total station (ATS) and electro-levels respectively.

*“**There is no technical reason to carry out manual monitoring of the track within cast-iron tunnels!”*** This statement will be investigated in this project by interrogation of observational monitoring data in order to justify or dispute the hypothesis on which this statement is based. The hypothesis takes the assumption that, as the tunnel structure moves due to events like nearby excavation and construction, the railway tracks within the structure will move in exactly the same manner and of the same magnitude. Hence structural monitoring alone will suffice and there is no need to specify manual monitoring of tracks in cast-iron tunnels for future projects. Data is available from the Crossrail project in London, from which the response of the track and how this compares with the cast-iron lining movement can be back calculated. The data and results of the analysis can be used to supplement existing data to limit the amount of manual track monitoring specified in the future. In addition, there is economical benefits and risk reduction associated with installation and carrying out of automated monitoring. A correlation between track and structure behaviour is needed in order to inform future projects in adopting alternative methods and strategies for checking track geometry and clearance and could be used when the structure monitoring shows unexpected behaviour.

As shown in the drawing in Fig.1 below, London Underground provides this specification defining clearances that must be adhered to avoid the rolling stock coming into contact with the tunnel structure, fixed surfaces or platform. The deep tube network is made up of small diameter tunnels by today’s standards and the kinematic envelope of the rolling stock is tight. The clearances are derived by considering the effects of curves, over hangs and velocities of the trains under different service conditions. Therefore, if the construction work from a new tunnel is to impose movements on the existing tunnel; in order to safeguard the integrity of the existing structures, movements must be monitored and changes must be reviewed to check compliance with the specifications. Back calculated limits of movement can be enforced by using trigger values of varying levels in order to quickly determine whether imposed movements are satisfactory.

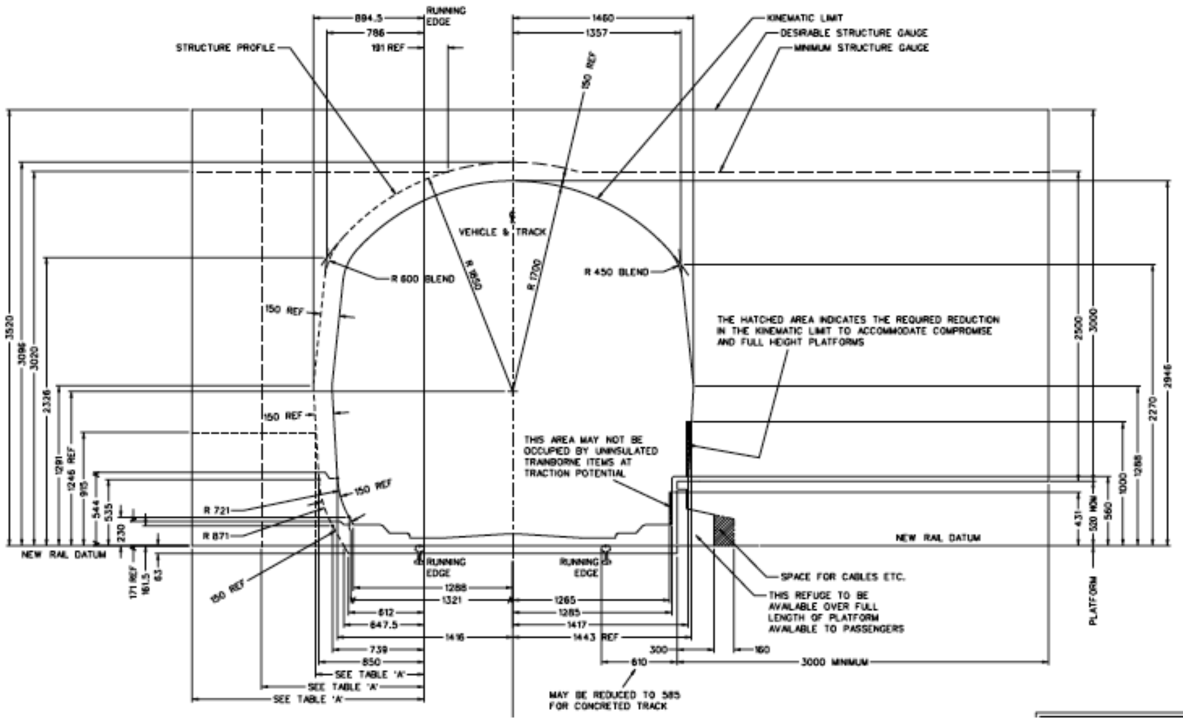


Fig.1 Track/Vehicle Interface Diagram 'F1", Diagram B1, Engineering Standard 1-156 Tube Line New Works General Issue, Engineering Directorate, Permanent Way Engineer (LU), LU 1-156 Gauging and Clearances, London Underground Limited, 55 Broadway, London SW1H 0BD

Therefore, the main objectives of this project are summarized as below:

- ❖To study the theories behind the surface and subsurface settlement profiles and to conduct prediction of the settlement profiles for the existing tunnels in this project,
- ❖To investigate modes of distortions and rotations in the content of the results obtained in this project,
- ❖To use the knowledge from the historical case of the effect of Jubilee Line extension on existing tunnels in this project to compare different shapes the settlement troughs from results of this project,
- ❖To plot settlement profiles derived from different monitoring systems (manual and automated) along the tunnel/track, interpretation and analysis are to be made based on the graphs,
- ❖To establish a correlation between track response and cast-iron/structural movement to find the correlation coefficient in each case, and

❖ To support a reduction in track monitoring by providing a guidance for specifying track monitoring through use of tunnel monitoring for future projects.

2. Theories and Literature Reviews

2.1 Modelling and Prediction of Ground movements

2.1.1 Surface Settlement

Soil relaxation around the tunnel due to volume loss contributes to settlement during excavation. For the case of construction of a single tunnel in "green field" condition, it will result in surface settlement trough due to ground movement above and ahead of the tunnel. The excavation of the tunnel causes a shallow depression, or 'settlement trough', at the surface along the line of the tunnel. The largest vertical displacement of the ground directly above the excavation, reducing first at a decreasing rate, then at an increasing rate and again later at a decreasing rate, moving from the construction activity, forming a smooth trough. This approach does not take into account of any structural stiffness and assumes that the effects of possible impart of ground stiffening shallow foundations, road surfaces, buried services or structures are negligible. It has been shown by many authors that the transverse settlement trough well followed a Gaussian distraction curve which is used as the empirical method commonly used to predict ground movements. The settlement profile S can be represented as equation.1 and is shown in Fig.2.1.1 below. [1]

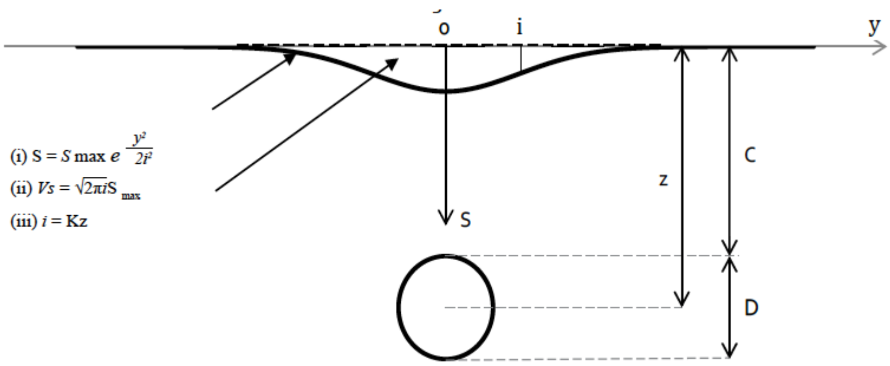


Fig. 2.1.1 Ground settlement profile proposed by O'Reilly and New, 1982-soft ground tunnelling [2]

$S=S_{max}\exp(-y^2/2i^2)$ —— eq. 1 ; and $i=Kz$

where: S = vertical ground movement, settlement is positive value

S_{max} = maximum settlement on the tunnel centreline

y = horizontal distance/offset from the tunnel centre-line

i = horizontal distance from the tunnel centre-line to the point of inflexion of the settlement trough

K = trough width parameter which is an empirical constant, assume a relatively constant value in the same ground

z = depth of the axis of the tunnel below the ground level
C = cover from ground level to crown of tunnel
Vs = volume loss per metre advance

The key factors affecting the ground movement profile include:

❖ Tunnel diameter and shape: Ground movement is proportional to the volume excavated. The larger the tunnel is, the greater the ground movements predicted. Circular tunnels are ideal for minimising ground movements. The diameters of CRL tunnel are invariant.
❖ Ground cover to ground: For shallower tunnels, settlement troughs tend to be narrower and the maximum settlements are larger. For deeper tunnels, settlement troughs tend to be wider and the maximum settlements are smaller. This factor will be investigated and discussed in Section 2.3 by considering different tunnelling work in this project.
❖ Tunnel construction method: A tunnel boring machine (TBM) tends to lower the ground movement due to construction. The tunnel construction method in this case is earth pressure balance (EPB) TBM for all the tunnelling works beneath the existing tunnels.
❖ Ground properties: For fine-grained materials, the settlement troughs tend to be wider and shallower, while for coarse-grained materials, the settlement troughs tend ti be narrower and deeper. For Crossrail project, the geology is mainly London Clay.

2.1.2 Subsurface Settlement

For subsurface settlement, where new tunnels are constructing beneath the existing structures such as existing tunnels, Mair et al. (1993) has carried out extensive analysis based on data from tunnel projects and test data. He showed that the subsurface settlement profiles follow the same Gaussian distribution as described in Eq.1. One of the key elements when generating a settlement profile is the rate of movement degradation with distance which is trough width parameter i. Its value comes from extensive survey data and correlation and relationship between tunnel depth, ground water and strata. Mair et al. (1993) has showed that the trough width parameter i has an approximate linear relationship with the difference in depth of the existing tunnel z and the advancing tunnel z_0. It could be represented as [3]:

$$i=K(z_0-z) \qquad \text{—— Eq.2}$$

where: K=trough width parameter, assume a relatively constant value in the same ground
z_0=depth of the axis of advancing tunnel below ground level
z =depth of the axis of the existing tunnel below the ground level

For Vs, the volume of the settlement trough per metre length of tunnel, can be expressed by the following Eq.3 and Eq.4

$$V_s=\sqrt{(2\pi)}\ i\ S_{max} \text{ —— Eq.3} \quad ; \text{ and } \quad V_s=V_L\,(\pi D^2/4) \qquad \text{—— Eq.4}$$

where: V_L is a percentage fraction of the excavated area of a circular tunnel, which is known as the volume loss

Volume loss is the key parameter to affect the ground movement. It is defined as the volume of ground loss as a percentage of the final excavated volume of the tunnel. For London clay, New and Bowers (1994) has reported a volume loss rang 1-1.5%, which was consistent with the value obtained in Jubilee Line Extension construction[4]. This value generally permit acceptable or controllable levels of surface movements in urban environments. The volume loss has been reduced further down to generally less than 1% today for tunnels constructed in London using modern TBMs [5]. By combining Equations 2, 3 and 4, the maximum predicted settlement S_{max} is generated as [6]:

$$S_{max}= 0.31V_L D^2/(Kz_0)$$

In addition, the interaction between soil and structure has an effect of reducing maximum settlement values and extending the settlement trough widths. [ref2]

2.1.3 Multiple Tunnels

For multiple tunnels, it may be assumed that superposition is applied to the ground movements that would occur for each tunnel acting independently. This assumption is generally valid when there is no interaction of tunnels in close proximity (further than about 1 tunnel diameter apart). For tunnels which are very close to each other (closer than about 1 tunnel diameter), when the second tunnel is constructed, the ground in this region will already have been subjected to some level of shear stress due to the construction of the first tunnel. Therefore, there would be a higher volume loss resulting from a lower stiffness for the second tunnel. [7]

For each of the case considered in this project: Victoria Line NB, Victoria Line SB, and Bakerloo Line NB, Crossrail tunnels constructing beneath them are well separated by far more than one tunnel diameter. The separation between Crossrail WB and EB tunnels running below Bakerloo Line NB and SB is 28.005m, while the internal diameter of the Crossrail tunnel is 6.8m. Therefore, it is about more than 4 tunnel diameters apart. The separation between Crossrail WB and EB tunnels for Victoria NB is 34.22m, and that for Victoria Line SB is 25.935m which are are about 5 and 4 tunnel diameters. Therefore, it is reasonable to use the principle of superposition to predict the overall settlement profile after Crossrail WB (TBM1) followed by Crossrail EB (TBM2) constructing beneath the existing tunnels.

2.1.4 Prediction of the Ground Settlement for the Victoria & Bakerloo Line

For this project of assessing the settlement profile of Victoria and Bakerloo Line due to the construction of Crossrail underneath, the volume loss due to Crossrail tunnelling determined by Crossrail is 0.7% [8]. Surface settlement profile is assumed to follow a Gaussian profile above the excavation by using the empirical design approach. Settlement trough width, i, defines the point of settlement profile inflection. The ratio K for clays is recommended at 0.5 and sands and gravels 0.25 [9]. In this project, the value for K is chosen to be 0.27 by Crossrail [10].

At surface level:

$S = S_{max} \exp(-x^2/2i^2)$; $i = Kz_0 = 0.27x\ z_0$

$S_{max} = Vs / (\sqrt{(2\pi)} * i)$; $Vs = V_L * \text{face Area} = VL\ (\pi D^2/4)$

where z_0 =depth of the axis of the new CRL tunnel

x = horizontal distance from the tunnel centre-line

i = horizontal distance from the tunnel centre-line to the point of inflexion of the settlement trough

To illustrate the empirical formula used to predict the settlement profile matches well with the prediction results given by Crossrail. Victoria Line NB has been chosen to be the example to demonstrate the predicted settlement profile with the predicted horizontal distance from the tunnel centre-line to the point of inflexion of the settlement trough, and the max settlement. For the settlement profile of Victoria NB, following Crossrail WB(TBM1) and EB(TBM2) construction. Table. 2.1.4(a) summaries the values used by Crossrail for the prediction of the settlement profiles. Table 2.1.4 (b) shows the results obtained from the predicted settlement profiles by using 0.7% volume loss, and comparisons have been made with the results obtained from the real-time settlement profiles derived from electro-level beams (EL). Fig. 2.1.4 (the sam as Fig.3.2.4(a) in Section 3.2.4) illustrates the the predicted Gaussian distribution and the final actual settlement profile for Victoria NB.

	Crossrail WB (TBM1)	Crossrail EB (TBM2)
Axis level z_0 (m)	30.686	31.673
Tunnel diameter (m)	7.18	7.18
Volume loss Vl	0.7%	0.7%
K	0.27	0.27

Table.2.1.4 (a) Summary of values used for the prediction of the ground settlement profiles

Victoria Line NB	After TBM1(actual settlement by EL)	After TBM1(predicted by Crossrail)	After TBM2(actual settlement by EL)	After TBM2(predicted by Crossrail)
horizontal dist. to inflexion i (m)	8.2422	8.241969	6.3346	8.507303

Victoria Line NB	After TBM1(actual settlement by EL)	After TBM1(predicted by Crossrail)	After TBM2(actual settlement by EL)	After TBM2(predicted by Crossrail)
Max settlement of Victoria NB Smax (mm)	11.87	13.7184	7.90	13.291
Percentage difference	-13.47%		-40.56%	

Table. 2.1.4 (b) results obtained from the prediction using 0.7% volume loss and the actual settlement troughs for the Victoria NB

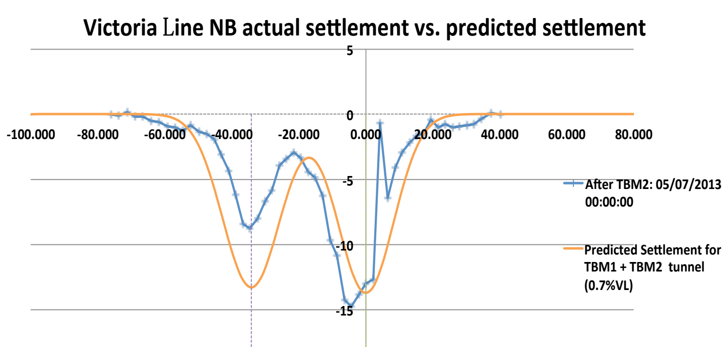


Fig. 2.1.4 Victoria Line NB actual settlement and predicted settlement profiles[31]

It shows that by using 0.7% volume loss for prediction, the percentage differences between the maximum settlement from Gaussian prediction and the actual maximum settlement from the results of real-time EL are not small. The actual maximum settlements are smaller than the predicted values, hence the predictions are safe.

For the best fit curves for the actual settlement profile of Victoria Line NB, Crossrail has back calculated the volume loss of each case for the construction of Crossrail WB and EB, which is 0.6% and 0.31% respectively [11]. Table. 2.1.4 (c) below summarises the best fit curve parameters for the real-time settlement profiles of the Victoria Line NB with the back-calculated volume loss values (derived from results from electro-level beams), the predicted max settlement following Gaussian distribution (S_{max} Gaussian) by using the back-calculated volume loss values, and the max settlement of the actual settlement profile produced by the datas derived from electro-level beams (S_{max} EL). [12]

best fit curve parameter	After TMB1(WB)	After TBM2 (EB)
K	0.27	0.20
Vl	0.6%	0.31%
i	8.2422	6.3346
Smax Gaussian (mm)	11.76	7.87
Actual Smax EL (mm)	11.87	7.90
Percentage difference between Gaussian and EL	-0.927%	-0.380%

Table. 2.1 4 (c) results obtained from the prediction using the back-calculated volume loss and the actual settlement troughs for the Victoria NB

It shows that by using the back calculated volume loss values for prediction, the maximum settlement troughs from actual electro-level beams data and from Gaussian distribution are very similar to each other with negligible percentage difference. Therefore it proves that the settlement profiles follow well with the empirical Gaussian distribution.

2.2 Distortions of the Existing Tunnels

As more and more tunnelling schemes are constructed in increasing urbanised cities such as London, there are more engineering challenges such as tunnelling below existing sub-surface structures. In particular, the influence of new tunnel construction beneath existing tunnels is an important issue for future tunnelling as there are increasing number of tunnel crossing.

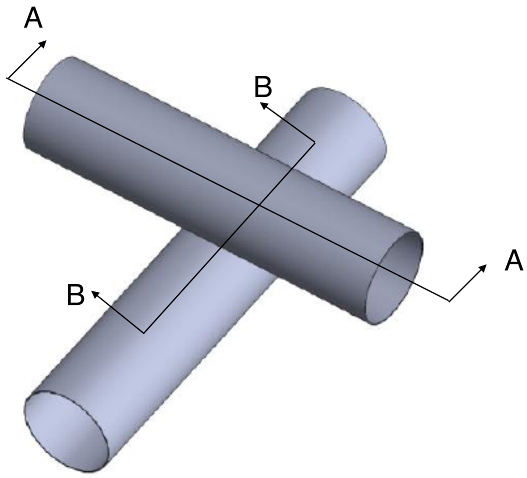


Fig. 2.2 (a) diagram of a new tunnel construction under an existing tunnel

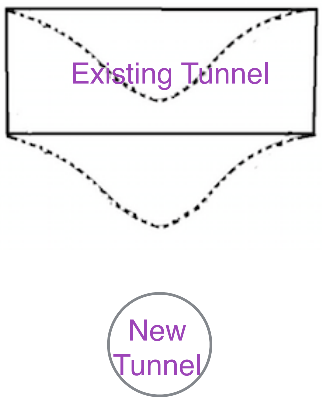


Fig. 2.2.1 longitudinal distortion of the existing tunnel looking into section A-A

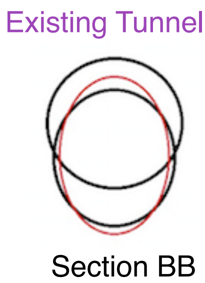


Fig. 2.2.2 (a) transverse distortion of the existing circular tunnel, looking into direction B-B

In initial assessment calculations, the empirical 'greenfield' ground movements around the existing tunnel would be used to assess the impact of movements on existing tunnels. The longitudinal effect, which is the effect of ground movements along the axis of the existing tunnel, and the transverse (radial) effect which is the effects of ground movements on the cross section of the existing tunnel can both be estimated using the empirical methods. Usually both modes of longitudinal and radial distortion occurred as shown in Fig. 2.2 (a), Fig.2.2.1 and Fig. 2.2.2 (a) [13]. In many cases, it is assumed that the existing structures move with the ground, hence their stiffness is not accounted for. However, tunnels with higher stiffness than the surrounding ground (as is usually the case) provide more resistance to movement, therefore the simplified 'greenfield' ground movement predictions will over-estimate the settlements and distortions of the tunnel. Hence monitoring can be introduced within the existing tunnels to observe actual movement during construction, giving scope for performance based damage mitigation.

Fig. 2.2 (b) below shows a 3D representation of greenfield settlement caused by tunnelling works [14]. Fig.2.2 (c) and Fig. 2.2 (d) above go further in illustrating the cross-sectional analysis of an existing tunnel (diameter D_S) as new tunnel (diameter D_T) is constructed in close proximity at a depth Z_O underneath and an angle β to the existing tunnel [15] [16].

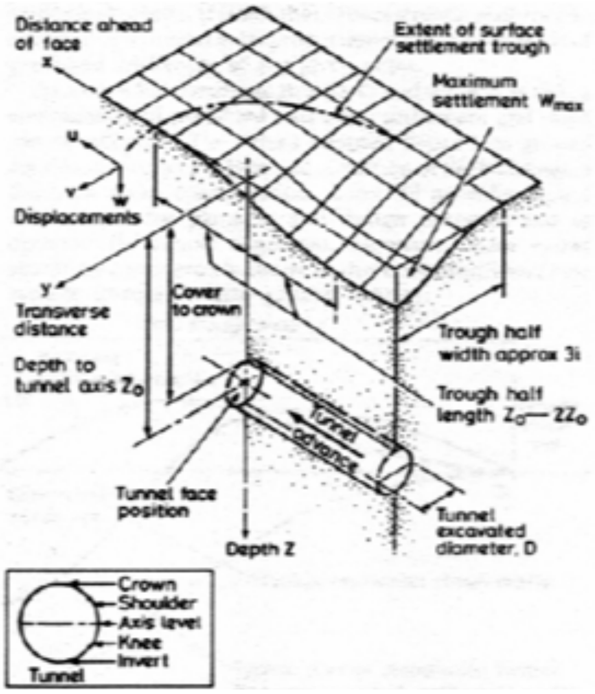


Fig. 2.2 (b) 3D diagram of greenfield settlement caused by tunnelling works. [ref 1]

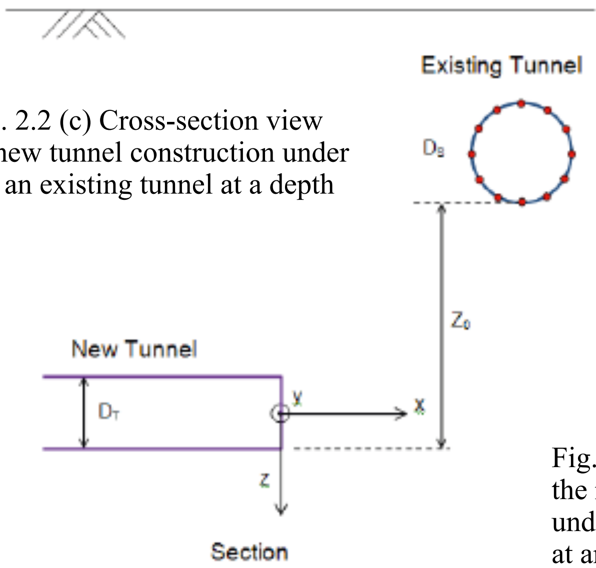


Fig. 2.2 (c) Cross-section view of new tunnel construction under the an existing tunnel at a depth Zo

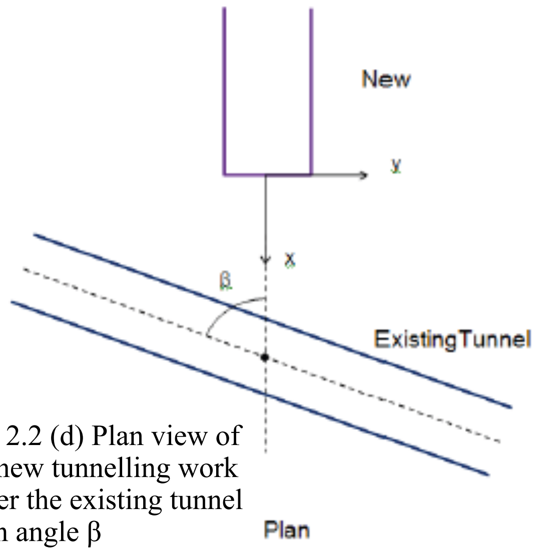


Fig. 2.2 (d) Plan view of the new tunnelling work under the existing tunnel at an angle β

2.2.1.Longitudinal Deformation

For longitudinal effect, it causes the structural response along the existing tunnel. The longitudinal distortion along the length of the tunnel follows cumulative normal distribution type curve (Gaussian). The radius of curvature of the longitudinal deformation is calculated between points of inflexion on the transverse settlement trough. This minimum radius of curvature is an important consideration in assessing the impact on the existing tunnel. As assuming the tunnel bends like a continuous tube, the inner and outer surfaces may become over-stressed. The hogging zone causes tensile strains at the crown of the tunnel lining, and the sagging zone causes tension to be experienced at the invert of the tunnel. Any possible shear deformation reduces the extreme stress and therefore an increased radius of curvature may be accommodated within the fibre stress limits. However, the mechanism of shearing behaviour of tunnel rings is not fully understood and generally omitted from calculation leaving results possibly over conservative. [17]

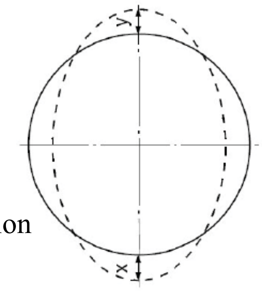


Fig. 2.2.2 (b) Ovalisation

Elongation=x+y

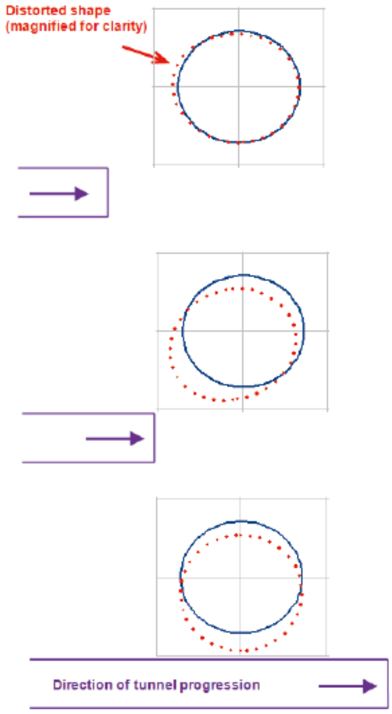
2.2.2 Transverse Deformation

For the transverse effect, the cross sectional behaviour of the existing tunnel is examined. The transverse movements occur largely due to the ground around the tunnelling face which follows the same Gaussian distribution as discussed in the longitudinal deformation in the previous paragraph. That means the points in the ground closer to the source of the ground movement tend to move more than those further away from the source. Again it is assumed that the tunnel movements can be predicted by 'greenfield' movement as the tunnel is considered flexible enough. In addition, it is assumed that the maximum vertical distortion does not occur at the same point as the maximum horizontal distortion. [18] Several assessments have been carried out to study the temporary ground movement and thus the distortion of the existing tunnel shape as new tunnel construction carried out beneath. Some key effects of the existing tunnel shape which were consistent with real life cases such as the Piccadilly Line at Heathrow are summarised as following [19]:

- ❖ The maximum distortion of the existing tunnel often does not occur on the vertical or horizontal principle axes, but at an angle as the TBM face passes, which is on a diagonal axis.
- ❖ The final maximum distortion is less than the maximum measured temporary distortion.
- ❖ The final distorted existing tunnel shape shows transverse distortion (*ovalisation)* of the tunnel, in which the horizontal diameter reduced and the vertical diameter increases as

❖shown in Fig. 2.2.2 (b) which shows elongation. The reason for this is due to the reduction in vertical stress relative to horizontal stress (where new construction takes place above or below. Squatting ovalisation will occur if new works exist alongside existing tunnels). Again 'Greenfield' empirical formula is often used to calculate radial displacement and hence degree of ovalisation [20]

Fig. 2.2.2 (c) on the right shows the distortion of the cross-sectional shape of the existing tunnel as the new tunnelling work or TBM approaches, at an angle to the axis, and exactly beneath the axis of the existing tunnel. It shows that the maximum distortion is temporary and on a diagonal axis. [21]



Left: Fig. 2.2.2 (c) cross-section view of the distortion of the existing tunnel as new tunnelling work pass underneath [21]

2.2.3 Rotation of the Existing Tunnel

Fig.2.2.3 (a) shows anticlockwise rotation of the existing tunnel in response to approaching under-crossing of the construction of the Heathrow Express tunnels (using Sprayed concrete lining SCL method) as they passed beneath the Piccadilly Line at Heathrow for different dates of construction [22]. The left side scale shows the degree of rotation which is positive means anticlockwise looking away from the station. The right side scale shows the face distance from the Piccadilly Line, with negative value means approaching the existing tunnel, 0 means directly below the axis of the existing tunnel, and positive value means leaving the existing tunnel. The dotted curve represented the progress of the drift face distance from the Piccadilly Line and the solid curve represented the progress of the enlargement face distance from the Piccadilly Line. The horizontal line represent the position of the Piccadilly Line. Initially, as the new Heathrow Express tunnel (the drift face or enlargement face) approached (when the dotted and solid curves are below the horizontal line), the existing Piccadilly Line rotated in the anti-clockwise direction as shown by the increasing degree of rotation of the curves. As under-crossing was directly beneath the existing Piccadilly Line tunnel (dotted curve crosses the horizontal line on about 11th Sep 94 and the solid curve crosses the horizontal line on about 23rd Sep 94), rotation halted as shown by the 2 crowns of the rotation curves. As under-crossing continued (when the drift face and the enlargement face were leaving the Piccadilly Line, or when the dotted and solid curves are above the horizontal line), the existing tunnel rotated to the clockwise direction as shown by decreasing degree of rotation of the curves. The process repeated in this instance as the new works took place in two operations, drift and enlargement. It also showed that the degree of rotation tended to remain at a certain value even after the tunnelling work have left away from the Piccadilly Line. It may represent the residual rotation of the tunnel so that the degree of rotation never came back to zero even after the new tunnelling work have left the existing tunnel.

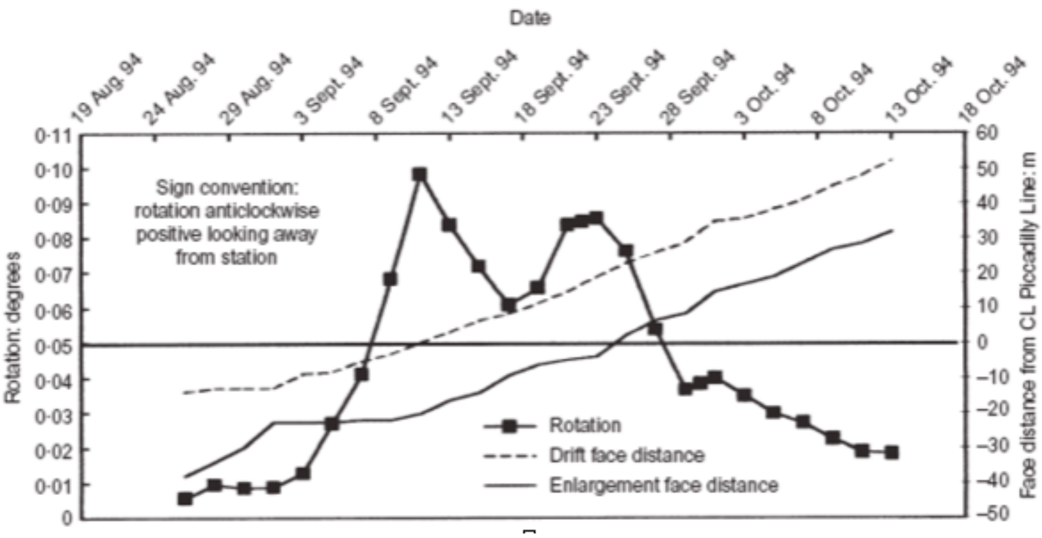


Fig.2.2.3 (a) Diagram showing the rotation of the Piccadilly Line tunnel as the new Heathrow Express tunnel Drift face and Enlargement face passed underneath

This is an important consideration for the monitoring requirements of the existing tunnels. Precise levelling or track-shoe monitoring systems are there for the manual monitoring of the track cant and twist, and it is difficult to implement. It may be argued that if the rotational response of the tunnel could be investigated and understood, then the relative track-shoe monitoring may not be required. If the tunnel structure has a corresponding rotational response, then the kinematic envelope will not be affected.

Application: Rotation of Victoria & Bakerloo Line due to Crossrail Construction

In order to assess the degree of rotation the Victoria & Bakerloo Line running tunnels for the Crossrail project, the combined final settlement profiles derived from track levelling points and electro-level beams will be used.

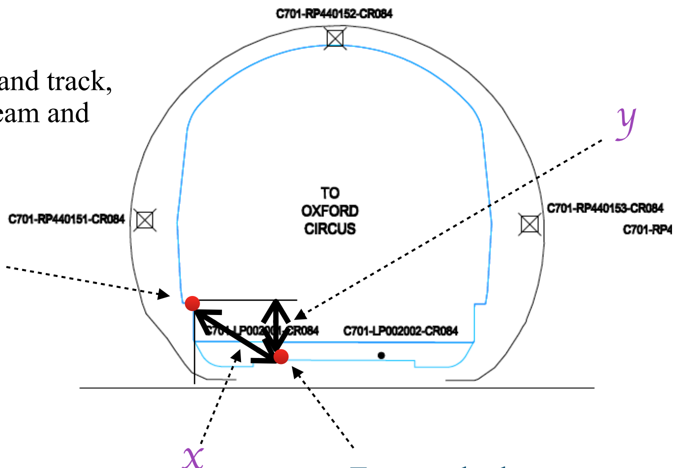
The difference in maximum settlement produced by one particular electro-level beam and one particular eastern track shoe levelling point is the difference in vertical height between them as denoted by y on Fig.2.2.3 (b).

$y = \Delta\text{settlement} = |z1-z2|$, where z1 and z2 are maximum settlements on the final settlement profiles produced by electro-level beam and track-shoe monitoring respectively. The difference in absolute distance between them is denoted by x on Fig.2.2.3(b) .

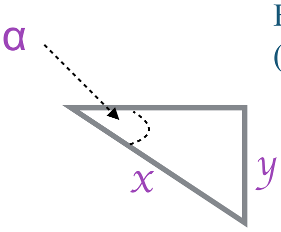
It is calculated by using equation: x=((E1-E2)^2+(N1-N2)^2)^0.5

where: (E1-E2) = the difference in Easting coordinates, and

(N1-N2) = the difference in Northing coordinates for data points from the electro-level beam and the track.



Right: Fig.2.2.3 (b) Victoria NB tunnel and track, and relative positions of electro-level beam and eastern track-shoe levelling point



Left: Fig. 2.2.3 (c) geometric representation of the relative position of the electro-level beam and the track-shoe levelling point with the angle of rotation α

Fig.2.2.3 (b) above shows an example of Victoria Line NB tunnel and track with the relative positions of a electro-level beam installed on the eastern wall of the tunnel and a track-shoe monitoring point on the eastern track. The absolute distance between them is x and the vertical distance between them is y, as shown on Fig.2.2.3 (c).

The degree of rotation α is calculated by: α = sin α= y/x rad(by small angle approximation). Then convert α in degree by times 360/(2π)

As the final settlement graph is used, the rotation calculated is the rotation of the tunnel when the two TBM left the existing tunnels. This degree of rotation is then compared with Fig.2.2.3(a) above to show whether it is within the correct range when the tunnelling work left the zone of influence of the existing tunnel.

Table.2.2.3 below shows the required information for 3 existing lines and the results of calculations for the degree of rotation.

	Victoria Line NB	Victoria Line SB	Bakerloo Line NB
E1 (m)	79349.5008	79398.5109	79403.175
N1 (m)	35853.4624	35854.0593	35859.1425
z1 (m)	0.0147844	0.0079987	0.0100073
E2 (m)	79348.624	79399.717	79402.878
N2 (m)	35849.494	35854.738	35858.101

	Victoria Line NB	Victoria Line SB	Bakerloo Line NB
z2 (m)	0.0145	0.0086	0.0101
x (m)	4.0641	1.38395	1.083020
y (m)	0.002844	0.0006013	0.0000927
α (rad)	0.0006998	0.00043448	0.000085594
α (degree)	0.0401	0.02490	0.00494

Table.2.2.3 Coordinates, settlement values, and results of calculation of degrees of rotations for existing lines

It shows that the degrees of rotation of the tunnels are all *smaller than 0.05 degree*, which lie in the region on Fig. 2.2.3(a) where the tunnelling work is leaving the zone of influence of the existing tunnel (where the right ends of the curves fall beyond and below the horizontal line which are less than 0.05 degrees). Given that the final settlement profiles are used for the values of x,y,α to be taken, and the time was after TBM2 left the existing tunnels. Therefore the degrees of rotation calculated have proved the correct time.

2.3 Historical Case —The Effect of Jubilee Line Extension on Existing Tunnels [22]

The construction of Jubilee Line Extension (JLE) passed beneath several existing tunnels in close proximity, including the District & Circle, Bakerloo, Northern and Waterloo & City Line tunnels. As our tunnels are small, deep level cast-iron type, the response and resulting settlement profiles for Bakerloo&Northern Lines are the most relevant ones and will be discussed here further in detail. They are located within London Clay. Different monitoring techniques were used to ensure the safety of the running tunnels. However, only data from precise-levelling points were used to present the results of the settlement profiles for different tunnels as they offered clear comparable datas. Comparisons were made between the plotted settlement profiles and the predicted ones. The interaction between adjacent settlement troughs were investigated with the principles of superposition. The influence of the depth on the trough-width parameter K was also investigated. Although electro-level beams were installed and monitored to provide real-time measurements, the results were not included in this literature.

2.3.1 Location of Work

From 23rd February to 16th June 1995, the westbound (WB) tunnel of JLE was constructed, and from 1st March to 19th June 1995, the eastbound (EB) tunnel of JLE was constructed. Fig.2.3.1 (a) below shows the plan of the existing Bakerloo, Northern and Waterloo & City Line tunnels, west of Waterloo station in relation to the new JLE running tunnels with the locations of monitoring points. [23]

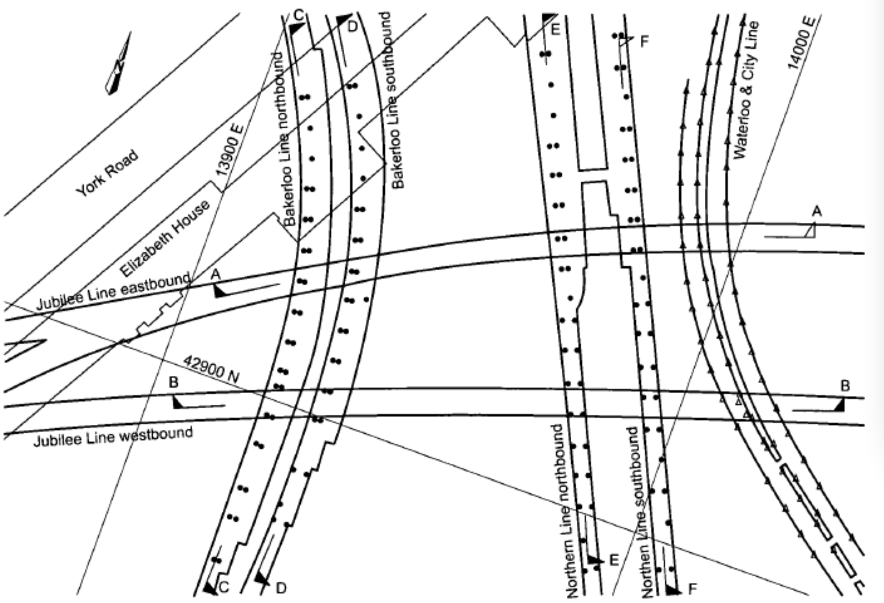


Fig.2.3.1 (a) the plan of existing tunnels: Bakerloo, Northern and Waterloo & City Line tunnels, west of Waterloo station in relation to the new JLE running tunnels with the locations of monitoring points.

The region of monitoring for existing tunnels due to the construction of Jubilee line extension are:

- ❖Waterloo&City Line: just beyond Elizabeth House on York Road
- ❖Bakerloo Line: in the vicinity of Jubilee Garden on the south bank of the Thames
- ❖Northern Line: Jubilee Line Extension passes beneath the West End branch of the Northern Line close to Waterloo station

In this case, the influence of the construction on Bakerloo and Northern Lines were considered.

For Bakerloo Line, it was monitored at close proximity at Jubilee Gardens on the south bank of the Thames and north of Waterloo International Terminal. The bolted cast-iron segmental lining running tunnels and platform tunnels have diameters of 3.6m and 6.8m respectively. Fig.2.3.1 (b) shows the cross-section diagram along the Bakerloo Line tunnel for the relative positions of Bakerloo Northbound (NB) and Jubilee Line WB and EB, looking into C-C and D-D directions respectively as indicated on Fig.2.3.1 (a). JLE tunnels passed beneath them at 10.5m and 13m below the tunnel inverts. [24]

For Northern Line, JLE passed beneath the West End branch of the Northern Line which is close to Waterloo station. The cast-iron lining running tunnels and platform tunnels have diameters of 3.6m and 6.7m respectively. Fig.2.1.3 (c) shows the cross-sectional diagram along the Northern Line tunnels for the relative positions of JLE and Northern Line NB and SB, looking into E-E and F-F directions as indicated in Fig.2.1.3 (a). JLE tunnels are about 8m beneath the Northern Line EB and WB tunnel inverts. [25]

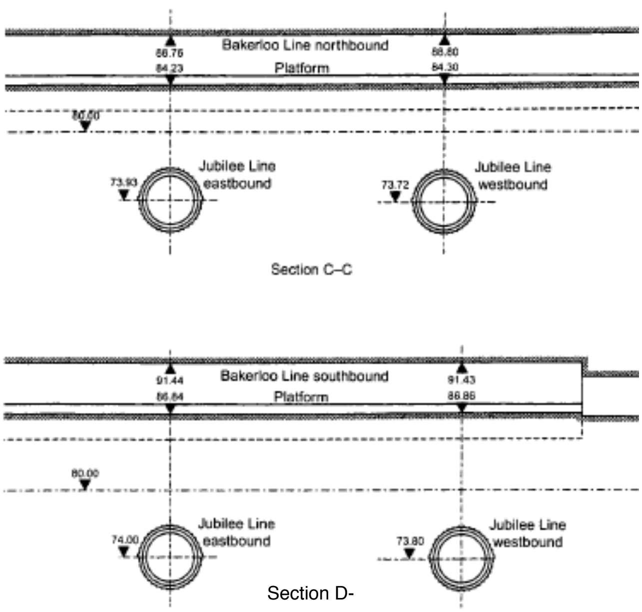


Fig.2.1.3 (b) cross-section view of the Bakerloo Line NB & SB tunnels in direction C-C and D-D, with positions of JLE WB&EB tunnels

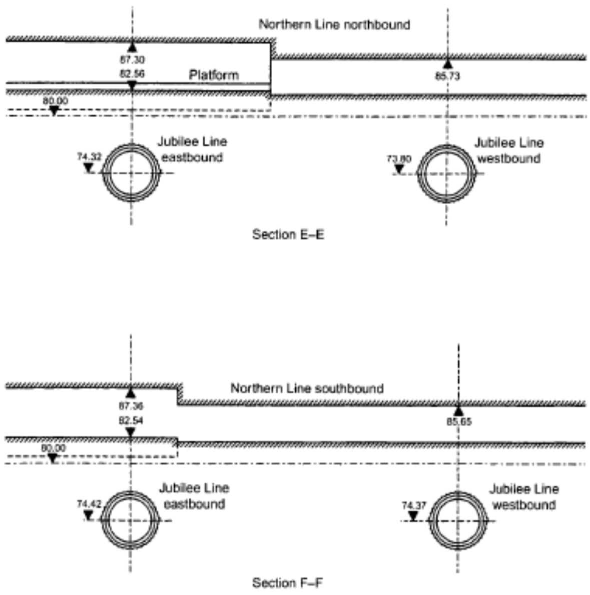


Fig.2.1.3 (c) cross-section view of the NorthernLine NB & SB tunnels in direction C-C and D-D, with positions of JLE WB&EB tunnels

2.3.2 Monitoring Techniques and Accuracy

The main monitoring methods used to produce the data results for the settlement profiles was Precise Levelling with levelling studs installed on the concrete trackbed at ~5m intervals. The datum used was a reference point which was outside the region of influence. Level measurements were monitored using foresights and backsights at approximately equal distance. The instruments have a typical resolution of 0.1mm and a accuracy within ± 1mm [26].

2.3.3 Response of Existing tunnels

The movements of the existing tunnels due to the construction of JLE were derived from precise levelling and used to produce settlement profiles along the tunnels at different dates when the JLE tunnelling approached, right under and leaving the existing tunnels. Fig.2.3.3 (a) show the progressive settlement profiles along the tunnel for the Bakerloo Line NB and SB tunnels due to the construction of JLE beneath just west of Waterloo International Terminal for different dates. They show that the WB JLE was constructed first, but the overall settlement was produced when the whole construction finished. There was an initial heave prior to the arrival of JLE tunnels of 1mm for NB and 1-2 mm for SB. The maximum settlements are 10mm for NB and 8mm for SB. The max settlement for SB is smaller because the distance from SB to JLE tunnel is larger. There is a merger of troughs in both cases. [27]

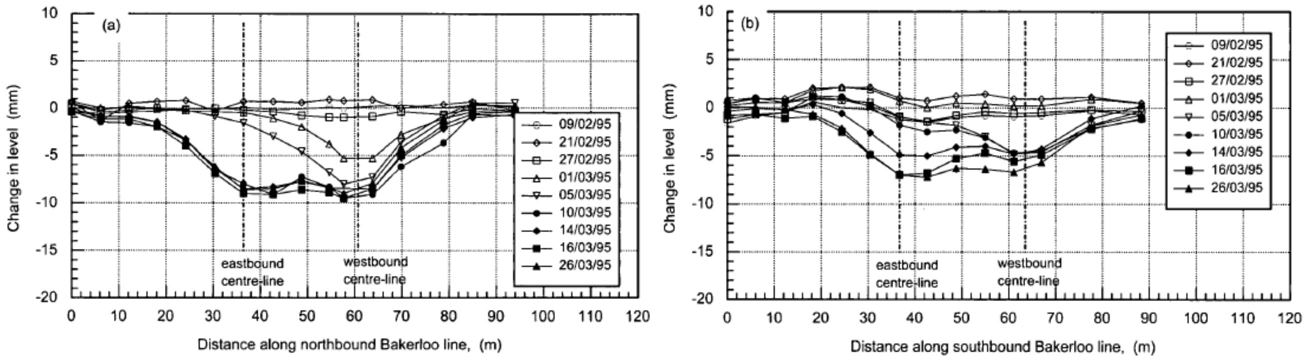


Fig. 2 3.3 (a) Settlement Profiles for Bakerloo Line NB (left) and SB (right) following the construction of the JLE for different dates

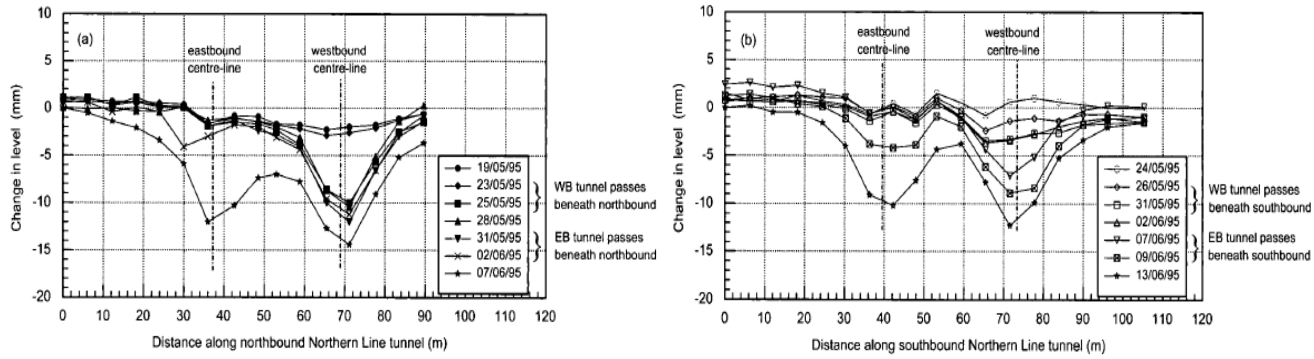


Fig. 2 3.3 (b) Settlement Profiles for Northern Line NB (left) and SB (right) following the construction of the JLE for different dates

Fig.2.3.3 (b) show the settlement profiles along the tunnel of the Northern Line NB and EB tunnels due to the construction of JLE beneath at Waterloo. They show similar shapes to the settlement profiles for Bakerloo Lines, but with greater settlements due to the reason that the distance between Northern Line tunnels and JLE tunnels are smaller than that for Bakerloo Lines. Furthermore, the Bakerloo line is a platform tunnel at the considered longitudinal section, hence a stiffer structure that in effect dampened the settlement trough, actively imparting vertical settlement as the sharp greenfield troughs act like inverted reactions at the centre lines of the JLE tunnels. As the distance between Northern Line and JLE tunnels are closer at the position above the WB JLE, maximum settlements occurred at those positions, which were 12mm for WB and 10mm for EB. There were distinct settlement troughs, unlike the merged ones for Bakerloo Lines, partially due to the smaller and more flexible running tunnels may follow more closely the greenfield (soil) movement. Also, as the transition from platform to running tunnel occurs within the longitudinal section, articulation may occur about this point, further lessening longitudinal stiffness of the structures for Northern Line. [28]

2.3.4 Superposition of Settlement Troughs

The principle of superposition is used to assess the overall settlement profile for the combined influence when the two tunnels constructed close together. The closer the two tunnels is, the greater the interaction between them becomes. The overall profile is deduced by superposing their settlement troughs if only influenced by the construction of individual tunnel. The extent of interaction depends on the spacing between the two constructing tunnels, the distance between the new tunnel and the existing tunnel inverts, as well as the structural stiffness of the existing tunnels.

In this case, the settlement profiles for Bakerloo Lines NB&SB tunnels show mergers of settlement troughs as in Fig.2.3.4 (a). It shows that the actual maximum settlements extended over a larger distance than the predicted overall settlement profiles from the superposition of their individual profiles. While for Northern Line, there were distinct settlement troughs as the actual settlements follow the predicted ones from superposition closely as shown in Fig.2.3.4 (b). [29]

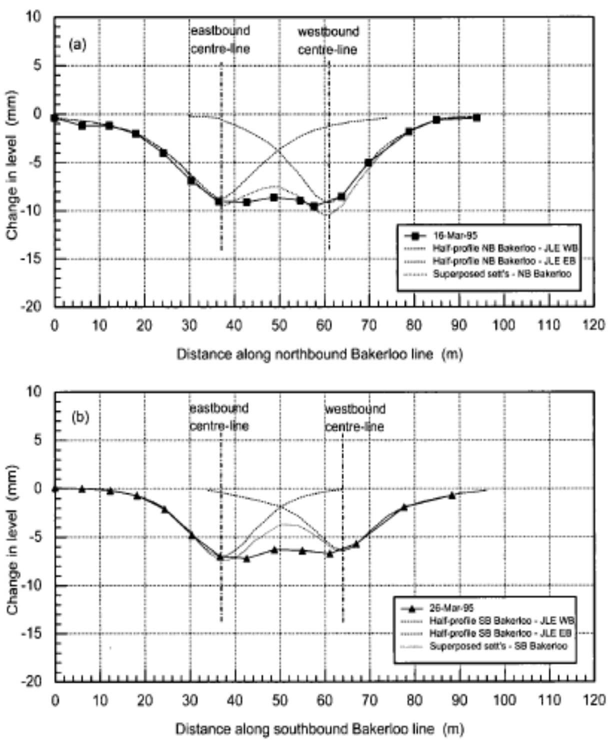


Fig.2.3.4 (a) Merger of settlement troughs for Bakerloo Line NB (top) and SB (below) tunnels

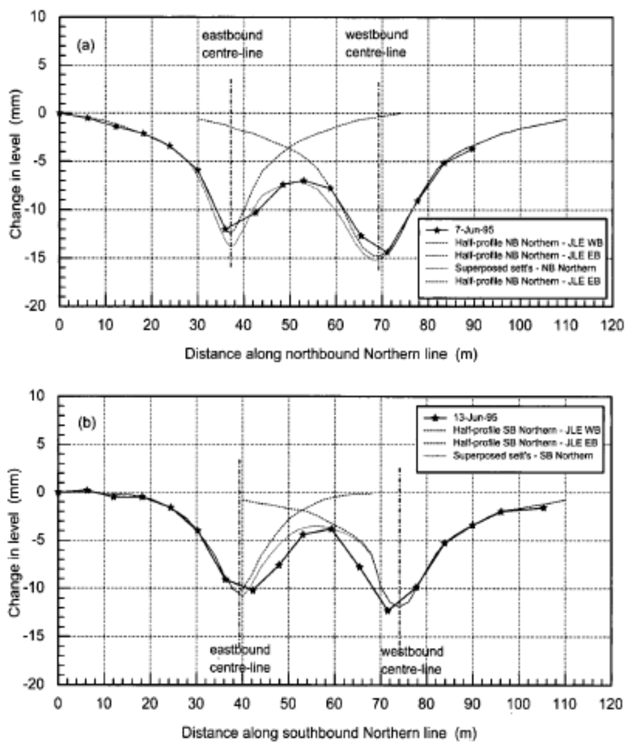


Fig.2.3.4 (a) Distinct settlement troughs for Northern Line NB (top) and SB (below) tunnels

Table.2.3.4 (a) summaries the factors that cause such difference in the combined settlement profiles for Bakerloo and Northern Lines. [30] Other factors such as the trough-width parameter K and the relative position of the tunnel faces may influence the settlement profile. Therefore, the larger the separation, the closer the new tunnel to the existing tunnel, the smaller and less stiff the existing tunnel, the more distinct settlement troughs.

Factors	**Bakerloo Line Platform Tunnel Case** —Merger of settlement troughs, extended over larger distance than predicted settlement profile by superposition	**Northern Line Case** —Distinct settlement troughs, settlement profile follow more closely as the predicted one by superposition
• **Spacing between the JLE tunnel axes beneath the existing tunnels**	JLE tunnel axes are closer together:25.5-27m	JLE tunnel axes are further apart: 32.5-34m
• **Depth of JLE tunnels beneath the invert**	JLE tunnels are deeper beneath the invert: 10.5m and 13m below	JLE tunnels are less deep beneath: 8m below
• **Tunnel size and structural stiffness** **(only minor influence as the response of the existing tunnels were very flexible)**	➢ Internal diameter of platform tunnel: 6.8m which is larger ➢ Stiffer platform tunnels which dampen the effect of actual ground movement	➢ Internal diameter of platform tunnel: 6.7m; ➢ Internal diameter of running tunnel: 3.7m; ➢ Less stiff tunnels, so that its movement is more like the actual ground movement

Table.2.3.4 (a) Factors affecting the reasons for merger of settlement troughs for Bakerloo Line and distinct settlement troughs for Northern Line

3. Locations of Tunnelling Works

3.1 Tunnelling works near the Existing Tunnels

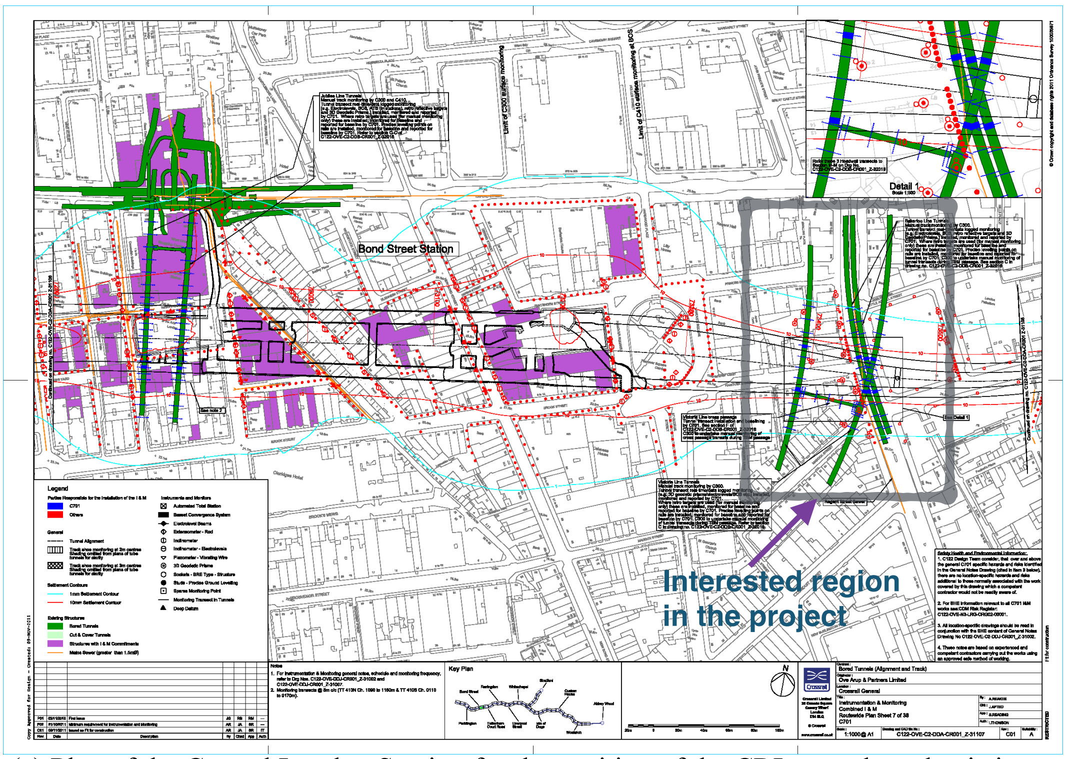


Fig.3.1 (a) Plan of the Central London Section for the position of the CRL tunnels and existing structures

Fig.3.1 (a) above is a plan of the central London section around Bond Street Station. In this project, the effects of the construction of Crossrail on the existing Victoria & Bakerloo Line running tunnels and tracks are to be investigated. Victoria & Bakerloo Lines are at the same site and they may be affecting each other, therefore, it makes sense to look at their behaviours together. The green sections on the right side of the diagram show Northbound (NB) and Southbound (SB) of the Victoria & Bakerloo Line south of the Oxford Circus platform areas [34].

Different legends shown on the diagrams are:

Purple sections: Important structures that must be monitored, with I&M Commitments

Green sections: Existing tunnels

Blue thin shot lines: prism arrays (retro-reflective targets), Blue thick short Lines: Basset Convergence Systems (BCS)

Light blue contour lines: 1mm settlement contours

Red contour line: 10mm settlement contour

Red dots: surface levelling points

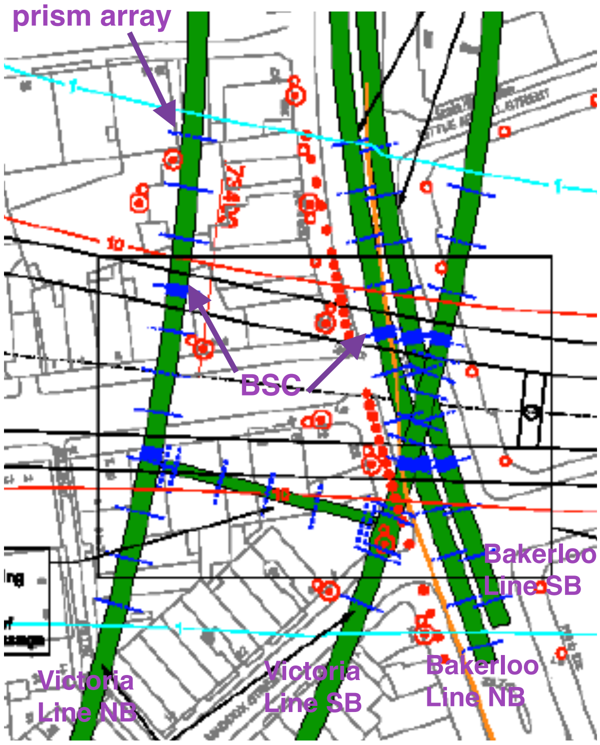


Fig. 3.1 (b) Zoom in of Fig.3.1 (a)

In this project, the scope of work is focusing on the monitored section of the NB and SB of the Victoria and Bakerloo Line running tunnels south of Oxford Circus Station, and their response due to the construction of Crossrail running tunnel WB and EB beneath. Monitored region is indicated by the blue lines. The detailed locations of proposed instrumentation and monitoring are shown in Fig.3.1 (b) [35]:

Victoria line SB (V044/VSB 0130 to V044/VSB0240)

- Victoria line NB (V044/VNB 0770 to V044/VNB 0890)
- Victoria line Cross-passage (V044/CP12)
- Bakerloo line SB (B126/BSB/0120 to B126/BSB/0240)
- Bakerloo line NB (B126/BNB/0610 to B126/BNB/0740)

The location of Crossrail work is at south of Oxford Circus Station and new Crossrail (CRL) tunnelling TBM1(WB) and TBM2 (EB) passed beneath the Victoria Line NB and SB tunnels. Table.3.1 below summaries the dates and times for CRL approached (50m before), crossed (directly beneath) and leaving (75m after) the existing Victoria &

Bakerloo Line runnel tunnels. CRL WB (TB1) passed beneath through the Victoria Line and Bakerloo Line running tunnels first, but the overall settlement profiles were produced after the CRL EB (TB2) passed through the existing tunnels.[36][37][38][39]

Existing Tunnels	CRL Tunnelling	50m before the existing tunnels	crossing the existing tunnels	75m after the existing tunnels
Victoria Line NB	TBM1	03/05/2013 02:17	04/05/2013 20:26	08/05/2013 19:34
	TBM2	01/07/2013 22:57	03/07/2013 16:54	05/07/2013 14:58
Victoria Line SB	TBM1	04/05/2013 20:26	08/05/2013 13:14	10/05/2013 22:48
	TBM2	04/07/2013 20:26	04/07/2013 22:25	10/05/2013 22:48
Bakerloo Line NB	TBM1	04/05/2013 23:13	08/05/2013 14:58	11/05/2013 00:52
	TBM2	03/07/2013 02:47	04/07/2013 18:12	07/07/2013 08:15
Bakerloo Line SB	TBM1	05/05/2013 01:09	08/05/2013 16:56	11/05/2013 03:32
	TBM2	03/07/2013 11:09	05/07/2013 03:13	07/07/2013 18:55

Table. 3.1 dates of the construction of CRL tunnels before, cross, and after the existing tunnels

At the crossing, the depths of axis of the Victoria Line NB and SB tunnels below ground level are 22.19 m and 18.26 m respectively, and that of the Bakerloo Line NB & SB tunnels is about 21.7 m. The relative location of CRL tunnels to the existing tunnels are shown in Section3.1.1 and Section3.1.2 below. The method of tunnel construction was by earth pressure balance (EPB) machine and the tunnels are formed of concrete segments linings.

3.1.1 Victoria Line

Fig. 3.1.1 (a) [40] shows the plan of location for the Crossrail construction works beneath the Victoria Line from Oxford Circus to Green park, and Crossrail EB and WB running tunnels. The blue parts are the monitored section for the Victoria line NB and SB and Victoria Line cross passage. The monitored LU Victoria Line assets between Oxford Circus and Green Park Station (Interface LU/08) consist of Victoria Line

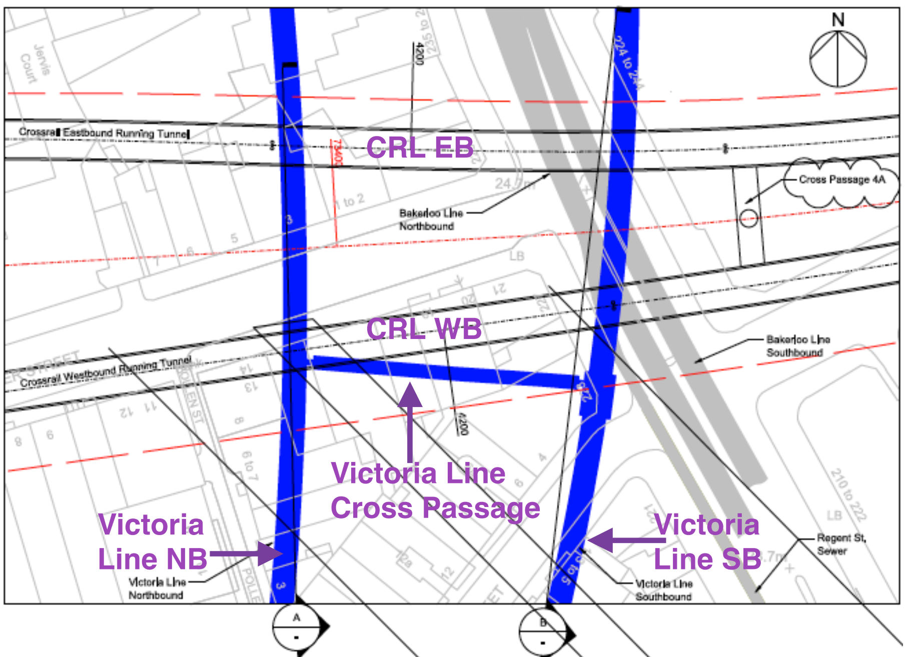


Fig.3.1.1 (a) Plan of location for the CRL construction under the Victoria Line NB&SB [40]

Northbound (Asset Number: V044/TT281N), Victoria Line Southbound (Asset Number:V044/TT281S) and Victoria Line Cross Passage (Asset Number V044/CP12) [41]. The angle of Crossrail to the Victoria Line is ~80º. This angle is important when considering the predicted settlements of the existing tunnels. The settlement trough will be narrower than if works are perpendicular.

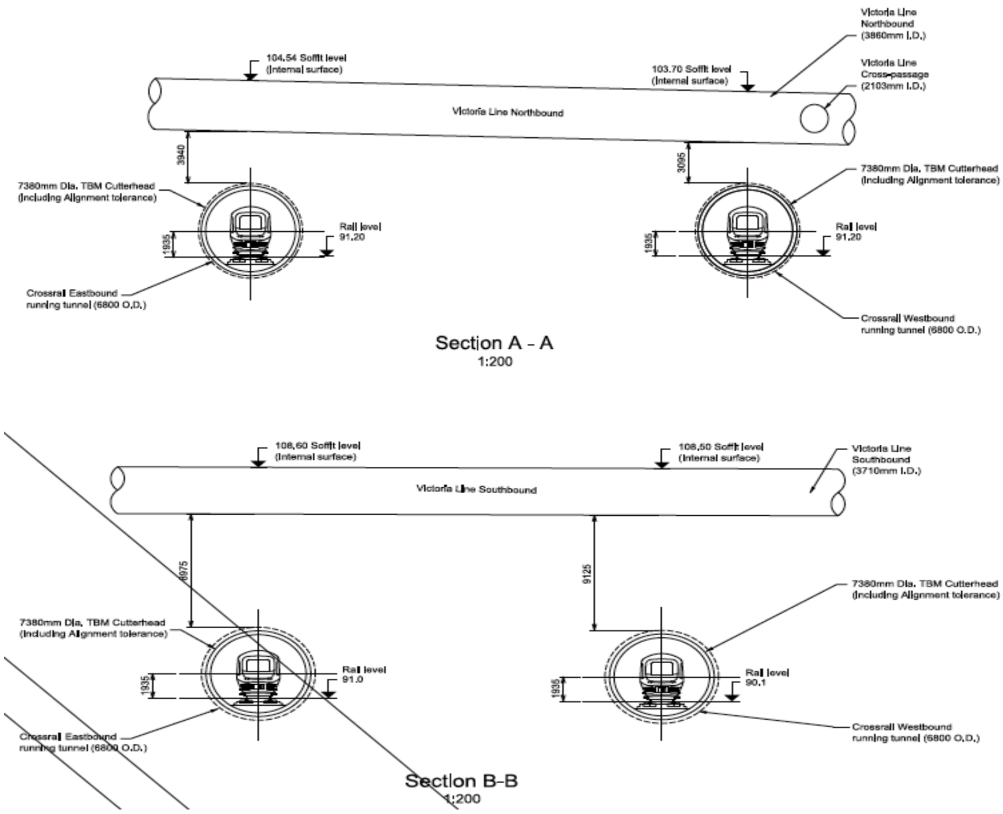


Fig. 3.1.1 (b) Cross-sectional diagram of CRL WB&EB tunnels relative to Victoria NB (above) in direction A-A and Victoria SB (below) in direction B-B of Fig. 3.1.1 (a) [42]

Fig.3.1.1 (b) [42] shows the cross-sectional diagram of the location of Crossrail tunnels relative to Victoria Line NB and Victoria Line SB and more details in terms of dimensions. They are taken from longitudinal section looking in the direction of the arrow A-A and B-B respectively for Victoria Line NB and SB as indicated in Fig.3.1.1 (a) above. The new Crossrail work is beneath the existing Victoria Line running tunnels .

From the diagram, it shows that,

For Victoria line NB:

- Crossrail twin tunnels internal diameter: 6.8m, external diameter: 7.38 m (TBM cutterhead diameter, including alignment tolerance)
- Victoria Line NB tunnel internal diameter: 3.86m
- ***Clearance*** (which is the distance from the top of the TBM1 and TBM2 to the inverts of the Victoria Line NB lining): 3.94 m for Crossrail WB (TBM1) and 3.095 m for Crossrail EB (TBM2).

- Spacing between the axis of 2 Crossrail tunnel WB and EB: 34.22 m [43]

For Victoria Line SB:

- Crossrail twin tunnels internal diameter: 6.8m, external diameter: 7.38 m
- Clearance which is the distance from the top of the TBM1 and TBM2 to the inverts of the Victoria Line SB lining): 8.975 m for Crossrail WB (TBM1) and 9.125 m for Crossrail EB (TBM2)
- Spacing between axis of 2 Crossrail tunnel WB and EB: 25.935m [44]

3.1.2 Bakerloo Line

Fig.3.1.2 (a) [45] shows the plan of location for the Crossrail work beneath Bakerloo Line from oxford circus to green park, and Crossrail EB and WB running tunnels. The blue parts are the monitored section for the Bakerloo line NB and SB, and Regent Street Sewer (not to be discussed in this project). The monitored LU Bakerloo Line assets between Oxford Circus and Piccadilly Circus (Interface LU/09) consist of Bakerloo Line Northbound (Asset Number: B126/TT78N) and Bakerloo line Southbound (Asset Number: B126/TT78S) [46]. The angle of Crossrail to the Bakerloo Line is ~20° to 30°.

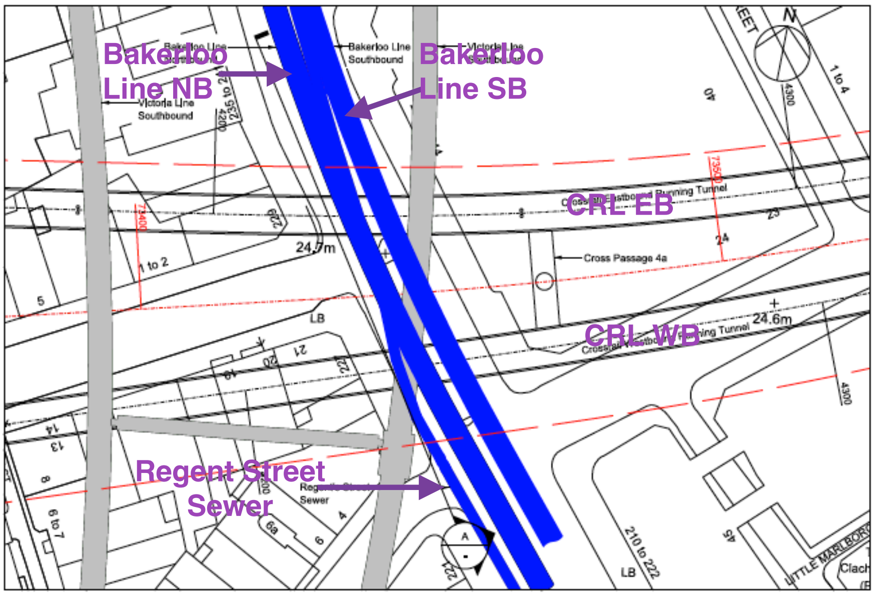


Fig.3.1.2 (a) Plan of location for the CRL construction under the Bakerloo Line NB&SB [45]

Fig.3.1.2 (b) [47] shows the cross-sectional diagram of the location of Crossrail tunnels relative to Bakerloo Line NB and SB and more details in terms of dimensions. They are taken form longitudinal section looking into the direction of A-A as indicated in Fig. 3.1.2 (a) .The new Crossrail work is beneath the existing Bakerloo Line running tunnels .

From the diagram, it shows that for Bakerloo line NB and SB:

- Crossrail twin tunnels internal diameter: 6.8 m, external diameter: 7.38 m
- Bakerloo Line NB and SB tunnel internal diameter: 3.66m

- Clearance (which is the distance from the top of the TBM1 and TBM2 to the inverts of the Bakerloo Line NB and SB lining): 5.315 m for Crossrail WB (TBM1) and 5.526 m for Crossrail EB (TBM2)
- Spacing between the axis of 2 Crossrail tunnel WB and EB : 28.005 m [48]

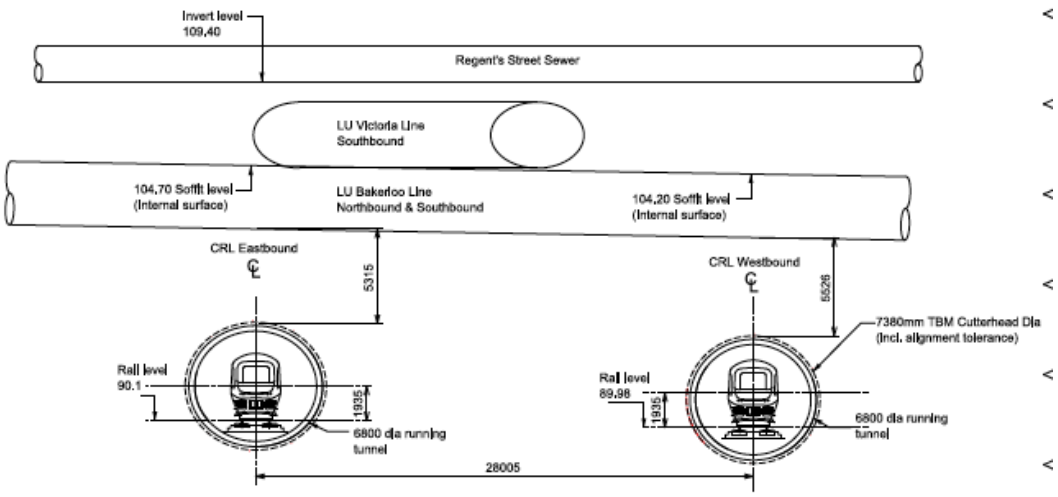


Fig. 3.1.2 (b) Cross-sectional diagram of CRL WB&EB tunnels relative to Bakerloo NB&SB in direction A-A of Fig.3.1.1 (a) [47]

Section A - A
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3.3 Factors affecting the Settlement Profiles due to CRL Construction

The settlement profiles for Victoria NB, Victoria SB, Bakerloo NB have different shapes. Table.2.3.4 (b) below summarise their characteristics affecting whether they have merger of settlement troughs, or distinct settlement troughs, especially in relation to the difference in CRL tunnelling locations and their relative positions to the existing tunnels.

Factors	Victoria NB running tunnels	Bakerloo NB running tunnels	Victoria SB running tunnels
• **Spacing between the Crossrail tunnel axes**	34.22m	28.005m	25.935m
• **Depth of Crossrail (CRL) tunnel beneath the invert**	3.94 m and 3.095m for CRL EB and WB respectively	5.315m and 5.526m for CRL EB and WB respectively	8.975m and 9.125m for CRL EB and WB respectively
• **Existing tunnel size in term of internal diameter**	Internal diamater: 3.86m	internal diameter: 3.66m	internal diameter: 3.71m
• **Settlement profile**	the most distinct settlement troughs	less distinct settlement troughs	The least distinct settlement troughs

Table.2.3.4 (b) Factors affecting the different settlement profiles of Victoria & Bakerloo Line tunnels

The difference in size of the existing tunnels is small as they have roughly the same internal diameters. Moreover, the tunnels are all running tunnels and the response of the tunnel is elastic, therefore the size and structural stiffness of the tunnels are minor factors.

Table.2.3.4 (b) shows that spacing between the CRL tunnel axes beneath Victoria Line NB is the largest, followed by Bakerloo Line NB, and that for Victoria SB is the smallest. The depth of CRL beneath Victoria Line NB is the smallest, followed by Bakerloo Line NB, and that for Victoria Line SB is the largest. Therefore, the actual settlement profile for Victoria Line NB is expected to have the most distinct settlement troughs which should follow more closely the predicted settlement profile produced from superposition of the individual Gaussian settlement profile due to the effect of TBM1 and TBM2 tunnelling of Crossrail. Bakerloo Line NB is expected to have less distinct or more merged settlement troughs. Finally, Victoria Line SB is expected to have the least distinct or the most merged settlement troughs, and the actual maximum settlements extended over a larger distance than that predicted overall settlement profile from superposition of their individual profiles.

Fig. 2.3.4 (a) (b) (c) show the comparisons of real time settlement profiles produced by Electro-level beams and the predicted overall settlement profiles produced by principle of superposition of individual Gaussian profile. (For the method of prediction, please refer to Section 2.1.) The blue curves are the actual settlement profiles derived from the electro-level beams after TBM2 passed underneath the existing tunnels, and the orange curves are the predicted settlement profiles derived from empirical methods. The vertical axis is the settlement in Z direction in unit of mm, the horizontal axis is the shifted distance along the tunnel in order to bring the position of the CRL WB to 0 m position. As shown in Fig. 2.3.4 (a), the actual settlement profile of Victoria NB has the most distinct settlement troughs which follow more closely with the predicted one. For Fig. 2.3.4(b), the actual settlement profile of Bakerloo Line NB has less distinct or more merged settlement troughs. Finally, for Fig.2.3.4(c), the actual settlement profile of Victoria Line SB has the most merged settlement troughs, with the maximum settlements extended over a larger distance than that predicted overall settlement profile from superposition of their individual profiles.

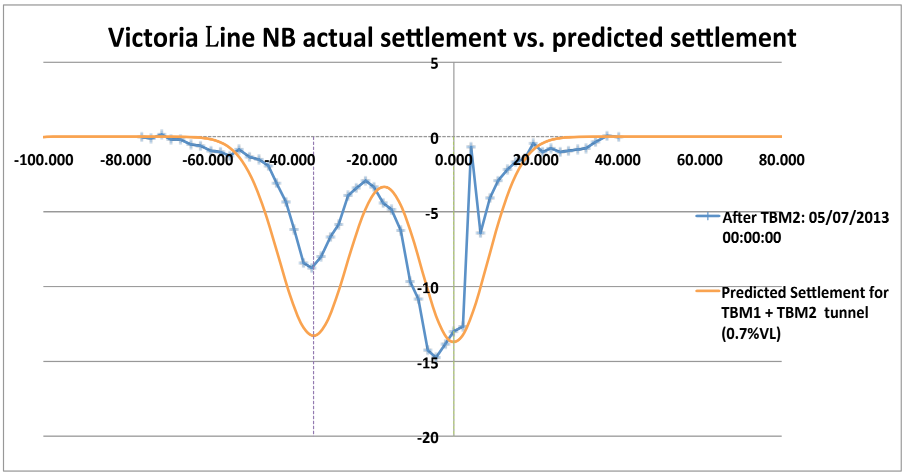


Fig. 2.3.4 (a) Victoria Line NB actual settlement and predicted settlement profiles, showing the most distinct settlement troughs[31]

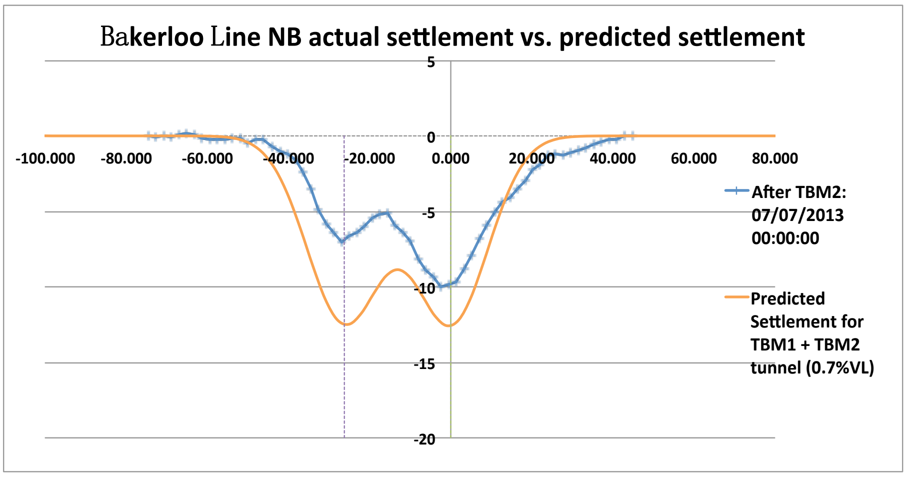


Fig.2.3.4 (b) Bakerloo Line NB actual and predicted settlement profiles, showing the less distinct/more merged settlement troughs [32]

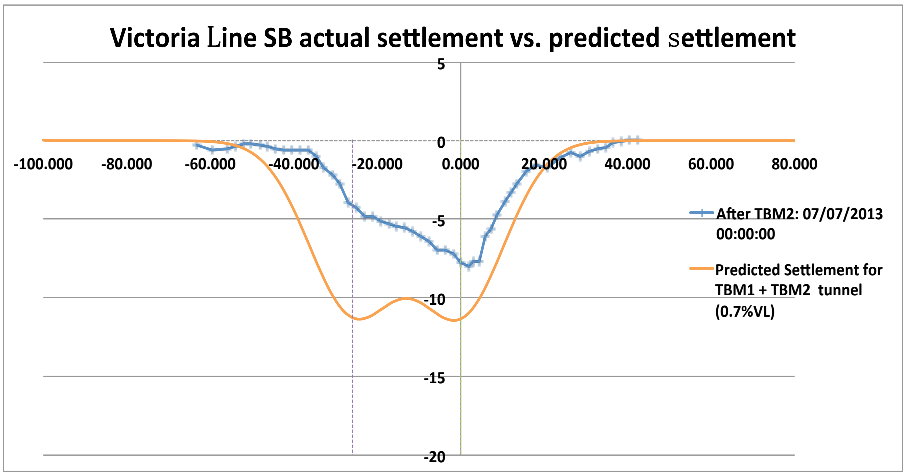


Fig.2.3.4 (c) Victoria Line SB actual and predicted settlement profiles, showing the least distinct/the most merged settlement troughs [33]

3.3 Trigger values

For asset protection purpose, a system of 4 trigger levels have been set on tunnel displacement and track geometry and clearance. Table.3.2 (a) shows a summary of trigger values for track of Victoria and Bakerloo Lines [49][50]. The trigger values for track geometry are the same for both lines and the same as the Central Line track geometry. Table.3.2 (b) and Table.3.2 (c) show summaries of trigger values for the tunnel of Victoria and Bakerloo lines respectively. The trigger values for Victoria Line NB and SB tunnel vertical displacement are different because the clearance are different. The clearance between Victoria Line NB and Crossrail tunnel is 3.94 m and 3.905 m for CRL WB and EB respectively, which are greater compared to that between Victoria Line SB and Crossrail tunnel which is 8.975 m and 9.125 m for CRL WB and EB respectively.

Cant is the change in cross-level of the track. It is a measurement of difference in elevation between the outer rail and the inner rail, when the outside rail is higher level than the inside rail, cant is positive, and the other way is negative cant. ***Twist*** is cant gradient, it is the amount by which cant is increased or decreased in a given length of the track. In this case, 2m and 10m track twist are measured. The vertical profile of the track is the measurement of the maximum difference from the baseline deviations, measured at 5m intervals. All the values are taken from LU standard for deviation of running tracks. Tunnel displacement (maximum displacement) is a form of construction control for each Crossrail tunnel construction and the entire works. The black trigger invokes immediate emergency response. The black trigger for vertical displacement of the tunnel is when there is an unexpected movement of the tunnel or other observed change considered to impact the safe operation of the railway [51] [52]. The trigger values for vertical displacement will be used in later chapters for comparison of the settlement profiles produced by the track-shoe monitoring systems, retro-reflective targets and electro-level beams.

Victoria and Bakerloo Line Track	Green	Amber	Red	Black
Track Twist 10m	30mm	37mm	40mm	50mm
Track Twist 2m	14mm	18mm	20mm	25mm
Track Cant	+2/-10mm	+4/-12mm	+11/-15mm	+15/-20mm
Vertical Profile (5m interval)	5mm	7mm	10mm	15mm

Table 3.2 (a) trigger values for tracks of the Victoria and Bakerloo Lines. [49][50]

Victoria Line Tunnel	Green	Amber	Red	Black
NB Vertical Displacement	+12mm	+15mm	+21mm	unexpected movement
SB Vertical Displacement	+10mm	+13mm	+18mm	

Table.3.2 (b) trigger values for the tunnel of Victoria lines [49]

Bakerloo Line Tunnel	Green	Amber	Red	Black
NB& SB Vertical Displacement	+12mm	+15mm	+21mm	unexpected movement

Table.3.2 (c) trigger values for the tunnel of the Bakerloo Lines [50]

4. Monitoring Methods and Data Analysis Methods

4.1 Monitoring Techniques for Data Collection

Between April 2012 and September 2012, different monitoring systems were installed within the Victoria and Bakerloo Line running tunnels. The C701 contract is responsible for the installation, commissioning and monitoring of Electro-level beams, BCS, Precise Levelling Points (PLPs), and Retro-reflective targets within both the North and Southbound running tunnels for the Victoria & Bakerloo Lines south of Oxford Circus Station. All control stations and datums were located outside the zone of influence. Control stations form adjusted baselines and the adjusted values of datums were considered to be fixed for any further monitoring works. The instrumentation and associated equipment and communication systems provided the real time monitoring of movements of the tunnels and tracks associated during the construction of the Crossrail running tunnels. All these monitoring systems were commissioning from 21st September 2012 [53]. The purpose of the monitoring systems was not only to check the consistency between the actual movements with the predicted movements during design process, but also could serve to investigate the relationships between manual and automated monitoring systems by comparing the settlement profiles produced from data collected by those different monitoring systems.

For the automated monitoring system which consisted of Electro-level beams and BCS systems, the data were read hourly continuously throughout the duration of the Crossrail tunnelling works, and relayed back to Crossrail's underground construction information management systems. They were installed, monitored and reported by Itmsoil. For the reliable and accurate monitoring systems to obtain measurements with high precision, some level of regular maintenance and inspection were undertaken. [54]

For the manual monitoring systems, Itmsoil carried out weekly monitoring for retro-reflective targets and fortnightly monitoring for PLPs during the initial baseline period. The relevant principle contractor would then continued the monitoring of them. For Victoria & Bakerloo Line tunnels, manual track monitoring was carried out by Itmsoil. Retro-reflective targets were installed and monitored for base line and reported for baseline by Itmsoil. Precise levelling points were installed and monitored for baseline and reported for baseline by Itmsoil as well. [55] A summary of the installation and the associated instrumentation accuracy is given below and in Table.4.1. [58]

- Electro-level beam arrays were installed above the knee level along the axis of the tunnel with sensor accuracy of ±0.1mm/m[56]. They were installed with the associated cabling and multiplexer units, on the Western walls of the SB tunnels and Eastern walls of the NB tunnels for both Victoria and Bakerloo Lines.
- Basset Convergence System were installed on the existing tunnel structure at the points where Crossrail tunnel crosses the existing tunnels, within sensor accuracy of ±0.05% full scale[57]. They are for the monitoring of the convergence and divergence of the tunnel.
- Retro-reflective targets were installed in arrays of three at approximately 10m centres which corresponded with every fifth array of PLPs, with 1 at the crown and 2 at the axis level.
- Precise levelling (track shoe monitoring) were installed on each rail and carried out at 2m centres, within the predicted settlement zones. They also served as a manual check for the automated system, i.e. the results obtained from the electro-level beams.

Monitoring Systems		Victoria Line NB	Victoria Line SB	Bakerloo Line NB	Bakerloo Line SB
Automated Monitoring Systems	**Electro-Level Beams**	53	54	64	58
	Bassett Conversion Systems	2	1	2	2
Manual Monitoring Systems	**Retro-reflective targets (each array contains 3 targets)**	13 arrays	12 arrays (4 in Cross-passage)	14 arrays	13 arrays
	Precise Levelling points (each array contains 2 PLP's)	62 arrays	57 arrays(5 in Cross-passage)	66 arrays	61 arrays

Table 4.1 Number of different monitoring systems installed in Victoria & Bakerloo Line Tunnels [58]

Fig.4.1(a)(b)(c)(d) show some photographs of the examples of the monitoring systems.[59]

Fig. 4.1 (a) Bakerloo NB Electro-level Beams (EL Beams 14-9) [59]

Fig. 4.1 (b) Victoria NB Electro-level Beams (EL Beams 15-8) [59]

Fig. 4.1 (c) Bakerloo NB Retro-reflective targets (Retro-Targets Array 6) [59]

Fig. 4.1 (d) Victoria NB Retro-reflective targets (Retro-Targets Array 4-7) [59]

Fig.4.1 (e) (f) [60] show examples of the relative positions of Precise levelling points and Retro-reflective targets in the cross section of Victoria and Bakerloo Line tracks and tunnels. Three points retro-reflective targets are shown by square times marks ⊠, they are installed on the tunnel walls, with retro-2 at the crown level and retro 1 and 3 at the axis level. PLPs are shown by black dots ● and are installed on the two tracks. [60]

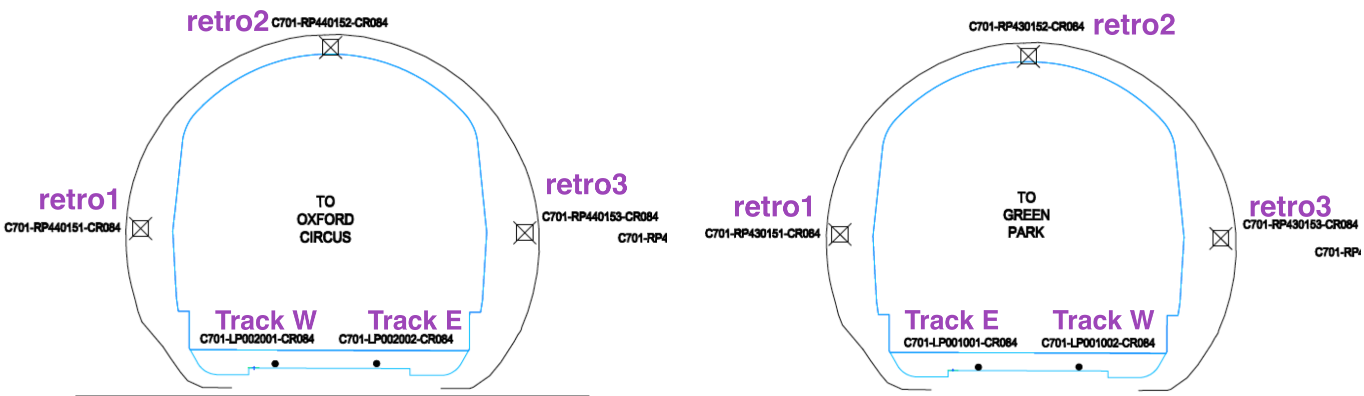


Fig. 4.1 (e) Victoria Line PLP array and Retro-Reflective Targets NB(left)array 401 and SB(right) array 301 [60]

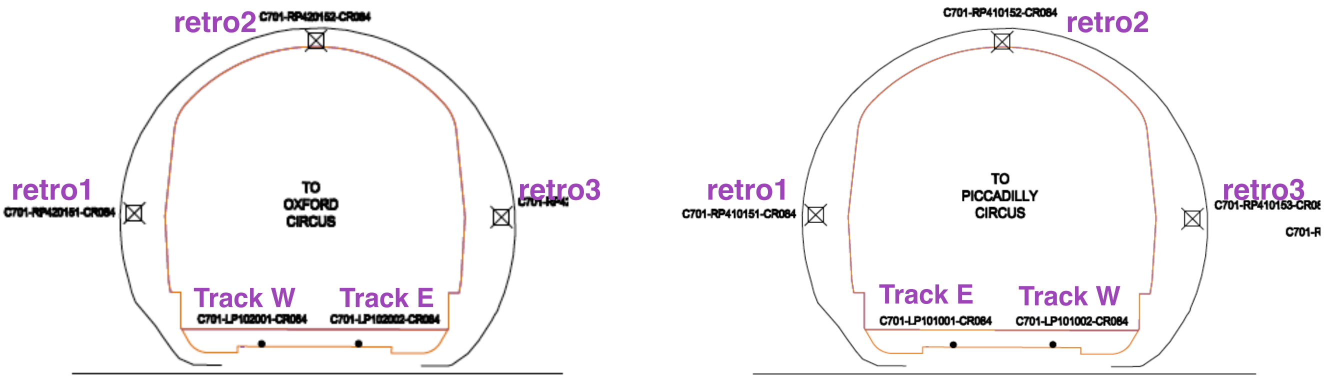
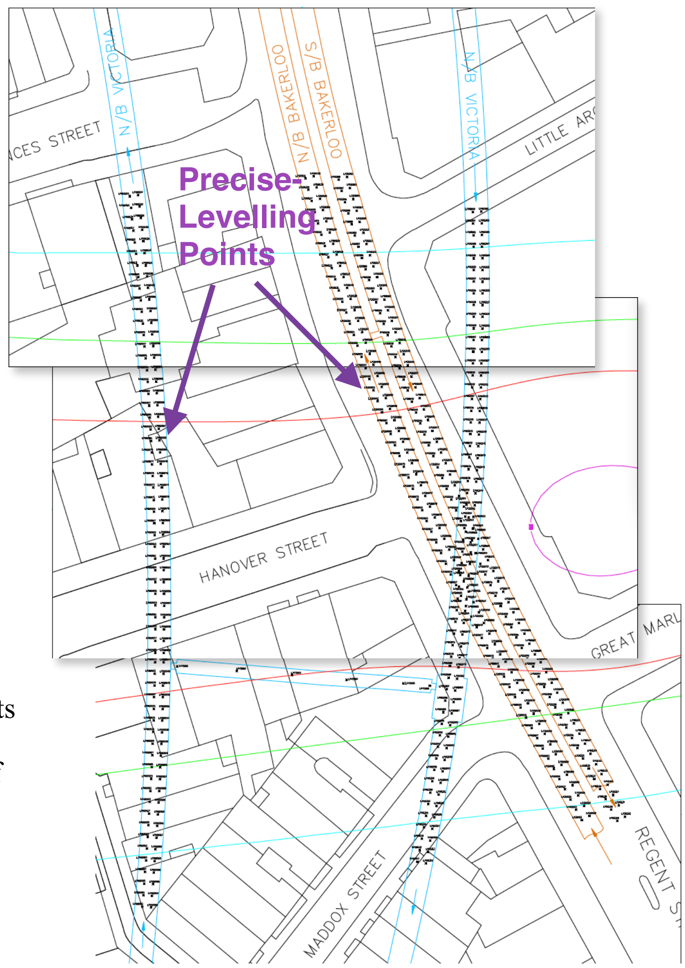


Fig. 4.1 (f) Bakerloo Line PLP array and Retro-Reflective Targets NB(left) array 201 and SB(right) array 101 [60]

Fig.4.1 (g) [61] on the right shows examples of drawing of the locations for Precise Levelling Points along the Victoria, Bakerloo lines and Cross passages for the region of manual monitoring. The three separate drawings have been combined together to produce a complete drawing. The installed Precise Levelling Points at 2m Transects are shown by square times marks ⊠.



Right: Fig. 4.1 (g) drawing of the locations for Precise Levelling Points along the Victoria&Bakerloo lines and Cross passages for the region of manual monitoring [61]

4.2 Data Interpretation Methods

The original raw data points are orientated by a plan of Easting E, Northing N and Height H coordinates and it is the change in height for each point that is interested in the study for the settlement profiles. All the original data points/chainage with original coordinates E,N, H for baseline, and then for different dates prior the construction, construction approaching, crossing and leaving the existing tunnel, all the movements are well captured within the dates of monitoring for the zone of influence. All the data are presented and interpreted in Microsoft Excel to produce different settlement profiles. OriginPro 8.5.1 is used to investigate the correlation of data obtained by Track and Electro-level beams. The data interpretation procedure for each instrumentation is given in the following sections.

4.2.1.Track-Shoe Monitoring Systems

❖Separate data for Track W and Track E with the difference in height from the baseline at different dates.

❖Convert the coordinates of E, N of each track to distance along the track using the first point of track W and track E as the reference point for track W and track E respectively. calculation equation: distance=(((E-E')^2+(N-N')^2))^0.5

❖where E and N are Easting and Northing coordinates of each track levelling point

❖E' and N'=Easting and Northing coordinates of the first track levelling point (For eg. it is LU08NBS0011 (79349.5008,35853.4624) and LU08NBTS0012 (79342.788, 35927.016) for Victoria Line NB track E&W respectively.)

❖Plot settlement profile for each track which is the curve of difference in height from the baseline value against the distance along the track for each dates, in order to get a complete progressive settlement profile for the construction work before and after CRL TB1, before and after CRL TB2. Different levels of trigger values of vertical displacement of the track are added to compare with real settlement levels. Fig.5.1 (a) (b) for the examples of the progressive settlement profile for Victoria NB track W and Track E respectively.

❖Final settlement profile for Track E and Track W are plotted on the same diagram to obtain the final track cant and twist for the final settlement. Fig. 5.1 (c) shows an example of the final settlement profile of Victoria NB track W and track E.

❖Final track cant: the difference in settlement of track W and track E for each chainage point is the track cant for 2. Graph is plotted of this difference against the average distance along the track for Track W and track E for all the chainage points, which is the 2m cant graph. Then the 2m track cant is divided by 2, to get the 2m track twist which is the rate of the cant. Then the 2m track twist is plotted against the average distance along the track between trackW and track E of all the chainage points. 10m track twist is obtained by dividing the 10m track cant (done by summing up the track cant for every 10m of distance along the track, i.e., five 2m track cant) by 10. Graph of 10m track twist can then be obtained by plotting the 10m twist along the track. 2m twist and 10m twist green triggers are added to compare with the real twist level. Fig.(d)(e) show examples of Victoria track cant and track twist graph for both 2m and 10m cases.

4.2.2. Retro-reflective Targets

- ❖Separate data for Retro1, Retro2 and Retro3 with the difference in height from the baseline at different dates
- ❖The reflective targets were installed 2 at shoulder level (retro 1 & 3) and 1 at the crown (retro 2), so they were possibly subjected to lining distortion, the recordings against settlement may not be the best for comparison since the crown may not move as much as the shoulder ones. In addition, as Retro1 and 3 were at the axis level on the tunnel which align with the 2 tracks, the data from Retro 1&3 are used to plot the final settlement profiles, in order to compare with the profile of the track W & E respectively.
- ❖The method of converting the coordinates of E,N to distance along the track is the same as that for the track levelling points. The reference point for the chainages of retro1 is the first point of track W, and that for retro 3 is the first point of track E.
- ❖Plot settlement profile for each retro which is the curve of difference in height from the baseline value against the distance along the tunnel for each dates, in order to get a complete progressive settlement profile for the construction work before and after CRL TB1, before and after CRL TB2.
- ❖Fig. 5.2 shows an example of final settlement profile for the Victoria Line NB retro1&3.

4.2.3. Electro-level Beams

- ❖Only one set of data for the difference in height compared to base line after TBM2 is used and plotted against the distance along the track. As Electro-level beams are installed on the Eastern wall of NB tunnel and Western wall of SB tunnel. The first point of Track E is taken to be the reference point of NB electro-level beams and the first point of track W is taken to be the reference point of SB electro-level beams.
- ❖The graph produced is the final settlement profile based on real-time data collected by automated electro-level beams. Fig.5.3 shows an example of final settlement profile produced by the Victoria NB electro-level beams along the tunnel.

4.2.4. Comparisons of Different Monitoring Systems

- ❖The final settlement profile produced by 3 different monitoring systems (track-shoe monitoring, retro-reflective targets and electro-level beams) are combined on the same diagram for comparison. Fig. 5.4 (a) shows an example of final settlement profile of the Victoria NB track-shoe W&E, retro1&3, and electro-level beams.
- ❖The settlement profile produced by retro-reflective targets are not representative as the number of data sets is relatively small, resulting in obvious straight lines between each

data point (the real settlement is expected to be a smooth curve follows Gaussian distribution).

- Therefore, comparison is focused on results from electro-level beam and Track E for NB tunnels and Electro-level beams & Track W for SB tunnels.

4.2.5. Correlation Assessment

In order to quantify the strength of relationship between the settlement profiles or datasets from electro-level beams and track-shoe monitoring systems, a correlation coefficient relating the two datasets may be required. The correlation coefficient is a numerical measure of the strength of the relationship between two random variables. It is a number between -1 to +1. A positive value means there is a positive linear relationship between the 2 random variables and they are said to be positive correlated. The closer this value to 1, the stronger the linear relationship between them. There are different kinds of correlation coefficient. Pearson's Product Moment Correlation Coefficient is the most commonly used correlation coefficient, which is denoted by r.[62]

The software used to quantitatively analyse the strength of relationship between the settlement profiles produced from results of electro-level beams and tracks is OriginPro8.5.1, which allows the direct presentation of the correlation coefficient of two datasets[63].

The principles and steps of how Origin works are as follows:

- Input the 2 datasets from track results and electro-level beam results, each with different X values (distance along the track) and Y values (settlement). Scatter plots are produced for each pair of variables for input data range. It is assumed that the 2 plots are smooth and continuos curves.
- Origin then performs linear interpolation by finding the corresponding Y values for one dataset based on the X values of the other dataset.
- Finally, Origin produces the correlation coefficient r of the 2 sets of Y values. If r value is larger than 0.9, it generally shows a strong linear correlation between the 2 datasets.

The example used here is to compare the correlation between the final settlement profiles produced by results of electro-level beams and track E for the Bakerloo Line NB.

Fig.4.2.5 (a) shows the inputs and outputs in OriginPro 8.5.1:

- The datasets for the final settlement profile for track E are A(X1) which is the distance along the track E and B(Y1) which is the corresponding settlement at each track-levelling point.

- ❖ The datasets for the final settlement profile for Electro-level beams are C(X2) which is the distance along the track E and D(Y2) which is the corresponding settlement at each electro-level beam point.
- ❖ Fig. 4.2.5 (b) on the right shows the scatter plot produced by these 2 datasets.
- ❖ E(Y2) is the output produced by Origin by using linear interpolation. It means, for each X value of the track plot, A(X1), there is a corresponding Y value on the Electro-level beams plot, which is shown by E(Y2) dataset. In the other words, now the 2 plots are sharing the same X values, A(X1), but each has a set of Y values, B(Y1) for the track plot and E(Y2) for the electro-level beam plot.
- ❖ Origin then compares the 2 datasets B(Y1) and E(Y2) to produce the correlation coefficient between them. In this case, the correlation coefficient r for Track E and Electro-level Beams is 0.96261449, which is sufficient to prove there is a strong positive linear relationship between the 2 settlement profile for Track E and Electro-level beams for Bakerloo Line NB.

The r value between Track E and Electro-level beams for Victoria NB is 0.97339481, and that between Track W and Electro-level beams for Victoria SB is 0.930. Therefore, the correlation between the settlement profiles produced by track and electro-level beams is strong and positive. However, when dealing with the datasets for Victoria NB, 2 abnormal data points are removed in order to get the results. The 2 abnormal data points are (82.46272398,-0.6964) for electro-level beam plot and (65.93107286, -1) for track E plot. The reasons for the abnormal data points are discussed in Section 5.1 and 5.3.

Book1

	A(X1)	B(Y1)	C(X2)	D(Y2)	E(Y2)
Long Name					Interpolate
Units					
Comments					Linear interp of B
1	0	0.4	2.43108	-0.0047	0.03259
2	1.97036	0.1	4.44193	-0.0773	-0.15721
3	4.0207	-0.2	6.46061	0.0309	-0.07032
4	5.98954	0	8.4768	-0.0966	-0.18019
5	7.99912	-0.3	10.48908	0.0467	0.05367
6	9.99256	0.2	12.50852	0.1764	-0.10832
7	12.02845	-0.4	14.52211	0.0521	0.45963
8	14.00353	0.8	16.53762	-0.1408	-0.55532
9	15.98418	-0.5	18.55393	-0.222	-0.44174
10	17.98524	-0.7	20.57849	-0.2582	-0.04928
11	19.96701	0.2	22.59619	-0.2521	-0.40269
12	21.92943	-0.6	24.61382	-0.1473	-0.03375
13	23.95702	0	26.63342	-0.1364	-0.20805
14	25.90337	-0.1	28.65755	-0.4724	-0.4
15	27.93032	-0.4	30.67724	-0.2602	-0.56101
16	29.84763	-0.4	32.69714	-0.2489	-0.91989
17	31.90862	-0.8	35.23445	-0.7284	-1.37091
18	33.88167	-1.1	37.25129	-1.0456	-1.63784
19	35.87906	-1.5	39.2694	-1.1941	-1.84054
20	37.87014	-1.7	41.28308	-1.5728	-2.40042
21	39.86143	-1.9	43.29513	-2.3852	-3.24166
22	41.85005	-2.6	45.31517	-3.4748	-4.2179
23	43.87693	-3.5	47.33592	-4.8517	-5.08612
24	45.88032	-4.5	49.35937	-5.849	-6.04886
25	47.86709	-5.3	51.38186	-6.4294	-7.31841

Sheet1

Fig.4.2.5 (a) Inputs and Outputs of two datasets in OriginPro 8.5.1 Using Linear Interpolation

Output of Origin by Linear Interpretation of B(Y1)

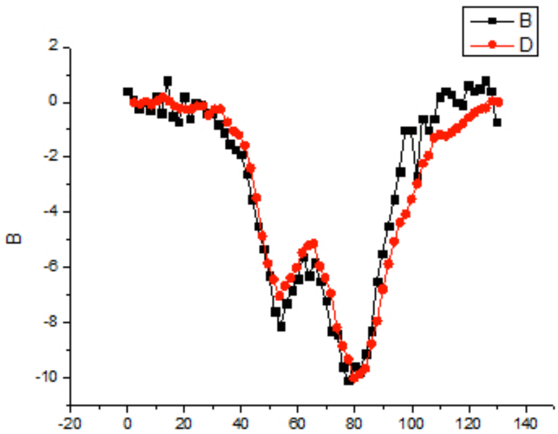


Fig.4.2.5 (b) Scatter diagram of 2 datasets

5. Results and Discussion

Following the westbound and eastbound Crossrail construction, results from precise levelling points (track-shoe monitoring), retro-reflective targets, and electro-level beams were collected by Crossrail and plotted the settlement profiles along the NB and SB track/ tunnel of Victoria and Bakerloo Lines accordingly. Results from retro-reflective targets and track shoe monitoring were used to plot the progressive settlement profiles and the maximum settlement profiles together with the results from the electro-level beams for further comparisons and analysis for the entire Crossrail tunnelling work. To illustrate the settlement profile derived from individual monitoring system, **Victoria Line Northbound (NB)** is used to be the example below for the results and discussions. The combined final settlement profile of different monitoring systems is the most important results for the project, hence it is produced for each of the existing tunnels. In the graphs, Crossrail WB was constructed first by TBM1 which cause the settlement troughs on the right side of the graphs. Crossrail EB then was constructed by TBM2 which caused the settlement troughs on the left side of the graph. It is assumed that the positions of CRL WB&EB are beneath the location of the settlement troughs. All the legend on the right hand side indicate which monitoring system and the date in which data points were taken from, as well as the different levels of trigger values set by Crossrail in this project. The vertical axis is settlement in z direction, with 0 being the base-line level. Positive movement points on the graph indicate heave and negative movement points indicate settlement. The horizontal axis is the absolute distance along the track/tunnel of the existing lines. Each graph has its own title indicating the types of monitoring systems producing these settlement profiles.

5.1 Track, track cant and twist

Settlement Fig. 5.1 (a) and Fig. 5.1 (b) below show progressive settlement profiles derived from track-shoe monitoring points along the western and eastern tracks of Victoria Line NB tunnel for a range of dates from 28/03/2013 to 18/07/2013, during which TBM1 and TBM2 construct the Crossrail WB and EB respectively to illustrate the response.

Fig. 5.1 (c) below shows the final settlement profiles of the Western and Eastern tracks derived from results of track monitoring systems on 18/07/2013

- Maximum settlement for Eastern track is 14.5 mm at 77.9 m along the eastern track, and that for Western track is 12.8 mm at 77.7m along the western track. They both happen at the location of TBM1 construction for CRL WB. Although the maximum settlement exceeded the green trigger for the vertical track displacement, they did not exceed the amber trigger, which shows good control of volume loss.

- The maximum settlement after the second tunnelling work (TBM2 for CRL EB) is less than that after the first tunnelling work (TBM1 for CRL WB). The reason for that is discussed in Section.5.4.
- There is an abnormal data set in purple) on 11/05/2013 for both tracks. This may due to the loss of reference for track-shoe levelling on that day.
- There is an abnormal data point which is (65.93107286, -1) in the final settlement. It may due to error of the precise levelling point.
- Slight heaves at 2 ends which is not expected. The reason of heaving is normally due to that tunnelling machine may exerts too much face pressure, or there may be high compensation grouting pressure on the ground. The excessive pressure may cause slight heave of the ground. In this case, although there are heaves shown at both ends in the settlement profile derived from the track-shoe monitoring system, there is no evidence of heaving in the real-time final settlement profile derived from electro-level beams. Therefore, the heaves may most probably due to the limitation of the precise-levelling points, but not due to the the excessive pressure issues.

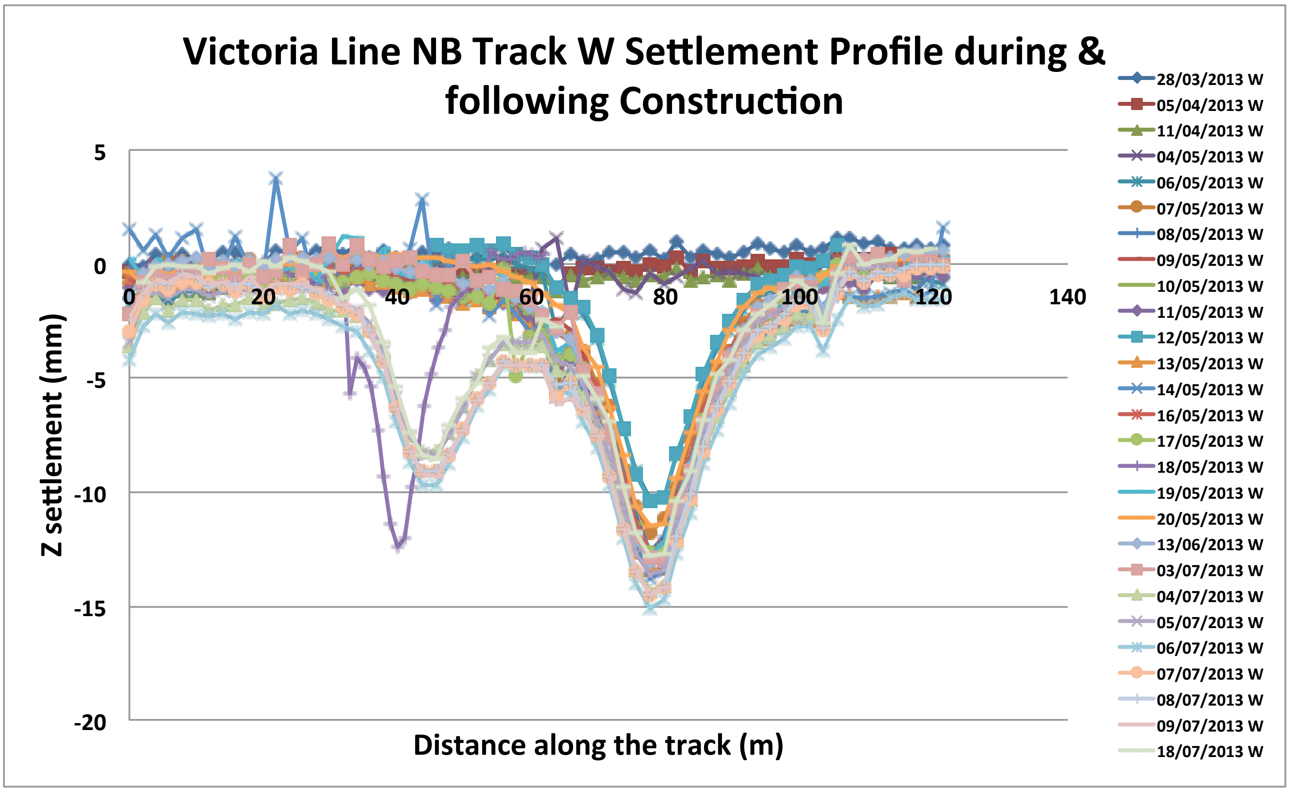


Fig. 5.1 (a) Progressive Settlement Profile of Victoria Line Northbound Western Track derived from track-shoe monitoring systems following and after the construction of the Crossrail Westbound and Eastbound from 28/03/2013 to 18/07/2013

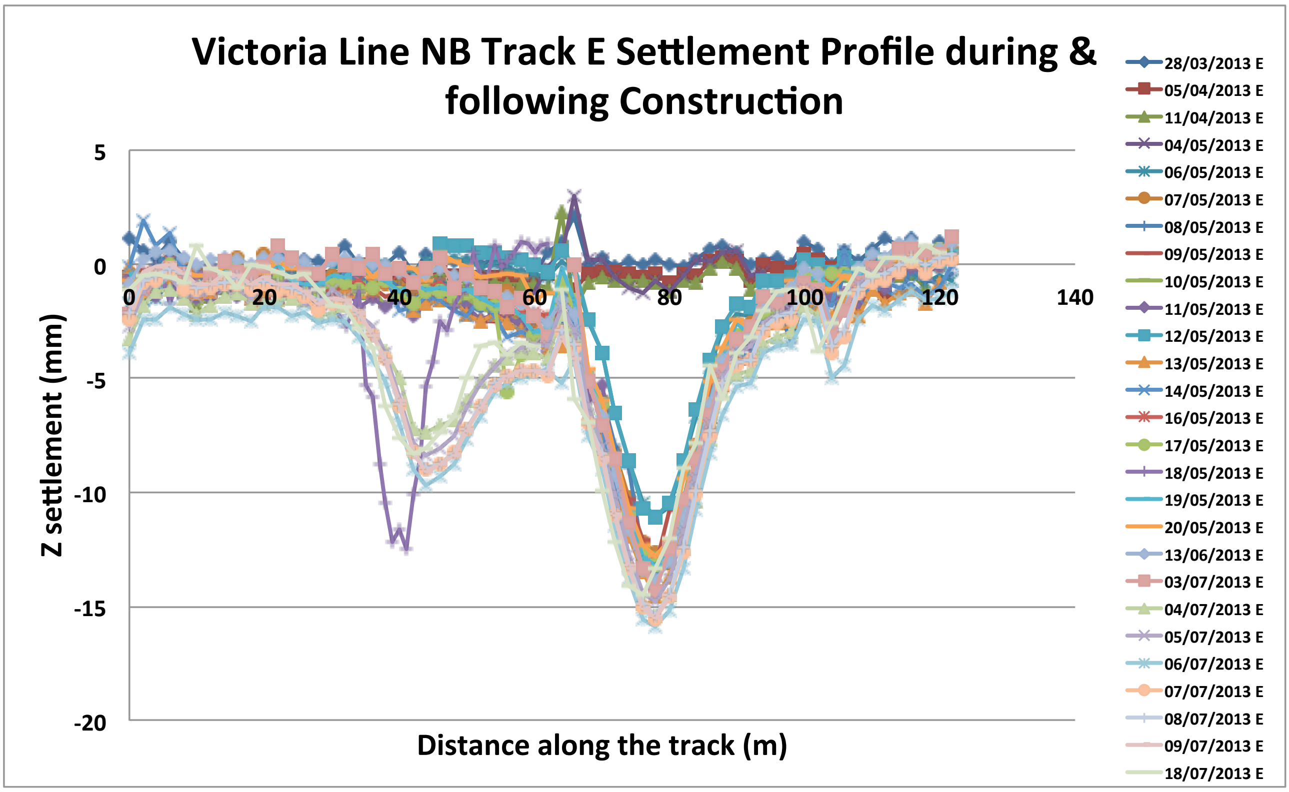


Fig. 5. 1 (b) Progressive Settlement Profile of Victoria Line Northbound Eastern Track derived from track shoe monitoring system following and after the construction of the Crossrail Westbound and Eastbound from 28/03/2013 to 18/07/2013

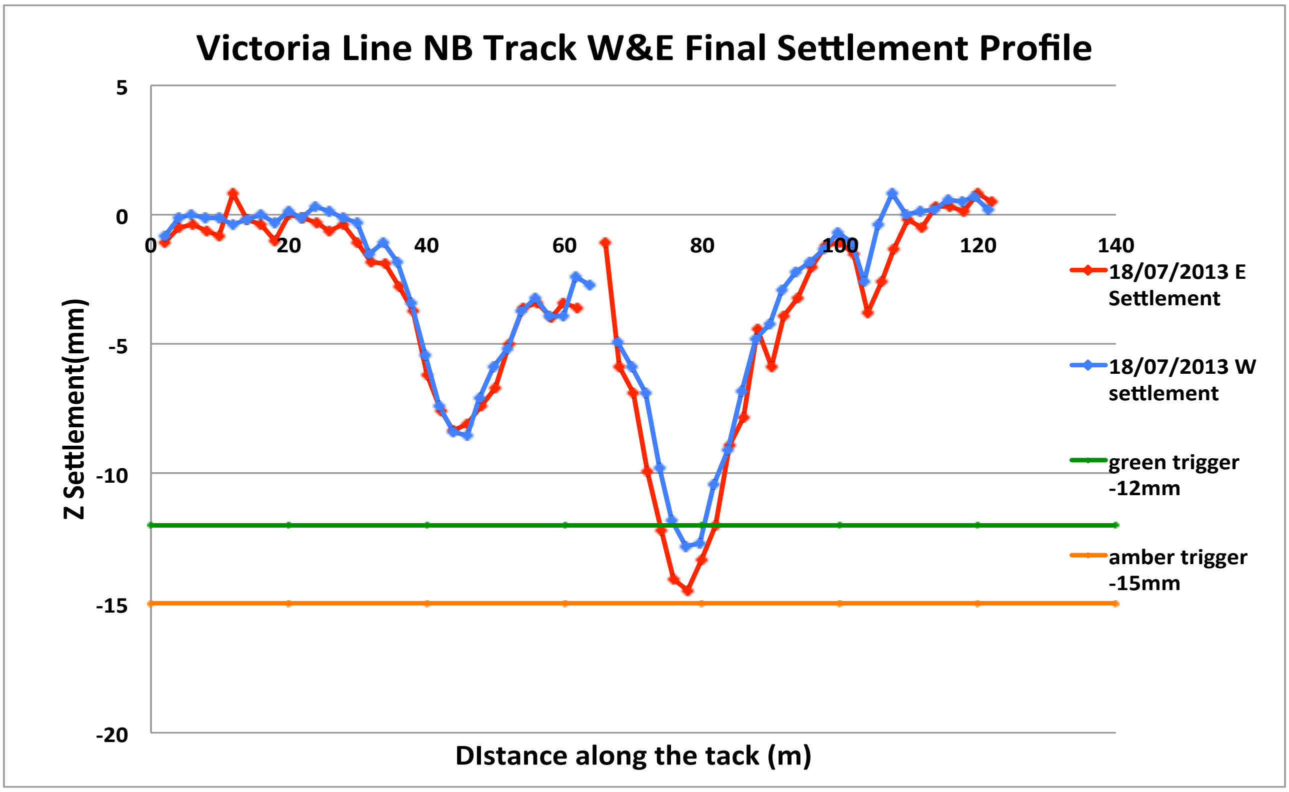


Fig. 5.1 (c) Final Settlement Profiles of Victoria Line Northbound Western&Eastern Track after the Crossrail TBM2 tunnelling work on 18/07/2013, with green (-12mm) and amber (-15mm) trigger levels

Track cant Fig. 5.1 (d) shows 2m and 10m track cant graph for Victoria NB along the middle of 2 tracks with 10m cant is larger than 2m cant as expected. The positive vales show clockwise cant and twist while the negative values show anti-clockwise cant and twist as indicated on the graphs.

The maximum 2m cant is -6 mm at 65.8 m position along the track

The maximum 10m cant is -17 mm at 75.8 m position along the track

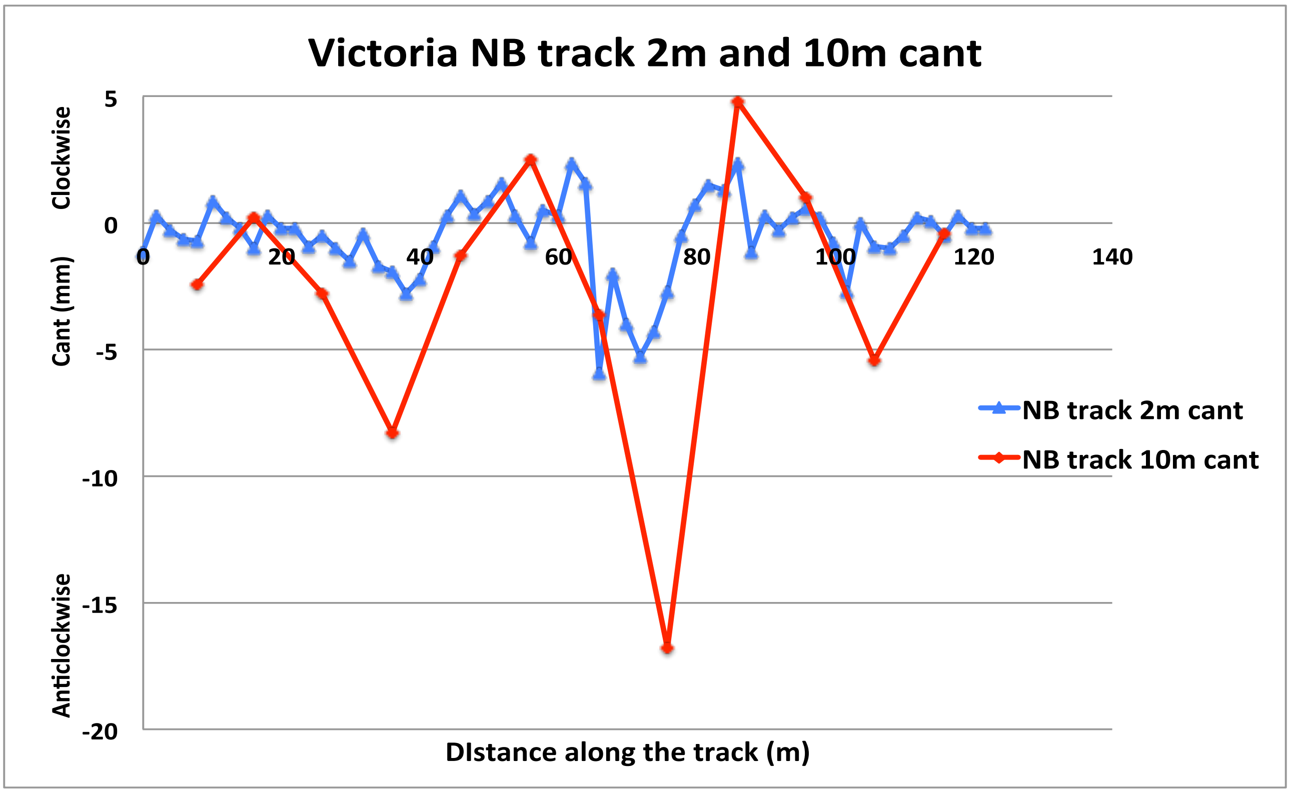


Fig. 5.1 (d) Victoria Line Northbound 2m&10m Final Track Cant after the Crossrail TBM2 tunnelling work on 18/07/2013

Fig. 5.1 (e) shows 2m and 10m track twist graph for Victoria NB along the middle of the 2 tracks merge to the bottom.

with 10m twist graph smoother (less fluctuated) and lower than the 2m twist graph as expected.

- ❖ The maximum 2m twist is -2.95 mm/m at 65.8 m position, the maximum10m twist is -1.68 mm/m at 75.8 m position along the track.
- ❖ All the track twist value is well below the green trigger value for 2m track twist which is already lower than the one for 10m track twist. That means the degree of track twist is actually very small. Therefore, manual track-shoe monitoring may not be needed to monitor the track twist. If the tunnel rotation response could be investigated and understand, then the track levelling monitoring may not be necessary for future project.
- ❖ The initial plan for this study was to find a relationship between the degree of maximum track cant and the clearance between the existing tunnel and the new CRL tunnel in term of the diameter of the existing tunnels. In this way, if the clearance between a new tunnel

and the existing tunnel is known, then the maximum track cant of the existing line could be derived and hence the track-shoe monitoring for the track cant/twist may not be needed. However, the maximum cant normally does not happen at the the location where under-crossing of the 2 tunnels happens. In addition, the data points available for Victoria & Bakerloo Lines are too few and scattered to illustrate any pattern in order to extrapolate or interpolate any threshold value. Therefore, this method of data interpolation was not used in this study, but might be useful for future project where there are enough data points.

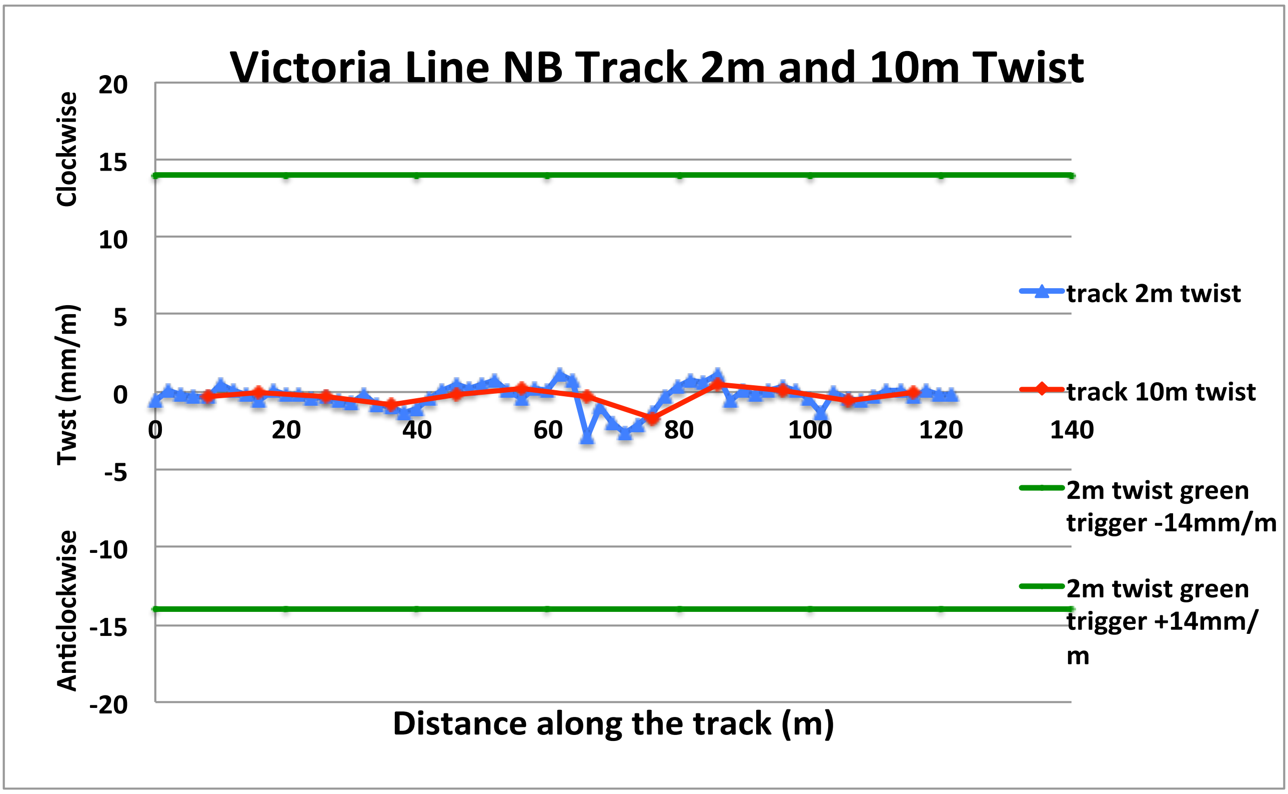
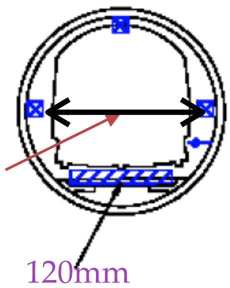


Fig. 5.1(e) Victoria Line Northbound 2m&10m Final Track Twist after Crossrail TBM2 tunnelling work on 18/07/2013, with green trigger levels for both clockwise&anti-clockwise direction (+14mm/m&-14mm/m)

5.2 Retro-Reflective Targets

Fig.5.2 shows the final settlement profile derived from the results of chainages of Retro-reflective targets 1&3 along the Victoria Line NB track/tunnel.



- ❖The max settlement indicated by retro1 is 11.2 mm at 79.8 m position, the max settlement indicated by retro3 is 11.6 mm at 79.8 m position along the tunnel.
- ❖For Retro twist: initially, it was planned to calculate for retro cant and twist and to produce the retro cant and twist graph for 2m and 10m as well. This graph could be scaled by using the ratio of horizontal distance (x mm) between each pair of retro-

reflective targets (retro 1&3) and that between each pair of track levelling points for track W&E(120mm). x could be calculated from the coordinates of each pairs of retro-reflective targets. As the results from retro-reflective targets represent the tunnel response and the results from track-shoe levelling points represent the track response. In this way, comparison could be made between the cant and twist for track and the tunnel. However, the number of data points for retro is far less than that for track-levelling points and the distances between 2 consecutive points are inconsistent/ varying without any pattern. Therefore, it is difficult to get the 2m or 10m cant and twist graph for retro. This method is not used in this case.

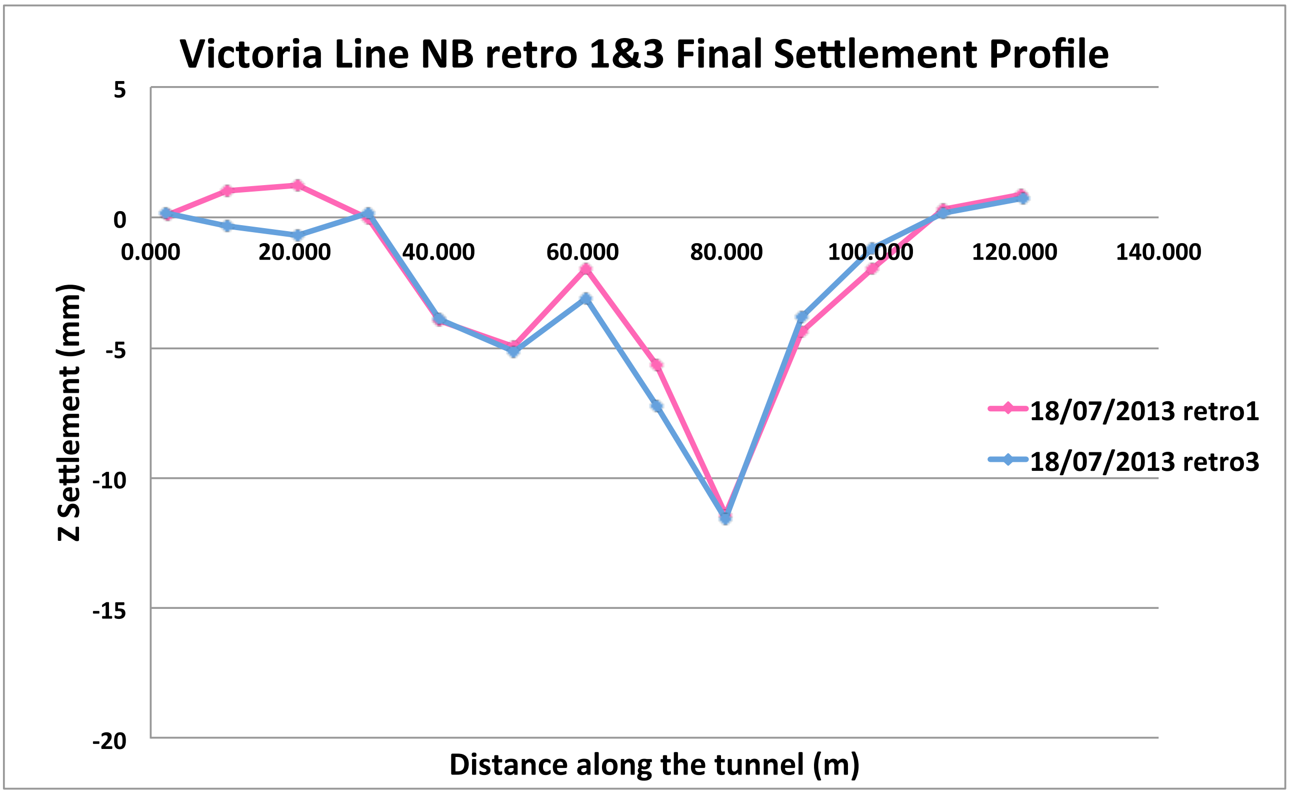


Fig.5.2 Final Settlement Profile of Victoria Line Northbound Tunnel derived from Retro-reflective Targets 1&3 after the Crossrail TBM2 tunnelling work on 18/07/2013

5.3 Electro-level Beam

Fig. 5.3 below shows the final settlement profile derived from the electro-level beam installed on the Eastern wall of the Victoria NB tunnel after TBM2 has passed the zone of influence of the tunnel.

❖ The maximum settlement is -14.78 mm at 74.3 m position along the track which assumed to happen at the location above the CRL WB.

❖There is one abnormal data point which is the point (82.46272398, -0.6964) , it may due to the error of that electro-level beam in terms of wrong reference point or orientation problems.

❖There is no heave shown by results from the electro-level beams which is expected.

❖As the accuracy of electro-level beams is ±0.1mm/m, If there is accumulation of errors, their measurements which start from zero will not return to zero. From the graph, it shows that he settlement results started from zero and ended at zero, therefore the electro-level beam measurements completed the cycle and were self-verifying.

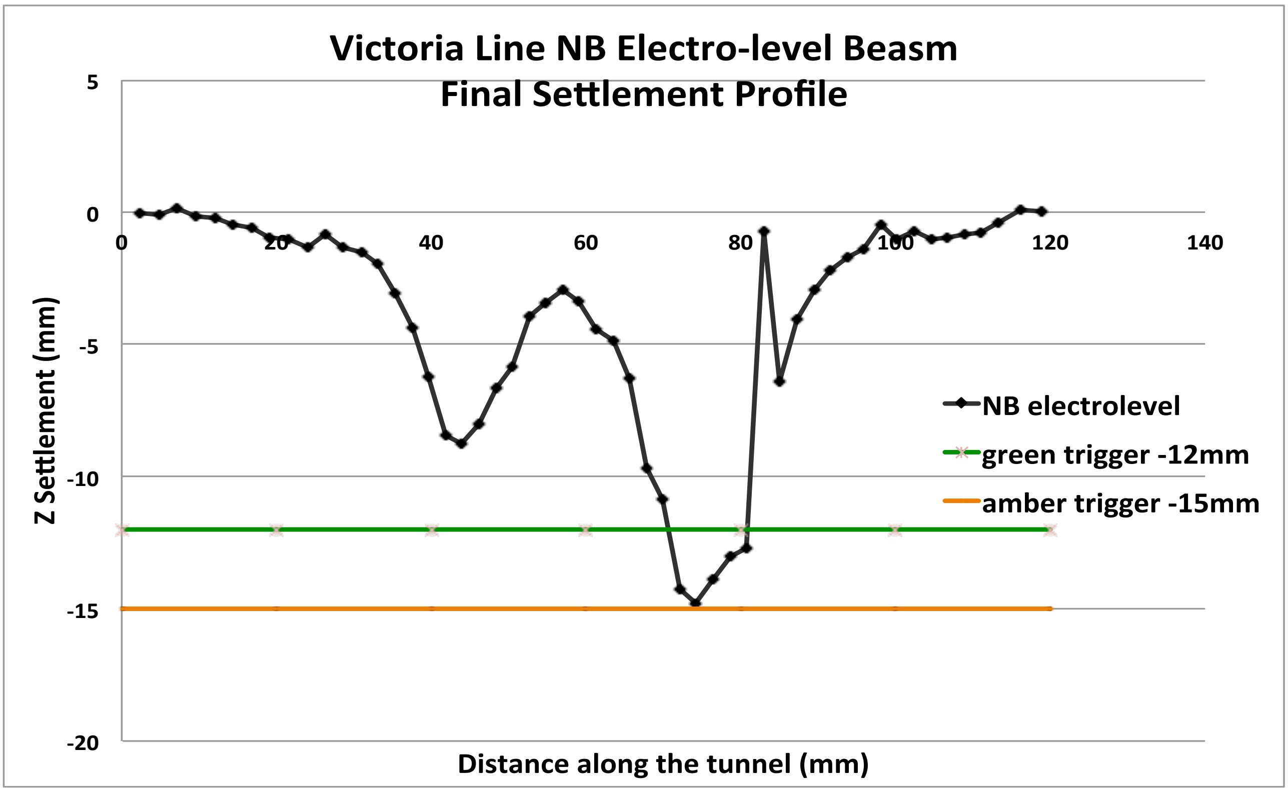


Fig. 5.3 Final Settlement Profile of Victoria Line Northbound Tunnel derived from Electro-level Beams installed on the Eastern wall of the tunnel after Crossrail TBM2 tunnelling work

5.4 Combined Settlement Profiles

Fig.5.4 (a) shows the combined final settlement profiles for the three monitoring systems, track-shoe/precise levelling points, retro-reflective targets and electro-level beams for Victoria Line NB.

❖Despite the 2 abnormal data points, one for track-shoe monitoring system and the other one for electro-level beams, the settlement profiles from different monitoring systems show good alignment. However they are not exactly the same because they are not installed at the same position inside the structure. Moreover, the accuracies of different monitoring systems are different and this may cause likelihood for error and misalignment caused by resolution.

- ❖The settlement profile produced by retro-reflective targets are not very representative as discussed in Section 4.2.4. Comparison is focused on results from electro-level beam and Track E for Victoria Line NB. By inspection they show high degree of alignment as they are similar in shape and values. The maximum settlements both happen at the location above CRL WB. The percentage difference in maximum settlement of only 1.924 %, and the percentage difference in the distance along the track for the maximum settlement is 4.62%, which are both small. The slight difference may due to the fact that the electro-level beams and the precise levelling points were installed at different positions at the structure. For example, the electro-level beams were installed along the axis of the tunnel, while the track measurements were taken at track level. However, it provides a good opportunity to investigate the rotation of the tunnel as described in Section 2.2.3.
- ❖All the graphs show that the maximum settlement after the second tunnelling work (TBM2 for CRL EB) is less than that after the first tunnelling work (TBM1 for CRL WB). According to the literature review on the prediction of settlement profiles for multiple tunnels in Section 2.1.3, if the two tunnels are very close to each other (closer than about 1 tunnel diameter), when the second tunnel is constructed, the ground in this region will already have been subjected to some level of shear stress due to the construction of the first tunnel. Therefore, there would be a higher volume loss resulting from a lower stiffness for the second tunnel and hence the maximum settlement for the second tunnelling work should be larger as seen in many historical cases. However, as in this project, the spacing between CRL WB and EB is larger than 4 tunnel diameters. Therefore this is not shown in our cases. The reason for the maximum settlement after the second tunnelling work being smaller may because there was possibly an improvement in tunnelling method to reduce the volume loss in the ground.

Fig. 5.4 (b) and Fig.5.4 (c) show diagrams of the combined final settlement profiles for Victoria Line SB and Bakerloo Line NB respectively, together with the green trigger value. They both show good alignment between the profiles derived from electro-level-beams and track-shoe monitoring systems. For Bakerloo Line SB, the data points from retro-reflective targets are not complete along the distance of the track/tunnel, therefore the results are not present. For all the diagrams of combined settlement profiles, the black curves are the settlement profiles produced by electro-level beams and the red curves are the tracks that are being compared with. For Victoria Line SB and Victoria Line NB, the maximum settlements do not exceed the green trigger value, showing that the volume loss for construction is very well controlled.

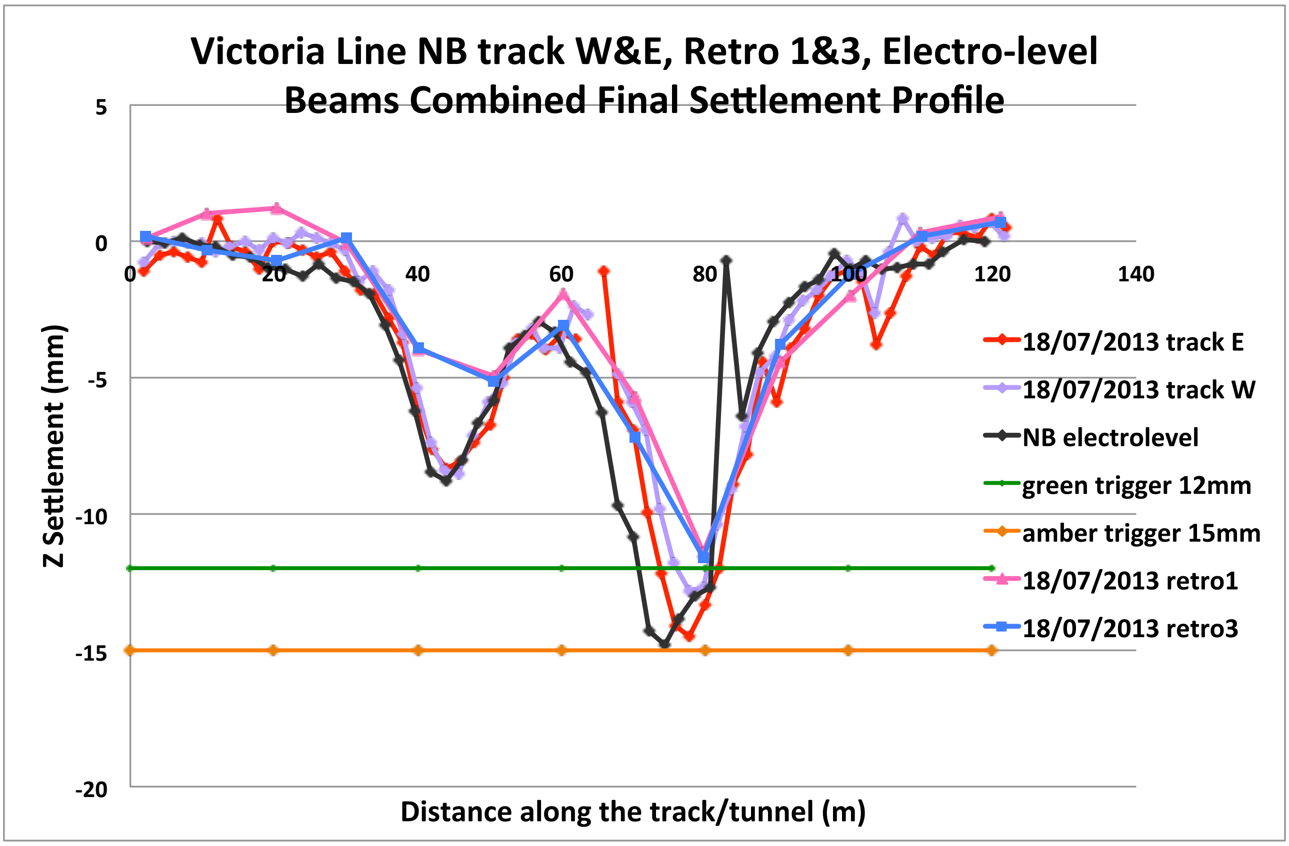


Fig. 5.4 (a) Combined Final Settlement Profiles of Victoria Line Northbound derived from Track-shoe Monitoring Systems, Retro-reflective Targets and Electro-level Beams after Crossrail TBM2 tunnelling work, with Green (-12mm) & Amber (-15mm) Trigger Levels

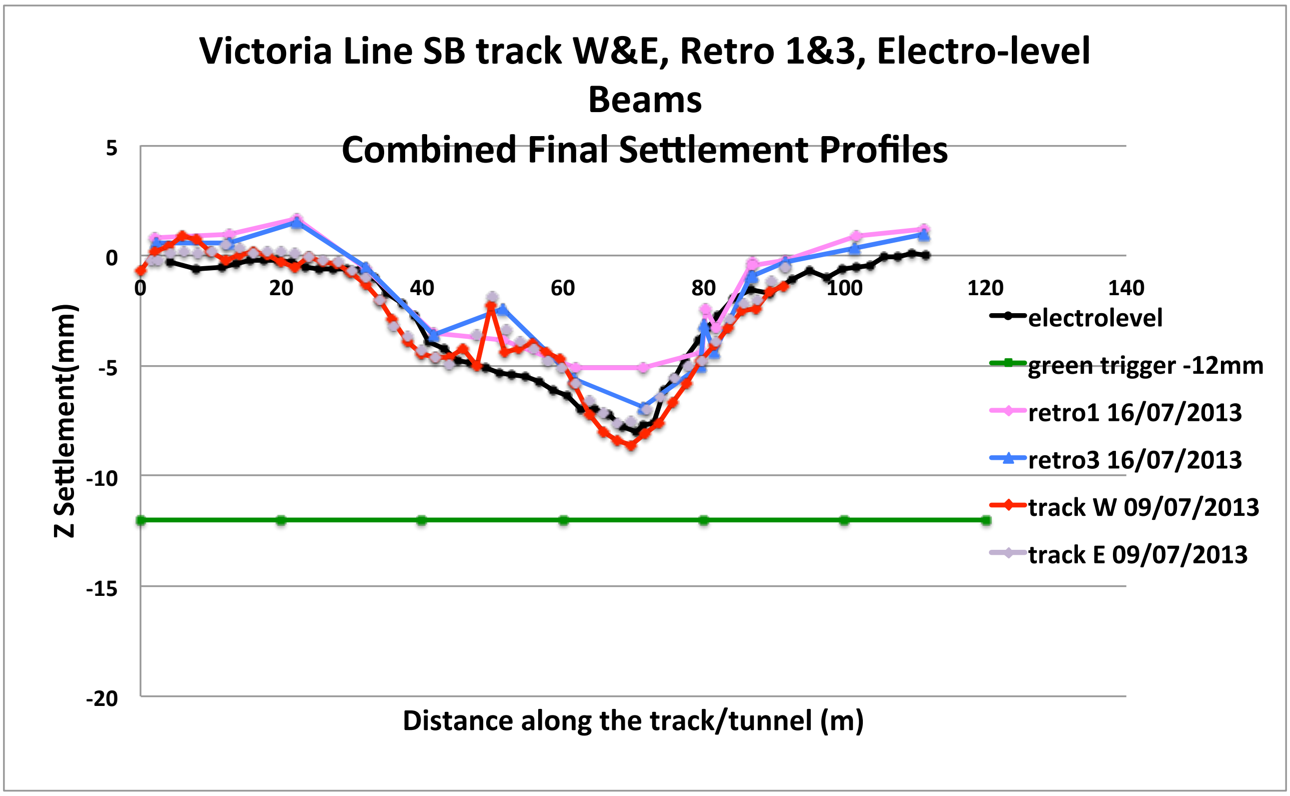


Fig. 5.4 (b) Combined Final Settlement Profiles of Victoria Line Southbound derived from Track-shoe Monitoring Systems, Retro-reflective Targets and Electro-level Beams after Crossrail TBM2 tunnelling work, with Green (-12mm) Trigger Levels

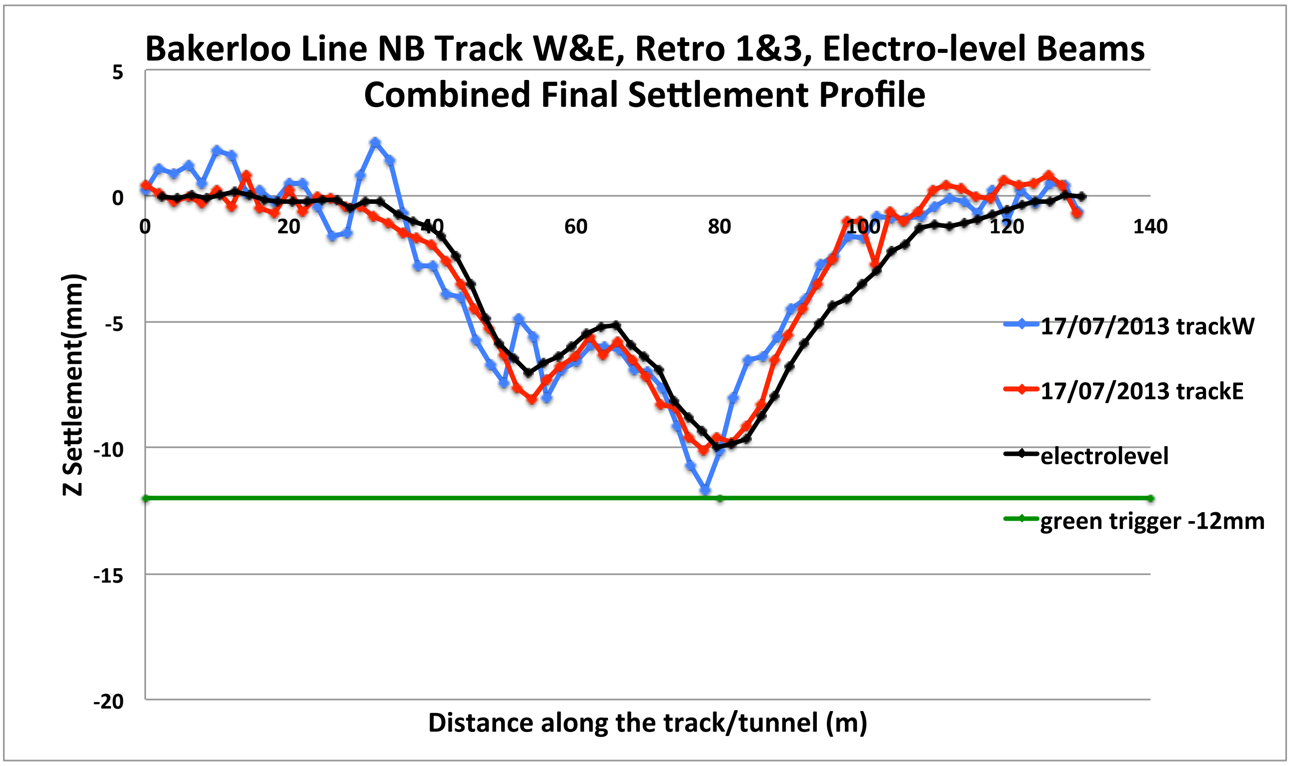


Fig. 5.4 (c) Combined Final Settlement Profiles of Bakerloo Line Northbound derived from Track-shoe Monitoring Systems, Retro-reflective Targets and Electro-level Beams after Crossrail TBM2 tunnelling work, with Green (-12mm) Trigger Levels

Table. 5.4 shows the summary of the maximum settlement for each existing line as recorded by electro-level beams. [64][65][66]

	Victoria NB	Victoria SB	Bakerloo NB
Maximum settlement (mm)	14.7844	7.9987	10.0073

Table.5.4 Maximum settlement for each existing tunnel considered in this project [64][65][66]

5.5 Correlation Assessment

The method of using OriginPro 8.5.1 was adopted to quantify the relationship between the settlement profiles produced by electro-level beams and track-shoe levelling points by using the correlation coefficient is discussed in Section.4.2.5. Table. 5.5 summarises the final results of the correlation coefficient r produced for each of the existing lines.

	Victoria NB Electro-level Beams & Eastern Track	Victoria SB Electro-level Beams & Western Track	Bakerloo NB Electro-level Beams & Eastern Track
Correlation Coefficient r	0.97339481	0.930	0.96261449

Table. 5.5 Correlation coefficient between settlement profiles of EL beams and Tracks

The correlation coefficients r produced between the 2 datasets for track and electro-level beams for all existing track/tunnel of Victoria&Bakerloo lines are larger than 0.9 and close to +1. Therefore it is sufficient to prove that there is a strong and positive linear relationship between the 2 settlement profile for Track-shoe monitoring system and Electro-level beams for each of the case considered. The correlation between the track response and cast-iron/structural movement is strong and positive.

5.6 Others—Possible Shadowing Effect

There may be possible shadowing effect between Bakerloo SB&NB on Victoria SB as they are close to each other in the zone of influence where CRL TBM1 & TBM2 constructed beneath them. Fig. 5.6 (a) (b) in Appendix illustrate the possible shadowing effect. The graphs are produced using Plaxis, imposing 2% V_L on the new tunnel. The lowest tunnel in the middle is the new CRL tunnel, the middle one is the Bakerloo Line tunnel and the highest one is the Victoria SB tunnel. The 2 diagrams show that the vectors of ground movement towards the new construction is limited by the structural stiffness of the existing tunnels. The limitation of this method is that they are only 2D diagrams so that they could not show the real vectors of ground movements very well.

Nevertheless, there is no evidence of shadowing effect presents in the cases we considered in this project.

6.Conclusion

Due to the effect of the construction of the new Crossrail project Westbound and Eastbound, there is an induced ground movements and movements of the existing tunnels and tracks of the Victoria Line from Oxford Circus to Green Park and Bakerloo Lines from Oxford Circus to Regent Street. The modes of the effect on the existing lines include longitudinal, transverse deformations, and rotation. The data from these monitoring systems are collected and interpreted, in order to produce progressive settlement profiles following different dates of the Crossrail construction. The final settlement profiles after TBM2 left the zone of influence of the existing tunnels for Track-shoe monitoring systems, Retro-reflective Targets and Electro-level beams are plotted along the tunnels/tracks. The main findings in this project are as following:

- ❖The 2D settlement profiles for Victoria & Bakerloo Lines follow well with the empirical Gaussian distribution where the percentage difference in maximum settlement between the actual settlement profiles and the predicted ones are only up to about 0.9%.
- ❖The final degree of rotation for existing tunnels are all smaller than 0.5 degrees which lie in the correct region where the new tunnelling works were leaving the zone of influence of the existing tunnels.

❖Victoria Northbound has the most distinct settlement troughs which follow the most closely with the predicted Gaussian distribution because the spacing between the Crossrail tunnel axes beneath it is the largest and the depth of the Crossrail tunnels is the smallest. In contrast, Victoria Southbound has the most merged settlement troughs because the spacing between the Crossrail tunnel axes beneath is is the smallest and the depth of the Crossrail tunnel is the largest.

❖The maximum settlements for different tunnels (up to about 14.8 mm for Victoria NB) are within the safe levels of trigger values set by Crossrail, showing the careful control of volume loss, which is as small as about 0.3%, compared to 0.7% which is the value used in the design and prediction for the settlement profiles.

❖Results from retro-reflective targets are not very representative due to the very few number of data points.

❖The correlation coefficient between the results from Electro-level beams and track-shoe monitoring systems are all larger than 0.9 for all the cases considered, which shows that there is a strong and positive correlations between them. Therefore there is a strong and positive correlation between track response and cast-iron/structural movement.

The reasons for supporting a reduction in track monitoring and some potential guidance derived from the project for specifying track monitoring through use of tunnel monitoring:

❖Firstly, from the key findings, the settlement profiles derived from the Electro-level beams and Track-shoe monitoring systems are similar with a strong and positive correlation between them. The correlation between the track response and cast-iron/structural movement is strong and positive. Therefore, the track is responding to the new tunnelling work underneath in a similar manner as the tunnel do to a very large extent.

❖Secondly, the track-shoe monitoring system incur safety risks as operatives must access the site to perform measurement. More importantly, it takes a long period of time to take a single set of results. Automated monitoring systems such as electro-level beams can be programmed to take readings at almost any desired frequencies.

❖The retro-reflective target monitoring for this project has not yielded the best data and the results are not representative. This is most likely due to the issues of setting-up of their installations and operations, rather than shortcomings of the technique. Within very confined spaces such as LUL running tunnels, there may not be sufficient space to have a fixed automatic total station (ATS). Hence the mobile ATS's may have been used here. They could have been set-up for each reading and incur larger data noise than expected level due to multiple setup calibrations.

- Electro-level beams results of settlements are more real-time datas (up-to-date, because they are taken in 1 hour-interval). Therefore structural/tunnel monitoring may be more reliable and accurate as differential movement has a fixed and common baseline and the data is more reliably interpreted with less human errors and errors due to loss of reference.
- Track monitoring for track cant and twist could be replaced by using tunnel monitoring by understanding the tunnel rotation in respective to tracks.
- Possible recommendations going forward would be:
  - To install the electro-level beams on each side of the tunnel so that the rotation of the tunnel may be explicitly derived. A holistic approach may be adopted to replace fully the capabilities of track shoe monitoring.
  - Alternatively, the frequency of retro-reflective targets may be increased and the distance between the consecutive retro-reflective targets may become consistent throughout the tunnel (for Eg. every 5m). This approach is important if large radial movement is expected, as convergence can be determined via the 3-points retro-reflective targets.
  - To identify locations where fixed ATS's may be installed to increase the system accuracy (particularly for longitudinal movement)

In conclusion, by considering all of the above, it will be prudent to continue track shoe monitoring, but on a less frequent basis throughout the period (for eg. weekly) of interest in order to double check the automated systems and ensure safe operation of the railway, which is paramount.

Furthermore, further analysis may be carried out to better understand the relationships between the track and tunnel responses, in order to provide more guidance for future projects such as:

- If there are enough data points and the distance between 2 consecutive retro-reflective targets is consistent, it is possible to find the tunnel cant and twist by calculating the cant and twist of the retro-reflective targets as the results derived from the retro-reflective targets represent the tunnel/structure movements.
- If it is possible to find the relationship between the degree of maximum track cant and the clearance between the existing tunnel and the new CRL tunnel in term of the diameter of the existing tunnels, a threshold value of the clearance could be found at which the clearance is large enough to reduce the track cant to near zero value. In this way, the track-shoe monitoring for the track cant/twist monitoring may not be needed.

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Appendix 1. Figures showing the possible shadowing effect

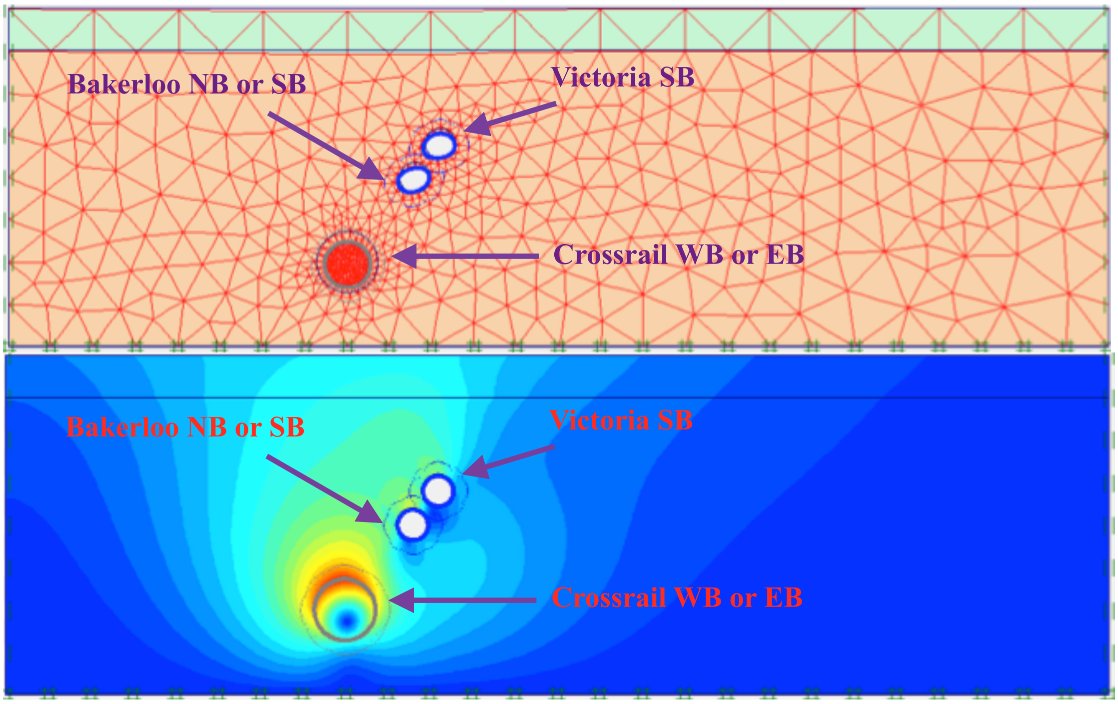

Fig. 5.6(a) (above) and Fig. 5.6(b) (below): possible shadowing effect of Bakerloo NB&SB on Victoria SB, produced by Plaxis, imposing 2% VL on the new tunnel

Appendix 2. Risk Assessment

The main methods used in this project involve data processing and graph plotting by using Microsoft Excel and OriginPro software. Therefore, there is no electrical, hazardous substances, laser, robotic, mechanical, biological hazards encountered during the course of the project. However, there may be other hazards related to computer use due to the long-time working on the computer for data processing and analyzing. The hazards are mainly health issues such as harms to the eyes, neck and spine. Efforts have been carried out the reduce these negative effects by the right position for computer use, stretch activities between every 1 hour of computer use, and some eye exercises. In retrospect, I might assess the risks in a similar way, but with greater awareness of the need to process huge amount of datas and the long working hours in front of the computer.