Engenuiti

St Giles Circus

St Giles Circus Basement VE

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1 Introduction

Consolidated Developments is redeveloping the site known as St Giles Circus, near Tottenham Court Road. St Giles Circus is bounded by Charing Cross Road, Andrew Borde Street, St Giles High Street and Denmark Street (Figure 1). The newly constructed Crossrail Eastbound tunnel crosses the site below basement level.

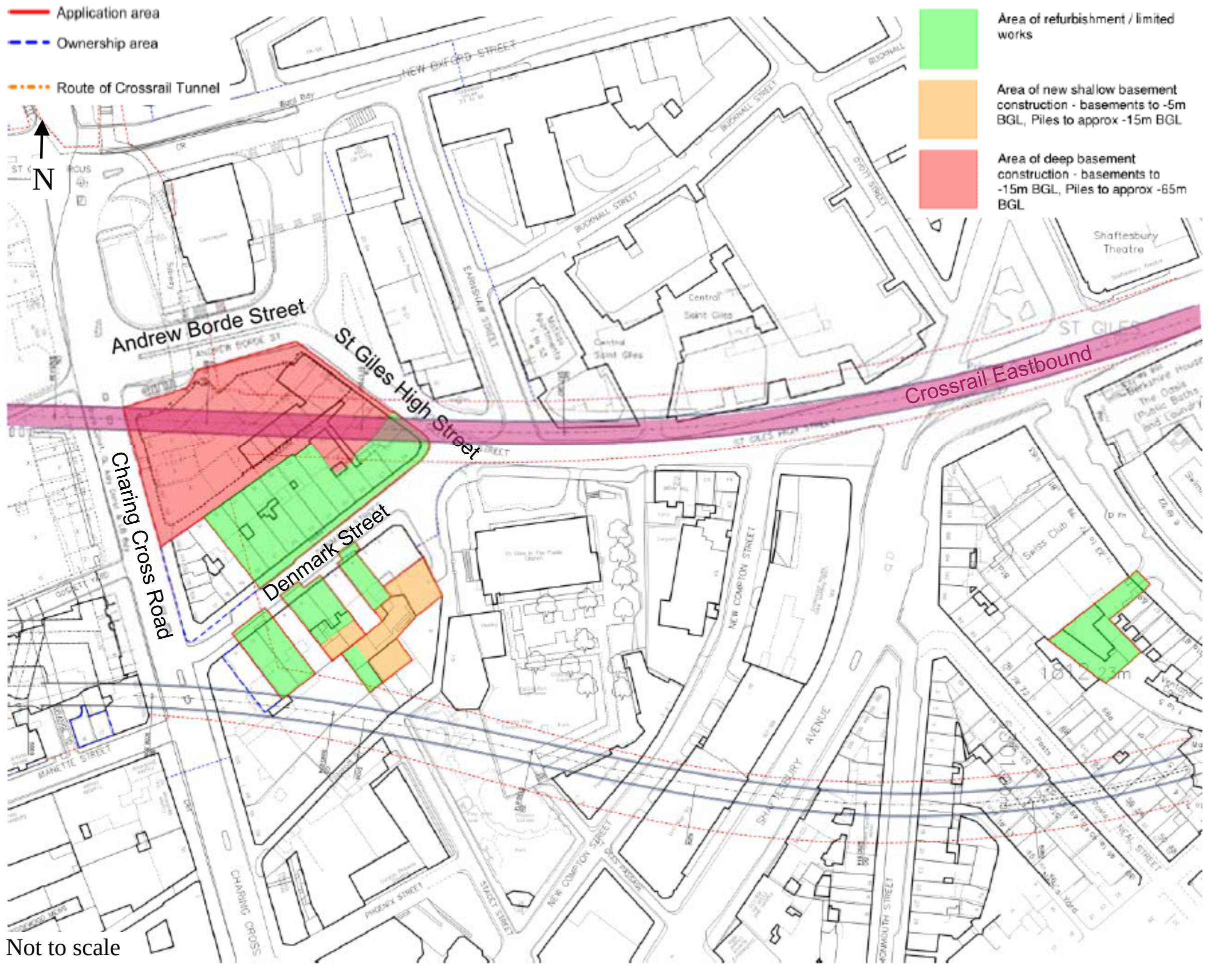


Figure 1 – Site plan (extract from Engenuiti Crossrail Ground Movement Impact Assessment).

Engenuiti is the structural engineer for the St Giles Circus scheme. Geotechnical advice services are provided by Donaldson Associates. The contractor is Skanska.

Arup are the designers of the Crossrail Tunnel and were also on site at Paddington reviewing monitoring data of tunnel performance in response to excavation above the tunnel crown. For this reason, Arup are in a unique position to review the provisions made for mitigating impact of the proposed basement construction for St Giles Circus on the Crossrail tunnel.

Arup was appointed by Engenuiti to undertake a feasibility study for an optimised basement construction scheme. The aim of this feasibility study is to look at:

1. Acceleration of the construction sequence by excavating the basement above and to the sides of the Crossrail tunnel at the same time.
2. Removal of heave-restraining adit beams above the Crossrail tunnel (other than those required for permanent loads); if required these are preferably to be constructed as conventional ground beams once the excavation as reached B1 formation level.
3. Reduction in number or length of heave-restraining piles installed to the sides of the Crossrail tunnel (adit piles) other than those required for permanent loads;

To give confidence in the modelling methods and to review the actual impact of the excavation above the Crossrail tunnels, the case of Paddington Station, where the station box was excavated above the Crossrail tunnels, has been analysed. The results of the analysis have been compared with monitoring data collected during the excavation works.

Subsequently, the St Giles Circus basement excavation has been modelled using the same Finite Elements (FE) methods adopted for the Paddington analysis, but incorporating:

- a revised construction sequence,
- the replacement of the adits with a ground slab, and
- a 50% reduction in stiffness of the adit piles.

Simple analytical methods have also been adopted to extrapolate 2d FE results in cross section to the longitudinal dimension.

The structural lining of the Crossrail tunnels has been checked to confirm that it can withstand the heave induced by the alternative construction sequence and foundations arrangements during construction and in the long term.

In addition, we have reviewed a number of internal tunnel systems which can be susceptible to ground movements (track slab, track alignment, overhead line equipment) and considered the potential impact of the calculated movements during construction and in the long term. These systems are reviewed in line with the criteria in the Developer / Third Party Interface document for 'St Giles Court' issued by Crossrail on 31/10/2011 and the Addendum to the Crossrail Safeguarding Guide: Information to Developers January 2014.

This report is not intended for and should not be relied upon by any third party other than Consolidated Developments and Skanska and no responsibility is undertaken to any third party for it.

2 Crossrail Paddington Station back-analysis

2.1 Introduction

This section describes the excavation of the Crossrail Paddington Station and its impact on the Crossrail tunnels. The construction of Crossrail Paddington Station bears similarities with the St Giles Circus basement as the tunnels were installed prior to the excavation of the station box above them. The tunnels were kept open and without internal propping until the overburden above the tunnels was practically completely removed. Movements of the tunnels were monitored during construction and provide valuable insight in the behaviour of the Crossrail tunnels subject to removal of overburden.

The aims of this section are:

- To illustrate a case study where a construction sequence similar to the one proposed for St Giles Circus has been adopted, resulting in acceptable movements which did not compromised the stability or structural integrity of the Crossrail tunnels.
- To validate modelling methods and parameters by creating a 2d FE model of the Crossrail Paddington Station and comparing the results of the analysis with actual monitoring data.

2.2 Station description and construction sequence

Crossrail Paddington Station is a large cut and cover box located in Eastbourne Terrace, immediately to the west of the Network Rail Paddington Station (Figure 2). The station is approximately 260m long and 22m wide.

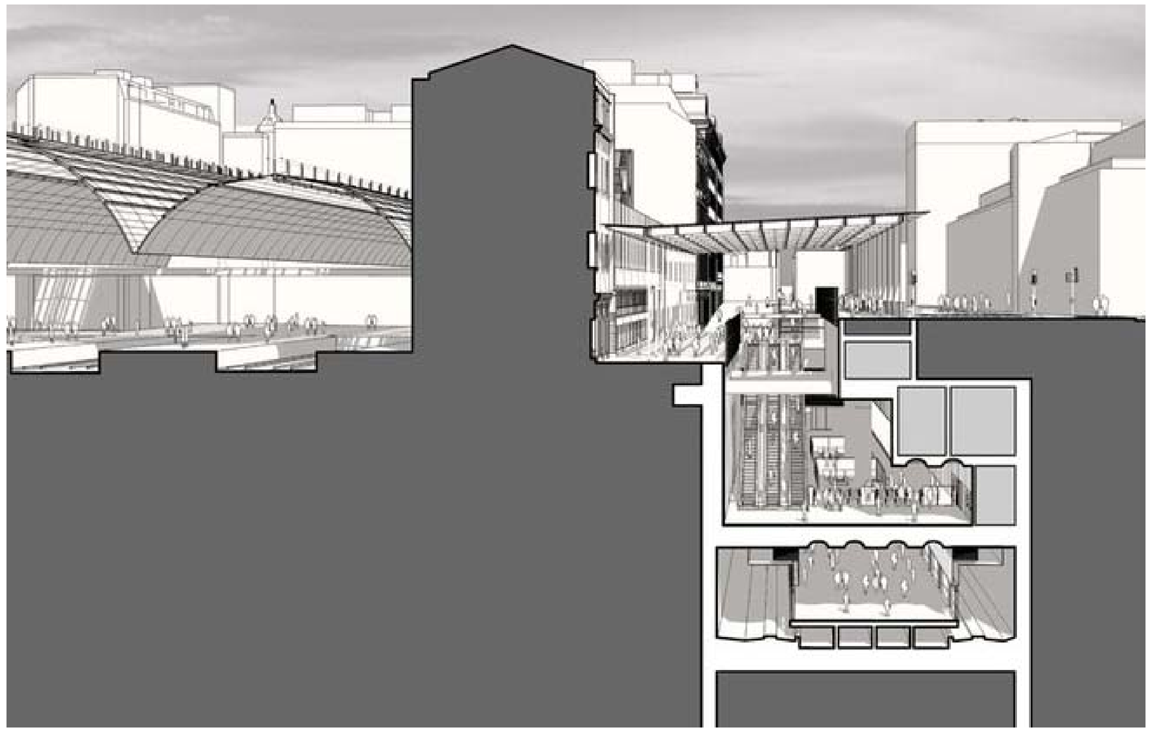


Figure 2 – Cross-section through the Crossrail Paddington Station.

The earth support system is provided by a 1.2m thick diaphragm wall, supported by reinforced concrete slabs in the permanent case. Bored piles of 1.8m diameter at 6m spacing, are also installed from street level in the middle of the station box. Plunge columns are installed in the bored piles to support the ground level slab during the top down excavation sequence.

Wider programme requirements meant that the tunnel boring machines constructing the running tunnels for the entire western section of Crossrail transited through this area whilst the D-Wall was being constructed, long before the excavation of the station box. The tunnels installed with tunnel boring machines have 6.8m outer diameter, with a 300mm lining made with fibre reinforced precast concrete segments.

After the transit of the tunnel boring machines, the construction sequence followed top-down principles, with the street-level slab installed prior to excavation. A single level of temporary props is used during excavation the break the span between the street-level slab and the mezzanine slab.

The construction sequence is top-down (with permanent slabs installed from the top before the excavation of the ground beneath them). The stages taken in consideration for the Crossrail Paddington Station back-analysis are:

1. D-Wall installation from ground level (123.0mATD);
2. Driving of bored tunnels (one at a time);
3. Excavation to 121.8mATD and installation of roof slab;
4. Excavation to 116.0mATD;
5. Excavation to 114.6mATD and installation of temporary props;
6. Excavation to 111.2mATD.

Once excavation reaches 111.2mATD, the clearance from the crown of the tunnels to the formation level is nominally 0.3m.

Further stages of construction, not relevant for this back-analysis, include the construction of a mezzanine reinforced concrete slab, the excavation to station formation level (with the concurrent demolition of the tunnels), and casting of the base slab.

2.3 Monitoring data

The Crossrail tunnels remained in use during the excavation of the station in order to maintain the full productivity of the tunnel boring machines. Therefore the tunnels were monitored to verify that the movements occurring during excavation were in line with the predictions, and the tunnels remained fully serviceable and safe for use.

Monitoring data is reported in the Crossrail document ‘Paddington In Tunnel Monitoring Report’ (C300-BFK-C-RGN-CRT00_ST005-50816 rev. 30).

Data is presented for sections located in the middle of the box for the westbound tunnel, in Figure 3 to Figure 5. The figures show vertical movement at the crown and knee of the tunnel, and the resulting ovalisation.

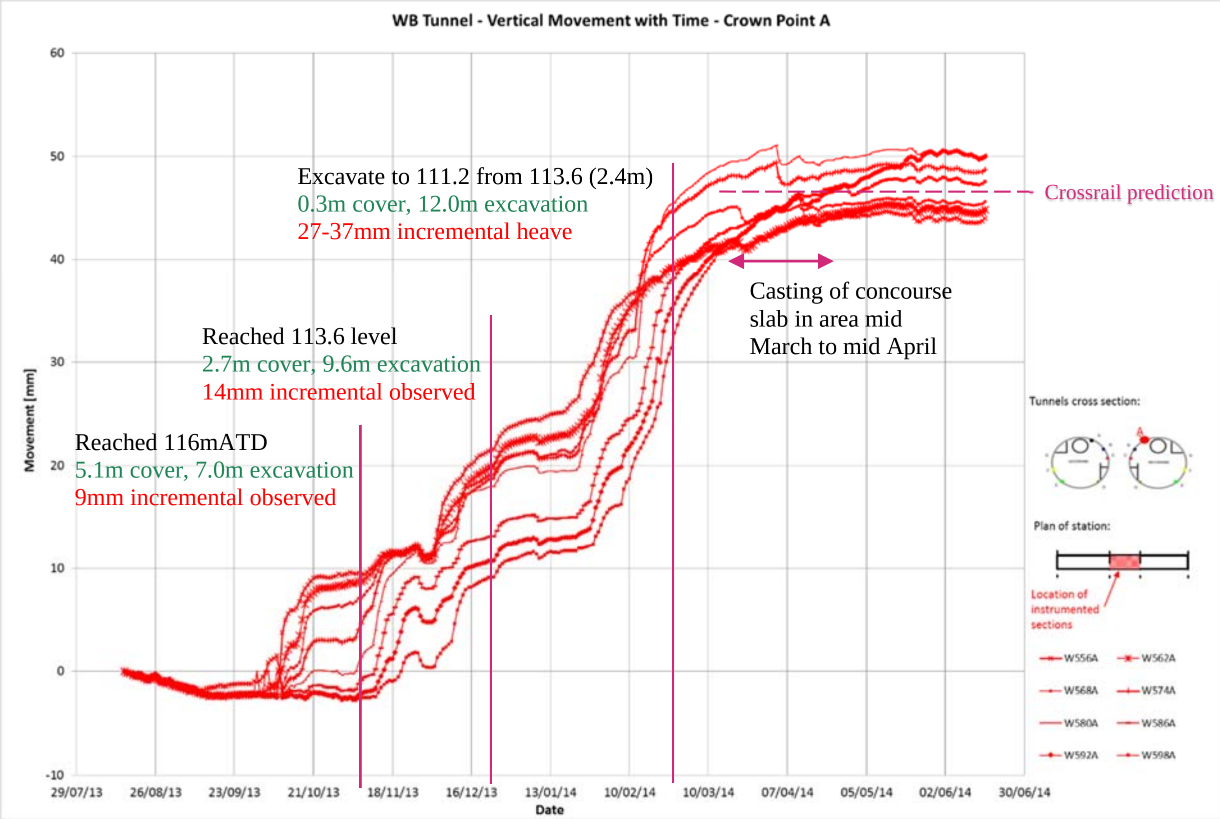


Figure 3 – Vertical movement at the tunnel crown.

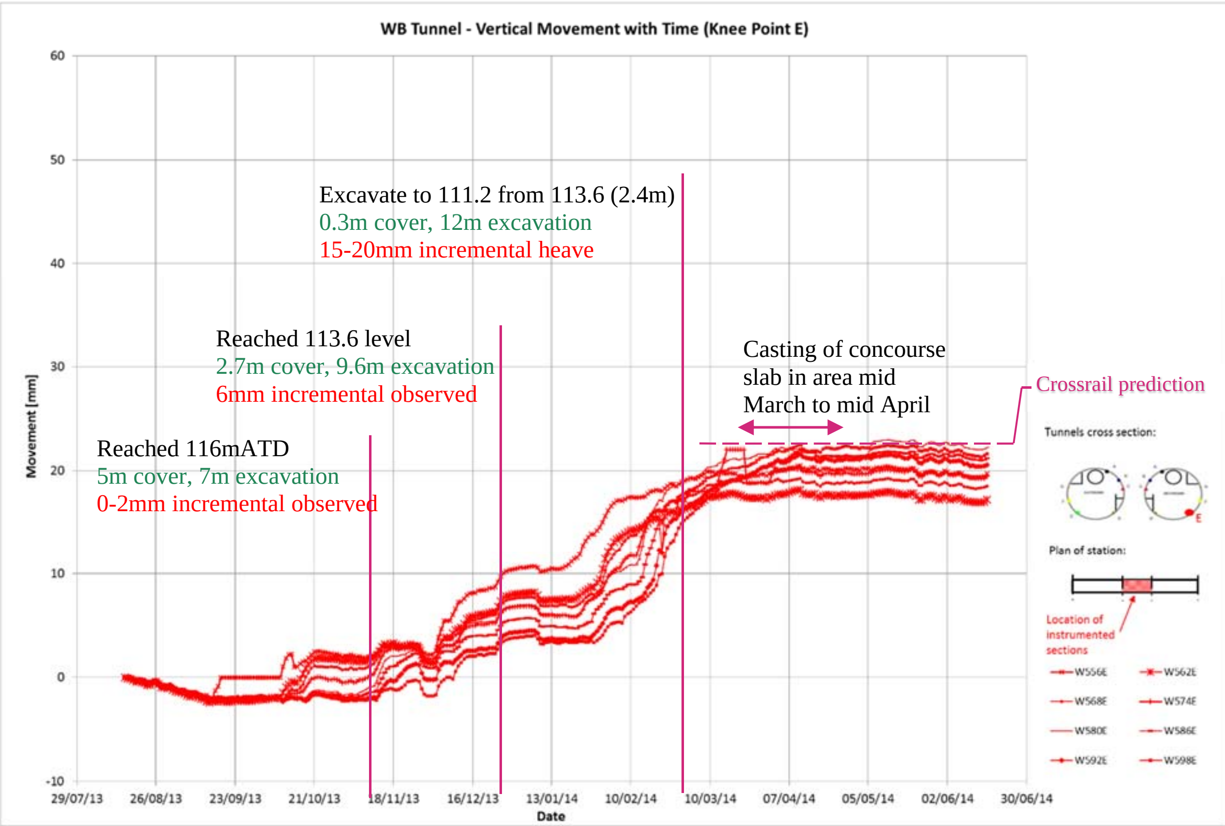


Figure 4 – Vertical movement at the tunnel knee.

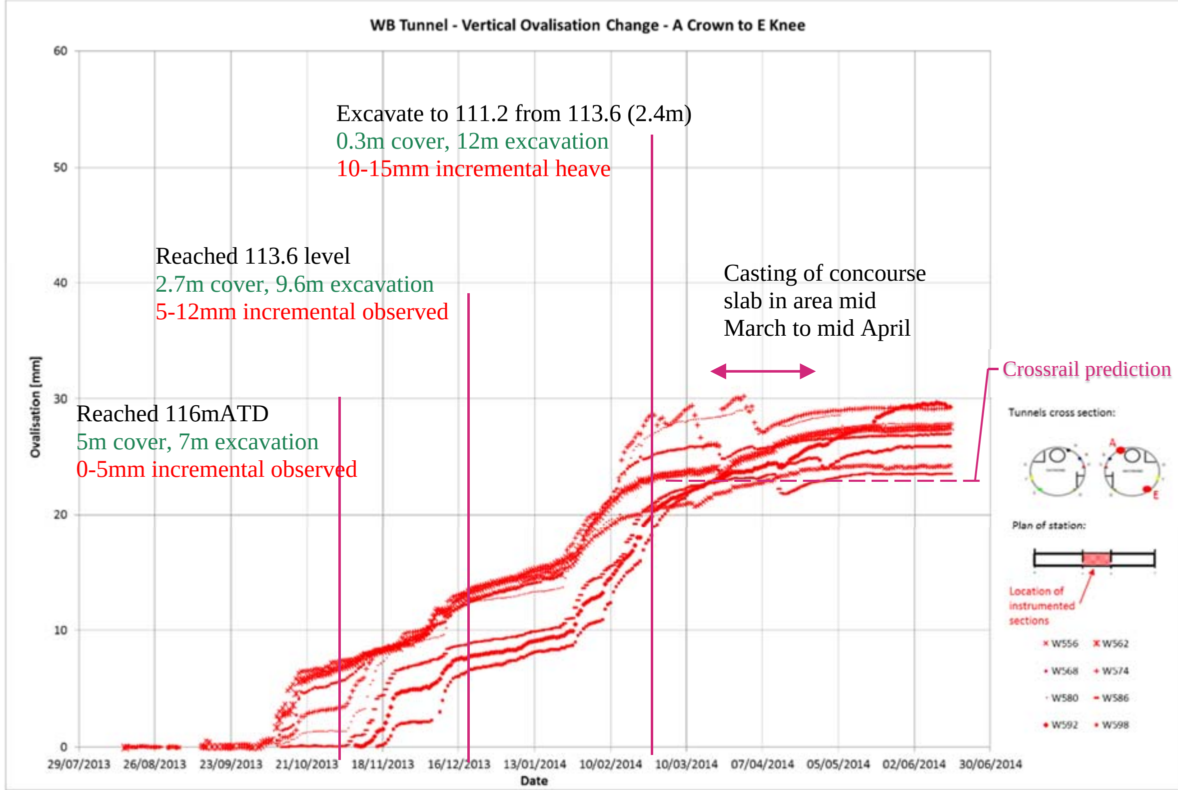


Figure 5 – Vertical ovalisation.

The tunnels heaved between 15mm (minimum at the invert) and 50mm (maximum at the crown). Ovalisation varied between 22mm and 29mm. The monitoring data was in accordance with the calculations carried out at the time (using a 3d model, with non-linear soil stiffness) to demonstrate that the tunnel would remain serviceable during the station excavation. The tunnels remained open until the installation of the mezzanine slab, as anticipated.

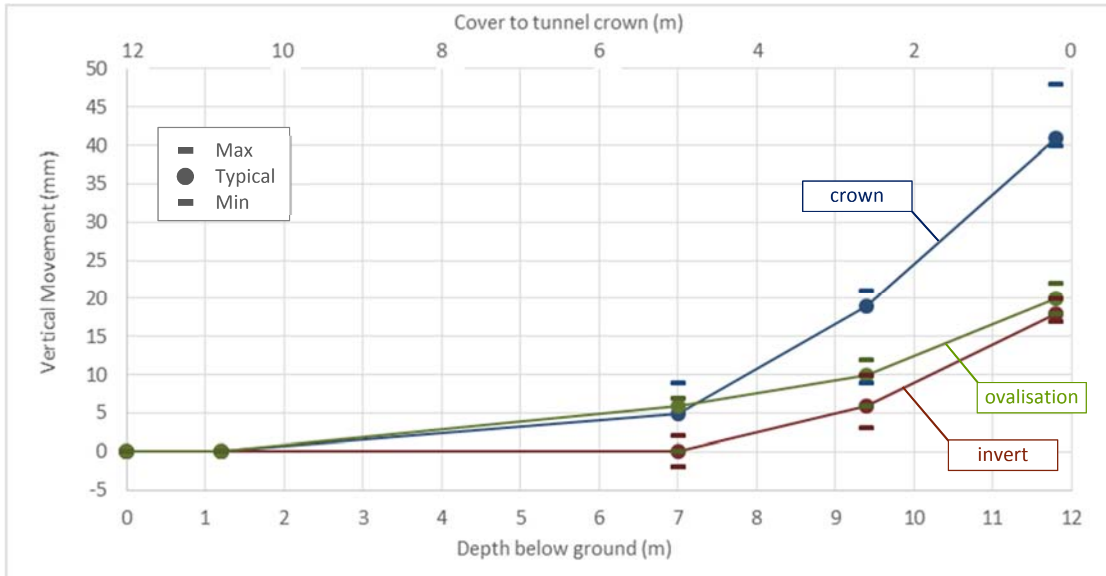


Figure 6 – Vertical movement and ovalisation with depth of excavation and cover to tunnel crown.

Figure 6 shows the development of heave and tunnel ovalisation against depth of excavation and cover to the tunnel crown. Movements increase more significantly as the cover to the tunnel crown reduces below 5m and the depth of excavation increases above 7m.

2.4 Ground parameters

Ground parameters are derived from the Crossrail Geotechnical Interpretative Report (CRL1-PDP-C2-RGN-CRG03-00001 to 3, rev. A-V1.2). The ground parameters are listed in Table 1 and shown in Figure 7.

Strata	Level at top (mATD)	Bulk Unit Weight (kN/m^3)	Undrained Shear Strength (KPa)	Undrained Young's modulus (KPa)	K0 (-)	Friction Angle (°)	Cohesion (KPa)	Young's Modulus (KPa)
Made Ground	123.0	18	-	-	0.5	25	-	5,000
River Terrace Deposits	121.0	20	-	-	0.5	36	-	50,000
London Clay	120.0	20	85+5z	500 Cu	1.0	25	3	400 Cu
Lambeth Group	65.0	20	360	500 Cu	1.0	30	3	400 Cu

Table 1 - Ground parameters for Paddington back-analysis.

Strata below the Lambeth Group, which are approximately 56m below the invert of the tunnels and 63m below the maximum excavation level, have been ignored for the purpose of this study as sufficiently deep to have negligible effect on the tunnel heave.

Groundwater level is hydrostatic below 120mATD (3m below ground level), and then rapidly reducing to zero between 85mATD and 63mATD. The head of the deep aquifer is located in the Chalk. For the long term, the aquifer is assumed to be hydrostatic from 120mATD. However, as the analysis is carried out with undrained / short term assumptions, the pore water pressure profile is of limited relevance in this instance.

2.5 Modelling method

A schematic analysis section in shown in Figure 7.

The software used for the analysis is Plaxis 2D 2015.1.

All soils are modelled with an elastic, perfectly plastic constitutive model, and Mohr - Coulomb strength criteria. After stress initialisation, London Clay and the Lambeth Group are modelled with undrained strength parameters and drained stiffness parameters (Method B).

Structural elements including the D-Wall, bearing piles, slabs and temporary props are modelled with equivalent stiffness 'smeared' over nominal 1m length, for compatibility with the 2d analysis method. The stiffness values used in the model are given in Table 2.

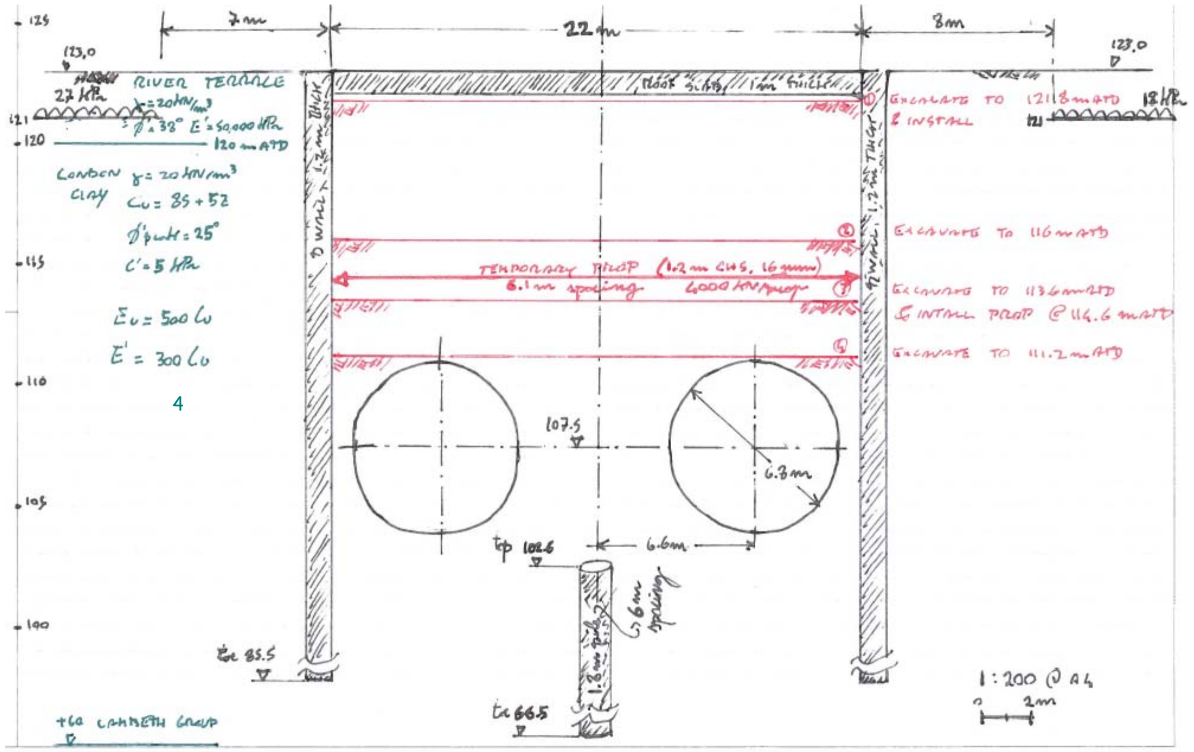


Figure 7 – Analysis section and ground parameters.

Element	Structural form assumed for design	Stiffness (short term)
D-Wall	1.2m thick, reinforced concrete	$0.7EI = 3.33GNm^2/m$
Roof Slab	1m thick. reinforced concrete	0.7EA = 2.1GN/m/m
Temporary Prop	1.2m CHS steel prop, 16mm thick, 6m spacing	EA = 96.4MN/m/m Preload to 656kN/m
Internal Piles	1.8m piles, 6m spacing (3% reinforcement)	EA = 2.6GN/m/m

Table 2 – Stiffness of structural elements.

The stiffness of the tunnel lining is modelled with an equivalent stiffness method[1] to account for the presence of joints between precast concrete segments. The calculated stiffness for the tunnel is:

$$EI = 15.1MN/m^2/m.$$

The tunnel lining is wished in place after allowing for 40% relaxation of soil stresses (using the 'M Stage' approach in Plaxis).

[1] Muir-Wood, A.M. (1975) The Circular Tunnel in Elastic Ground, Geotechnique, Vol. 25, No.1, pp.115-127.

2.6 Analysis results

Figure 8 shows the calculated heave of the tunnel crown and invert, and the ovalisation, against the depth of the excavation and the cover to the tunnel crown. The calculated values are in reasonable agreement with the monitoring data, with calculated heave giving typically greater heave at shallow depth that actual measure data (which is conservative in the context of this report).

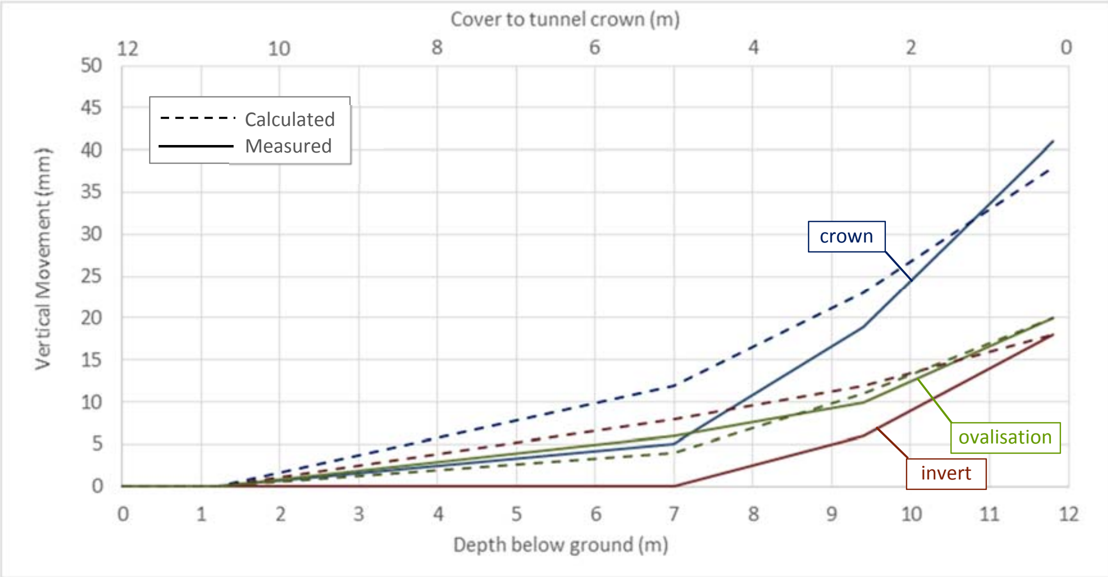


Figure 8 – Calculated heave and ovalisation against monitoring data.

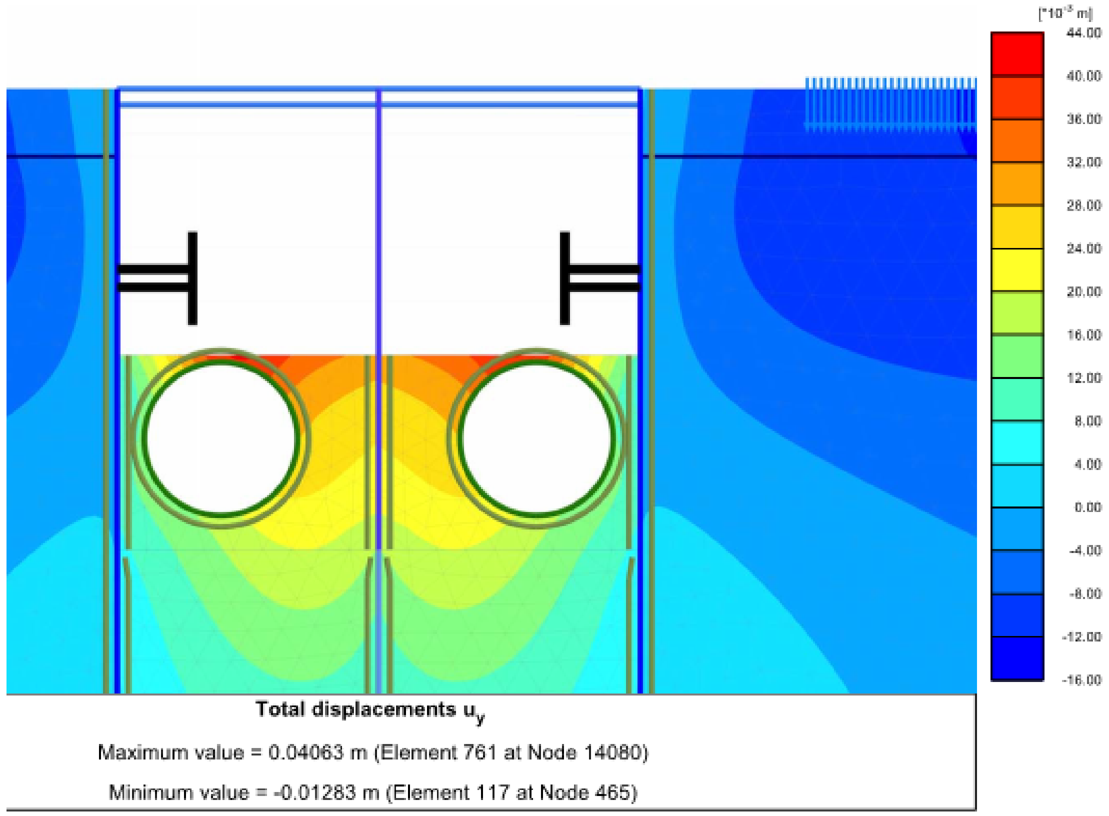


Figure 9 – Vertical ground movement at final stage.

Figure 9 shows vertical ground movement at the final stage of excavation, as the crown of the tunnel has been reached. The maximum heave at the crown of the tunnel is approximately 40mm, 16mm at the invert. Ovalisation is approximately 25mm. These results are in good agreement with the monitored data.

Good agreement is also achieved in terms of wall deflections (maximum of approximately 15mm for the deflection occurred between start of excavation and reaching of the tunnel crown).

2.7 Conclusions

There is good agreement between the 2d FE model analysed as part of this study and the tunnel monitoring data collected during the excavation of Crossrail Paddington Station. Therefore, the modelling method which will be used for the purpose of this feasibility study for the analysis of the St Giles Circus basement can be considered validated.

In addition, a set of case history data has been presented illustrating a construction sequence which will be similar to the proposed St Giles Circus basement excavation. In the case of Crossrail Paddington Station, excavation proceeded to the crown of the tunnels whilst maintaining the tunnels fully operational (for the purpose of the Tunnel Boring Machine operations), with the tunnel behaving safely and in accordance with calculations.

3 St Giles Circus analysis

3.1 Introduction

The aim of this section of the feasibility study is analyse the impact on the Crossrail tunnel of a construction sequence which allows the simultaneous excavation of the St Giles Circus basement above and to the sides of the tunnel. Such a sequence would remove the need for substantial high risk temporary works, such as the tunnelling of adit beams above the Crossrail tunnels. The sequence would also speed up the basement construction, thereby reducing the overlap between the basement construction and tunnel fit out and reducing the risk that basement works could continue beyond fit out of the tunnel.

In addition, the analysis reconsiders the measures proposed to restrain long term heave, including the adit beams to be installed above the Crossrail tunnel and the two rows of deep heave-restraining piles (adit piles) installed to the sides of the Crossrail tunnels. It is assumed that the adit beams are replaced by a 1m thick raft, and the nominal stiffness of the adit piles is reduced by 50%. This may be achieved with a reduction in length, diameter or number of the adit piles.

3.2 Basement description and construction sequence

The proposed St Giles Circus basement is described in detail in the Conceptual Design Statement for Crossrail (029-S-REP-001 Rev. 1) by Engenuiti. The basement is approximately 60m by 40m wide. The Crossrail Eastbound tunnel, which is located at an approximate depth below street level of 17.5m (to the tunnel crown), was constructed in 2013. Works are ongoing for the fit out of the tunnel with railway systems. A plan and cross section of the basement are shown in Figure 10 and Figure 11.

The proposed St Giles Circus basement is supported by a secant piled wall of 0.9m diameter installed along the perimeter. Bearing piles of diameter varying between 0.6m and 1.2m, some of which incorporate plunge columns, are proposed to be installed from ground level. Separately from this feasibility study, it is proposed to simplify the basement construction sequence around the 'Smithy's' by temporarily relocating it during the piling operations and returning it to its current location after completion of the piling works. This will standardise the interface of the basement with the Crossrail tunnel.

Two rows of deep piles of 0.9m diameter are also proposed to be installed along the sides of the Crossrail tunnel (adit piles); the majority of these piles are currently proposed for the purpose of restraining the heave potentially induced by the excavation of the St Giles Circus basement on the Crossrail tunnels and forming a retaining wall for the B2 basement excavation.

The proposed alternative construction sequence was confirmed with Skanska via email on 8th October 2015. The construction sequence is top-down (with permanent slabs installed from the top before the excavation of the ground beneath them). The stages taken in consideration for the St Giles Circus basement analysis are shown in Figure 12 and consist of:

1. Installation of secant piled wall and bearing piles from ground level;
2. Installation of ground level slab;
3. Excavation to 120.3mATD and installation of lower ground level slab;
4. Excavation to 113.5mATD and installation of B1 slab and, if required, adit beams;
5. Excavation to 109.9mATD and installation of B2 slab.
6. Installation of BM slab.
7. Construction of the superstructure / long term loads.

The duration from excavation below ground level to casting of the B1 slab and beams above the Crossrail tunnels is estimated to require approximately 6 months.

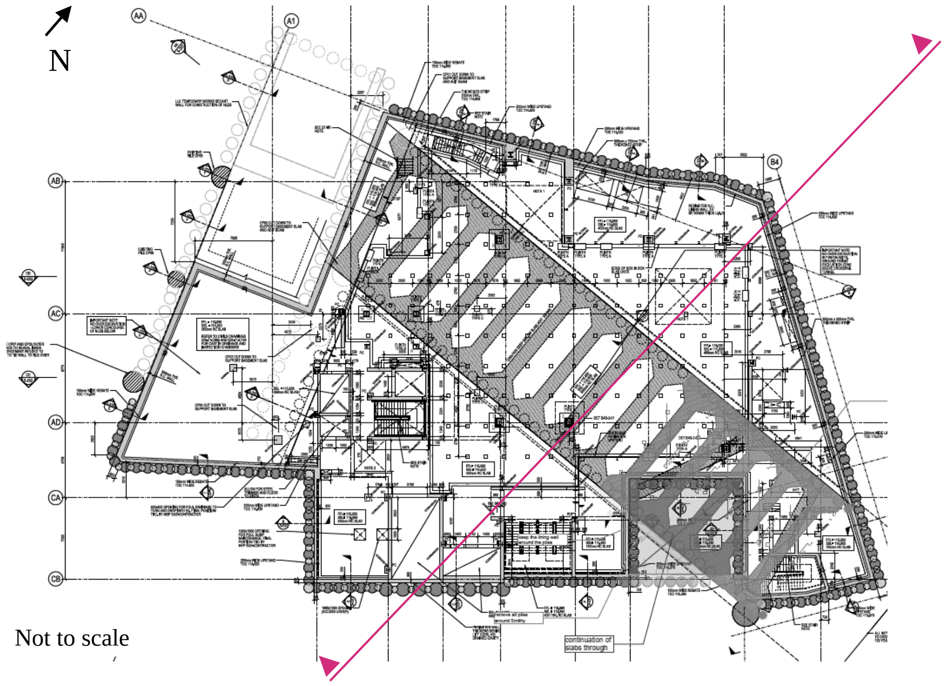


Figure 10 – Extract from basement B1 general arrangement (Engenuiti ref. Z1-S-071)

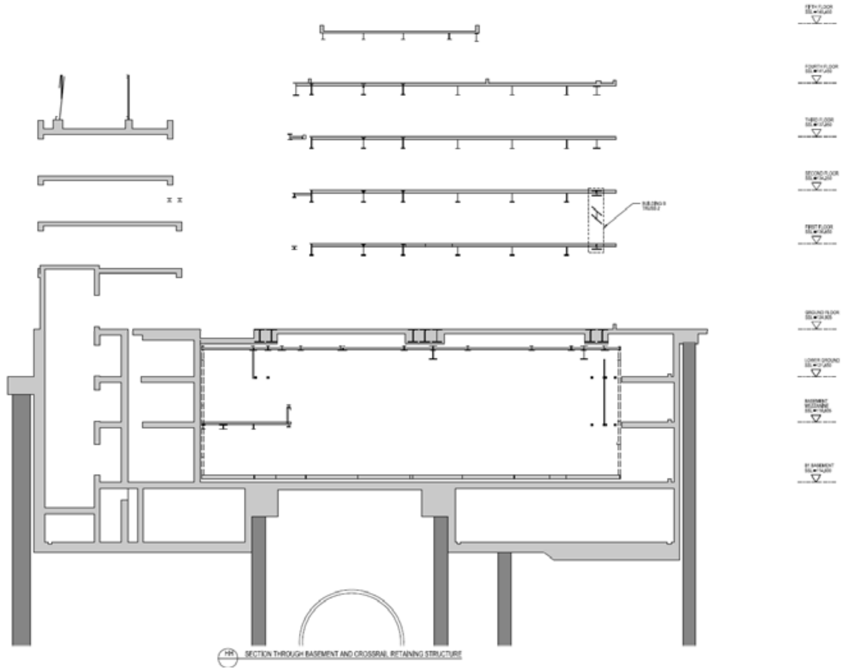


Figure 11 – Extract from building section HH (Engenuiti ref. Z1-S-205)

Not to scale

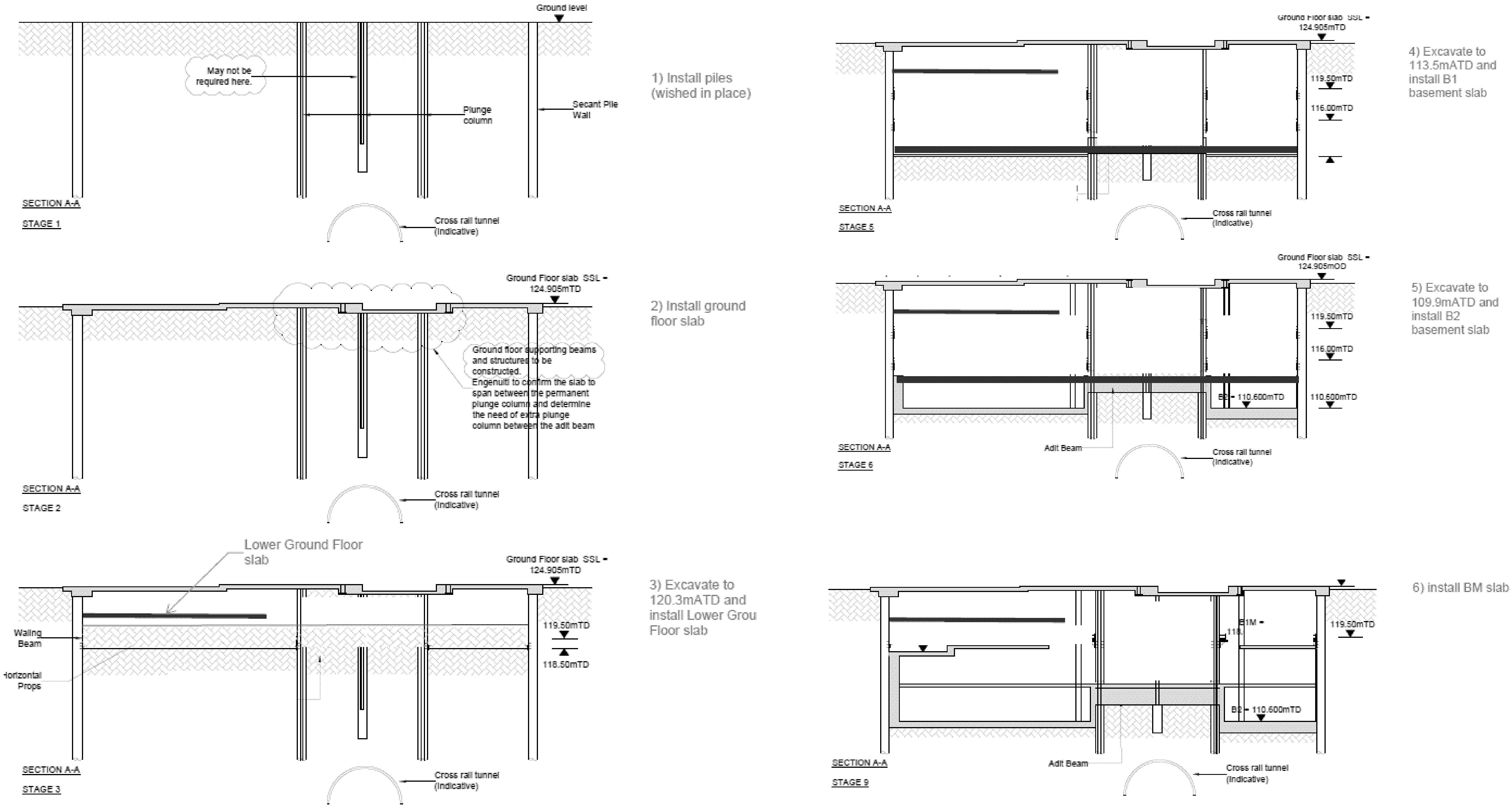


Figure 12 – Proposed alternative basement construction sequence (not to scale).

3.3 Ground parameters

A review of ground parameters is shown in Table 3. Where possible, the same parameters established by Engenuiti and Donaldson Associates in the London Underground Conceptual Design Statement (029-Z1-REP004 rev. 03) have been used in this feasibility study. Due to the different modelling methods, it has been necessary to determine undrained parameters and a Young's modulus adequate for the constitutive model described in Section 3.4.

Strata	Level at top (mATD)	Bulk Unit Weight (kN/m³)	Undrained Shear Strength (KPa)	Undrained Young's modulus (KPa)	K0 (-)	Friction Angle (°)	Cohesion (KPa)	Young's Modulus (KPa)
Made Ground	125.1	20	-	-	0.577	25	3	4,000
River Terrace Deposits	121.2	21	-	-	0.441	34	3	30,000
London Clay	119.1	20	100+5.5z	500 Cu	1.2	25	5	400 Cu
Lambeth Group (cohesive)	94.6	21	235	500 Cu	1.2	25	5	400 Cu
Lambeth Group (cohesionless)	78.1	21	-	-	0.5	30	3	150,000
Thanet Sand	76.3	19	-	-	0.426	30	3	300,000

Table 3 – Ground parameters for the St Giles Circus analysis.

The Chalk formation (to of stratum at 71.7mATD), underlying the Thanet Sand, is not considered for the purpose of this analysis.

Derivation of the strength profile of the London Clay and cohesive Lambeth Group is illustrated in Figure 13. It is based on the ground investigation data made available by Engenuiti in the Conceptual Design Statement for Crossrail and the Crossrail Ground Movement Impact Assessment (029-Z1-REP001 Rev. 02).

Ground parameters are relatively similar to the Paddington analysis, although the different thickness and overburden of the London Clay and cohesive Lambeth Group determine slightly different strength and stiffness profiles.

The pore water pressure profile is assumed to be underdrained in short term, and then hydrostatic from 121.0mATD in the long term (Figure 14).

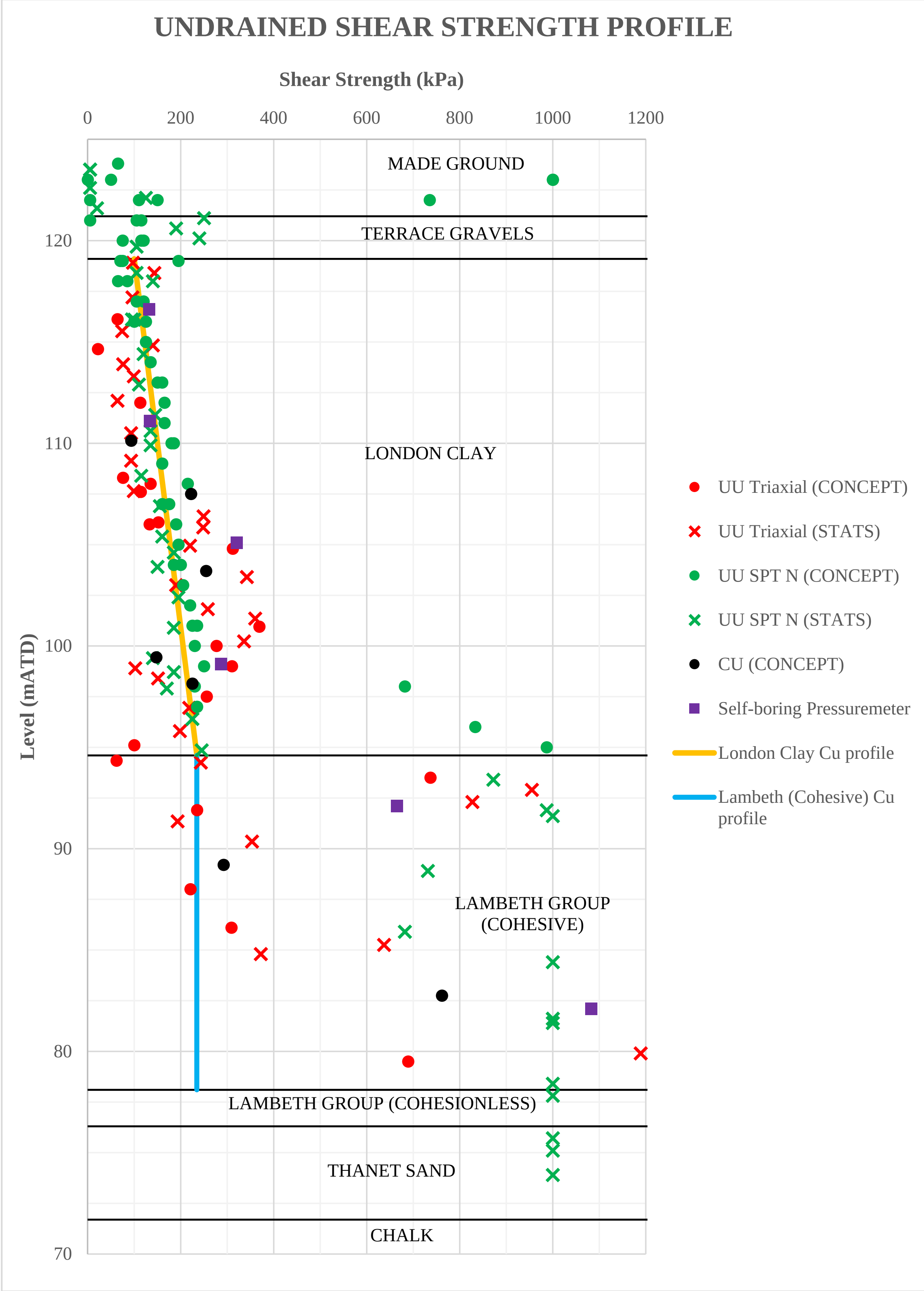


Figure 13 – Derivation of undrained parameters for London Clay and cohesive Lambeth Group.

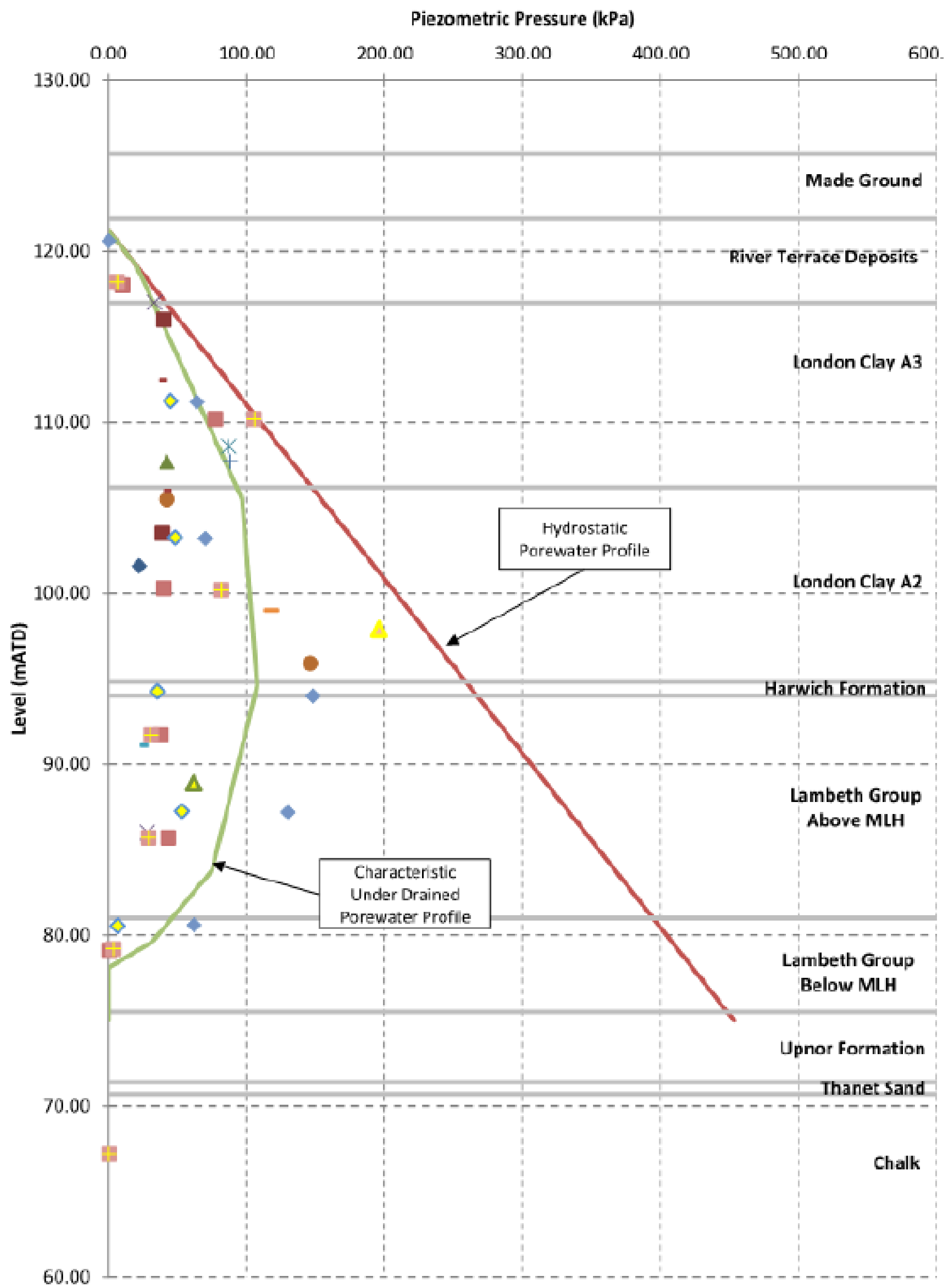


Figure 14 Pore water pressure profile (extract from Engenuiti Ground Movement Impact Assessment).

3.4 Modelling methods

A schematic analysis section in shown in Figure 15.

The software used for the analysis is Plaxis 2D 2015.1.

All soils are modelled with an elastic, perfectly plastic constitutive model, and Mohr - Coulomb strength criteria. After stress initialisation, London Clay and the Lambeth Group are modelled with undrained strength parameters and drained stiffness parameters (Method B).

Structural elements including the secant piled wall, bearing piles and slabs are modelled with equivalent stiffness ‘smeared’ over nominal 1m length, for compatibility with the 2d analysis method. The stiffness values used in the model are given in Table 4. The ground floor, lower ground and mezzanine level slabs are modelled as springs, as the voids in the centre of the basement will limit the interaction of these slabs with the heave restraining piles.

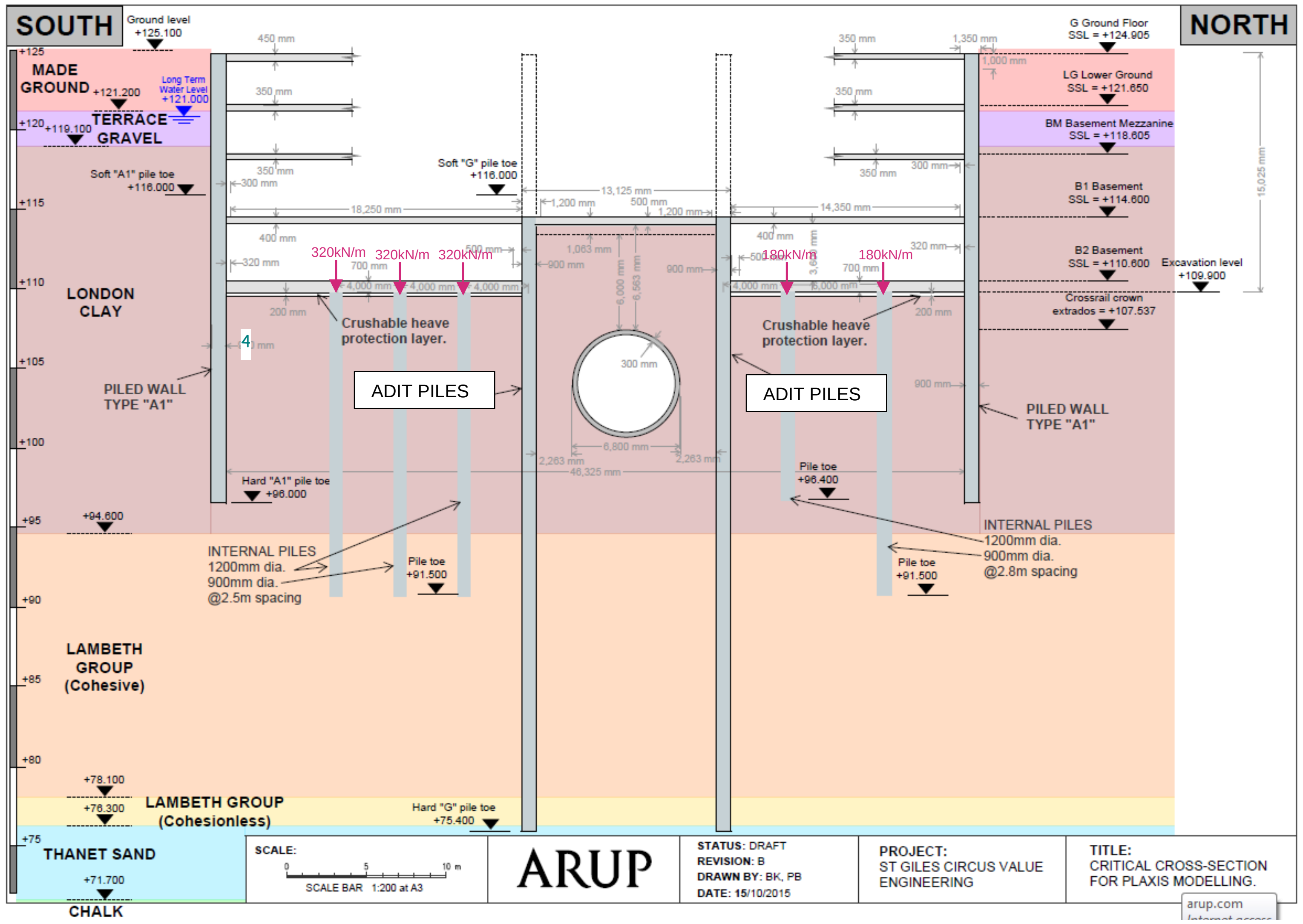


Figure 15 – Analysis section for St Giles Circus.

Element	Structural form assumed for design	Stiffness (short term)	Stiffness (long term)
Secant piled wall	0.9m diameter, 1.2m spacing	EI = 626MNm^2/m EA_{steel} = 3,896MN/m	EI = 447MNm^2/m EA_{steel} = 3,896MN/m
Adit piles	0.9m diameter, 1.2m spacing, 3.5% steel	EI = 626MNm^2/m EA_{steel} = 3,896MN/m	EI = 447MNm^2/m EA_{steel} = 3,896MN/m
Bearing piles	0.6 to 1.2m diameter	EA = 96.4MN/m/m	EA = 96.4MN/m/m
Ground floor slab **Lower ground floor slab** **Basement mezzanine slab**	0.35m thick, 15m effective length	EA = 544MN/m/m	EA = 389MN/m/m
B1 slab	0.4m thick	EA = 11,655MN/m	EA = 8,325MN/m
B2 slab	0.7m thick	EA = 16,317MN/m	EA = 11,655MN/m
B1 slab, above Crossrail	a) 1.0m thick raft	EA = 23,310MN/m EI = 1,925MN/m	EA = 16,655MN/m EI = 1,375MN/m
	b) adit beams (as per Engenuiti CDS)	EA = 25,641MN/m EI = 12,427MN/m	EA = 18,315MN/m EI = 8,876MN/m

Table 4 – Stiffness of structural elements.

The stiffness of the tunnel lining is modelled with an equivalent stiffness method[2] to account for the presence of joints between precast concrete segments. The calculated stiffness for the tunnel is:

EI = 15.1MN/m^2/m.

The tunnel lining is wished in place after allowing for 40% relaxation of soil stresses (using the ‘M Stage’ approach in Plaxis).

The existing buildings and demolition stage are ignored for the purpose of this model. However, excavation is initiated from ground level, which achieves an unloading of similar magnitude to the weight of the existing buildings.

The long term stage is modelled by allowing the ground to consolidate from the suction generated during the undrained excavation to the long term pore water pressure profile. The basement slabs are modelled as ground bearing. Long term building loads are also applied, although these are small compared to the long term heave and water pressure and the basement will be in a state of net unloading, with the piles mobilised in tension to resist it. Assumed 'smeared’ long term loads on the internal piles are shown in Figure 15. Loads on the secant piled wall are conservatively ignored.

[2] Muir-Wood, A.M. (1975) The Circular Tunnel in Elastic Ground, Geotechnique, Vol. 25, No.1, pp.115-127.

3.5 Analysis results

Vertical displacements for the final stage are shown in Figure 16 and Figure 17 and summarised in Table 5. The following differences between the proposed alternative and the previously proposed construction methodology (Engenuiti CDS analysis) are highlighted:

- The revised construction sequence is illustrated in Figure 12. The basement is now proposed to be excavated all the same time, whilst the original sequence required first the excavation to the sides of the Crossrail tunnel, then the installation of the adit beams, and finally the excavation above the Crossrail tunnel.
- A 1m thick raft is assumed to be placed above the Crossrail tunnel, instead of the currently designed adit beams.
- The piles to the sides of the Crossrail tunnel (adit piles) are assumed to have 50% of their current nominal stiffness. This may be achieved by either varying the number, length or diameter of the adit piles.

Vertical displacements for the final stage are shown in Figure 16 and Figure 17 and summarised in Table 5.

ST: short term LT: long term	Revised sequence, ground slab, reduced adit pile stiffness	
	ST	LT
Max movement (invert)	14	22
Max movement (crown)	24	36
Ovalisation	10	14

Table 5 – Summary of movements from St Giles Circus analysis (all results in mm).

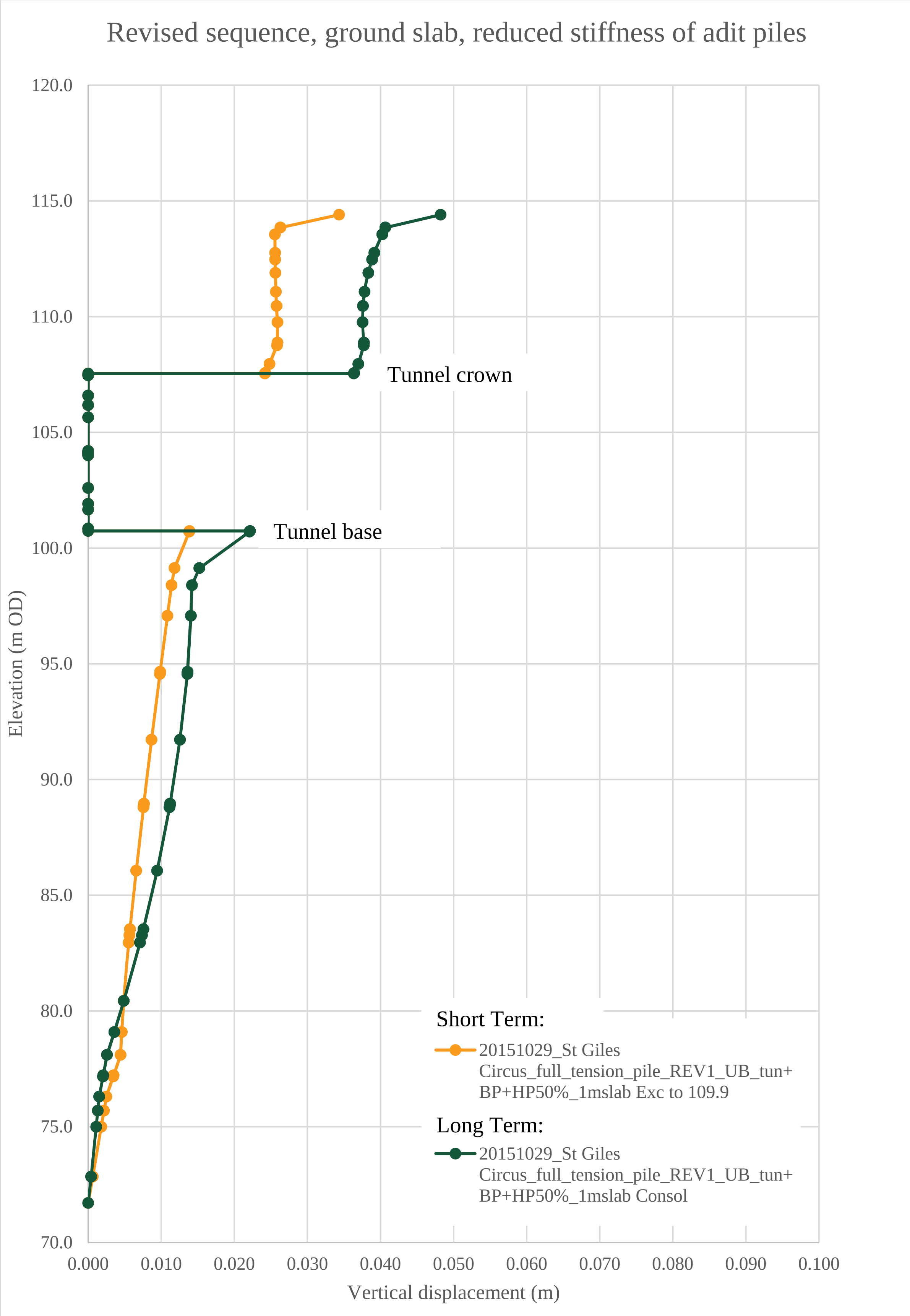


Figure 16 – Short and long term vertical displacement, St Giles Circus, section along tunnel centreline.

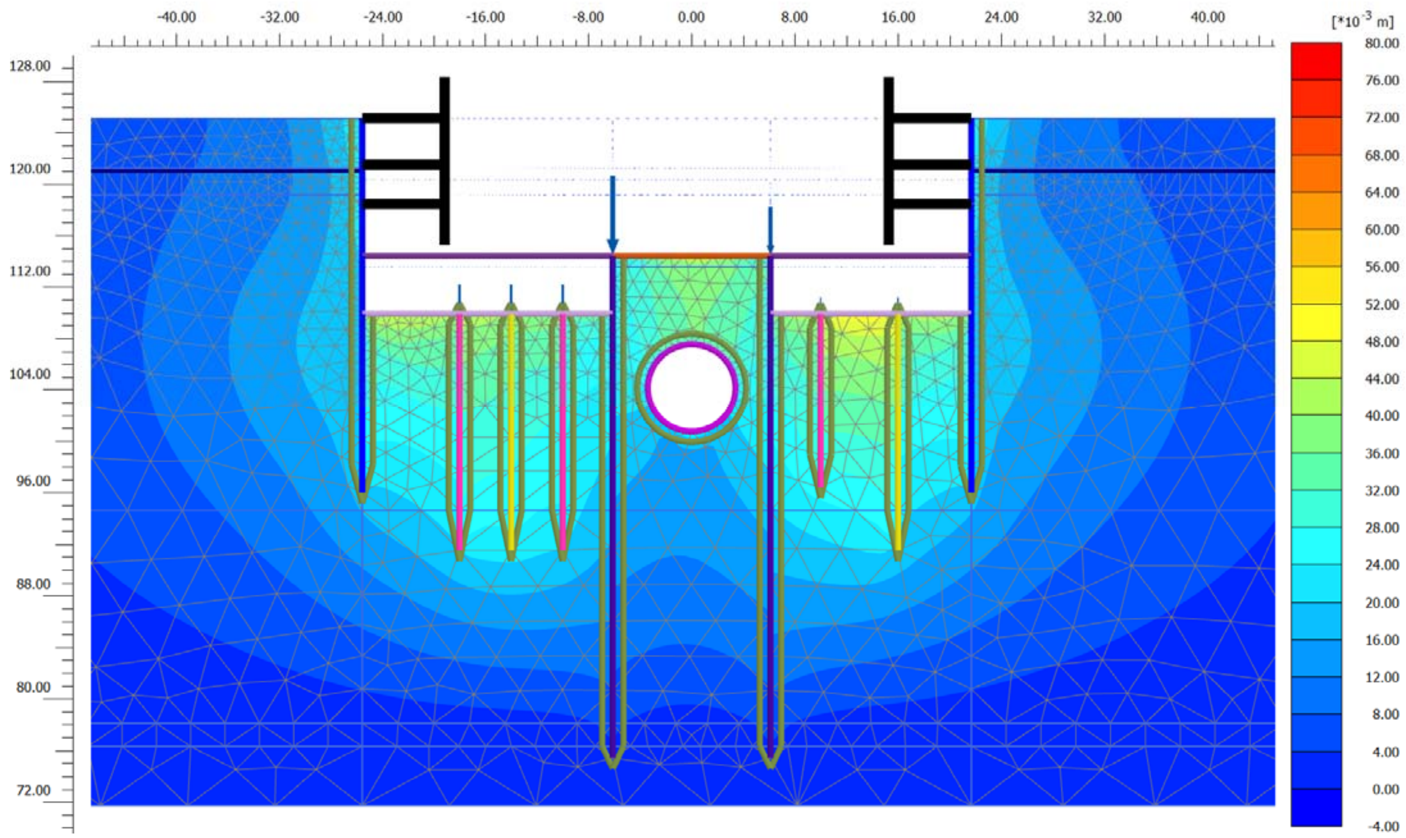


Figure 17 – Long term vertical displacement, St Giles Circus.

3.6 Extrapolation to longitudinal tunnel section

The assessment of the impact of the St Giles Circus basement excavation on the Crossrail tunnel requires an understanding of longitudinal as well as cross-sectional distortions. Whilst the latter are immediately available from the 2d plane strain analysis carried out in Plaxis, a 3d analysis is required to understand longitudinal distortions.

For this purpose, an analysis based on the Boussinesque elastic solution is carried out with the Oasys software Pdisp. The calculation is necessarily carried out under greenfield assumptions, ignoring the stiffness of any structural element. Therefore the magnitude of greenfield displacements is scaled to match the 2d Plaxis analysis at the cross section analysed in the Section 3.5.

Results of the calibration of the longitudinal analysis, are presented in Figure 18 and Figure 19. The calculated maximum radii of curvature in the short and long term are given in Table 6.

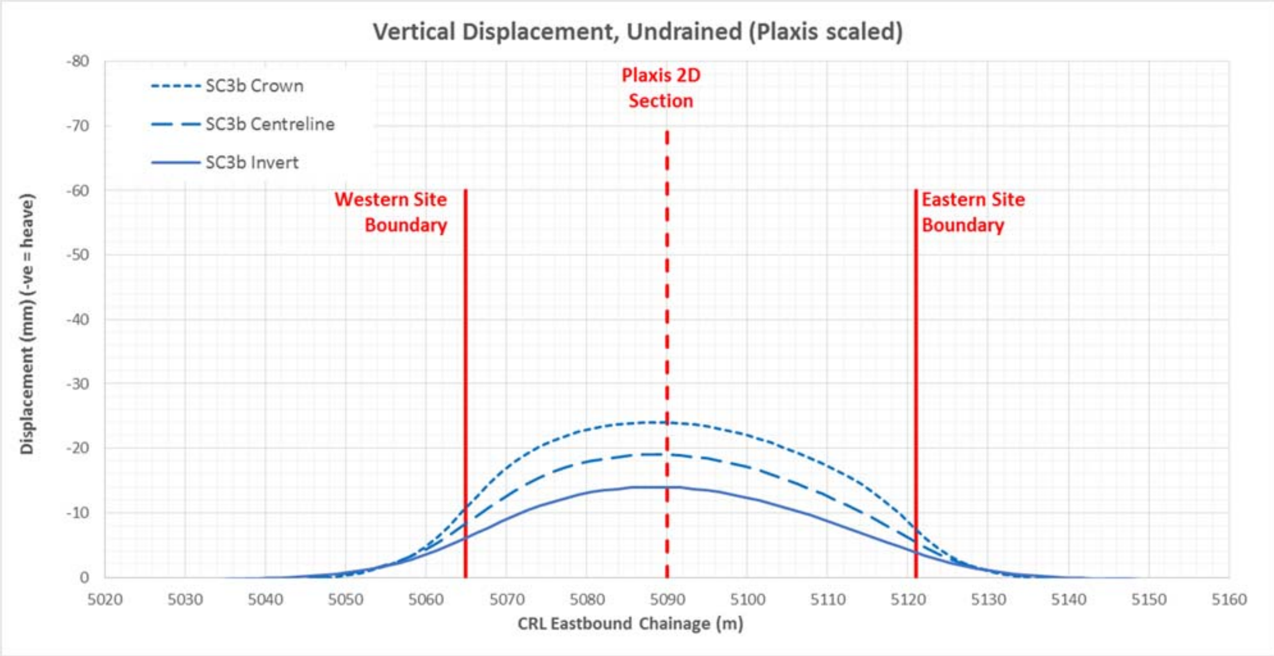


Figure 18 – Longitudinal short term vertical displacement of the Crossrail tunnels, St Giles Circus.

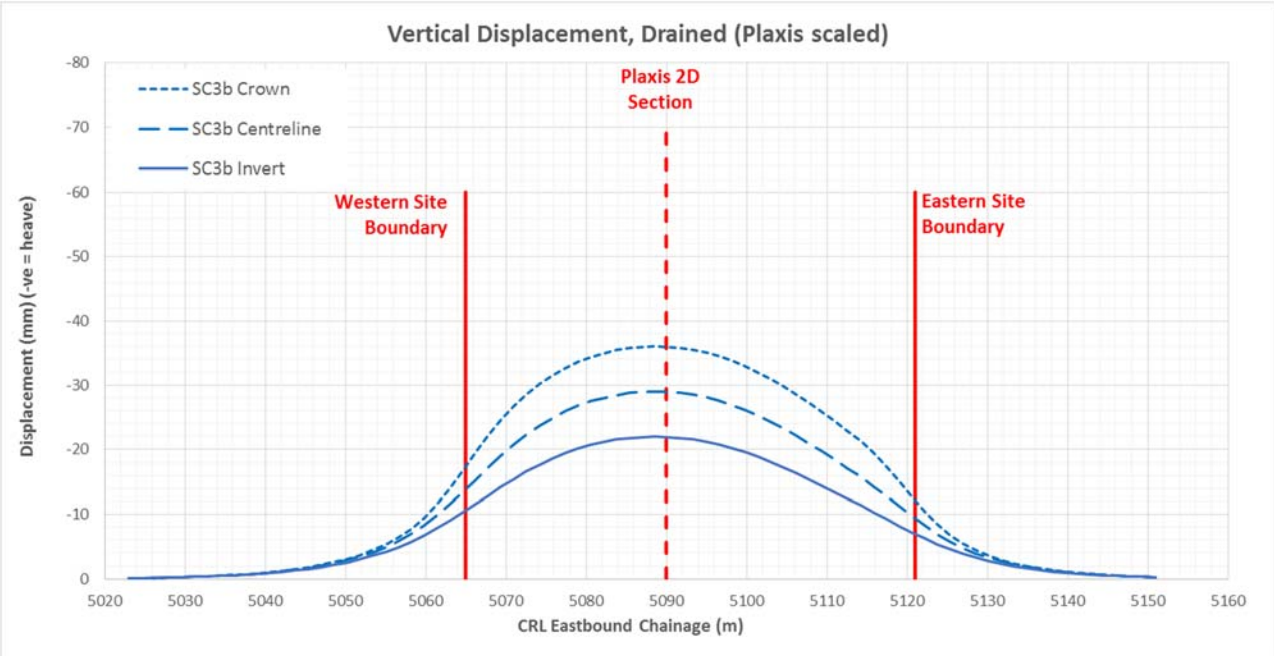


Figure 19 – Longitudinal long term vertical displacement of the Crossrail tunnels, St Giles Circus.

ST: short term LT: long term	Revised sequence, ground slab, reduced pile stiffness	
	ST	LT
Max curvature (invert)	28.6	21.2
Max curvature (crown)	7.2	6.5

Table 6 – Summary of radii of curvature from St Giles Circus analysis (all results in Km).

3.7 Conclusions

A range of analysis has been carried out for St Giles Circus in order to assess the impact of a revised construction sequence, which allows the simultaneous excavation of the basement above and to the sides of the Crossrail tunnel. In addition, the adit beams have been replaced with a 1m thick ground bearing raft above the Crossrail tunnels, and the stiffness of the piles to the sides of the Crossrail tunnel (adit piles) has been reduced to simulate either a reduction in the number of piles, or in their length, or diameter.

Whilst a direct comparison with the Crossrail Paddington data cannot be made, due to the difference in geometry and ground conditions, the analysis methods validated for Paddington have been used at St Giles to provide a more accurate estimate of the heave induced by the proposed St Giles Circus development. It should be noted that the input parameters and results presented in this report are fully unfactored, however, input parameters are based on characteristic values (cautious estimates of the values affecting the occurrence of the limit state). Therefore, it is expected that the analysis carries an adequate margin of safety.

The results of the St Giles Circus analysis have been compared in the following sections against the Crossrail tunnel structural lining capacity and other elements of Crossrail infrastructure.

4 Crossrail tunnel lining capacity

4.1 Introduction

The aim of this section is to review the tolerances of the Crossrail tunnel lining on the basis of the following information:

- As built information for the Crossrail eastbound tunnels;
- Knowledge of the structural design of the Crossrail tunnels.

Our intimate knowledge of the lining design, and information on as-built tunnel position, may allow demonstrating that larger than anticipated lining distortions can be tolerable without suffering undue damage.

4.2 As built information

As built tunnel centreline and ovalisation has been obtained at three locations at the west, centre and east of the St Giles Circus footprint. Figure 20 illustrates a comparison of the actual tunnel position and ovalisation against the construction tolerances.

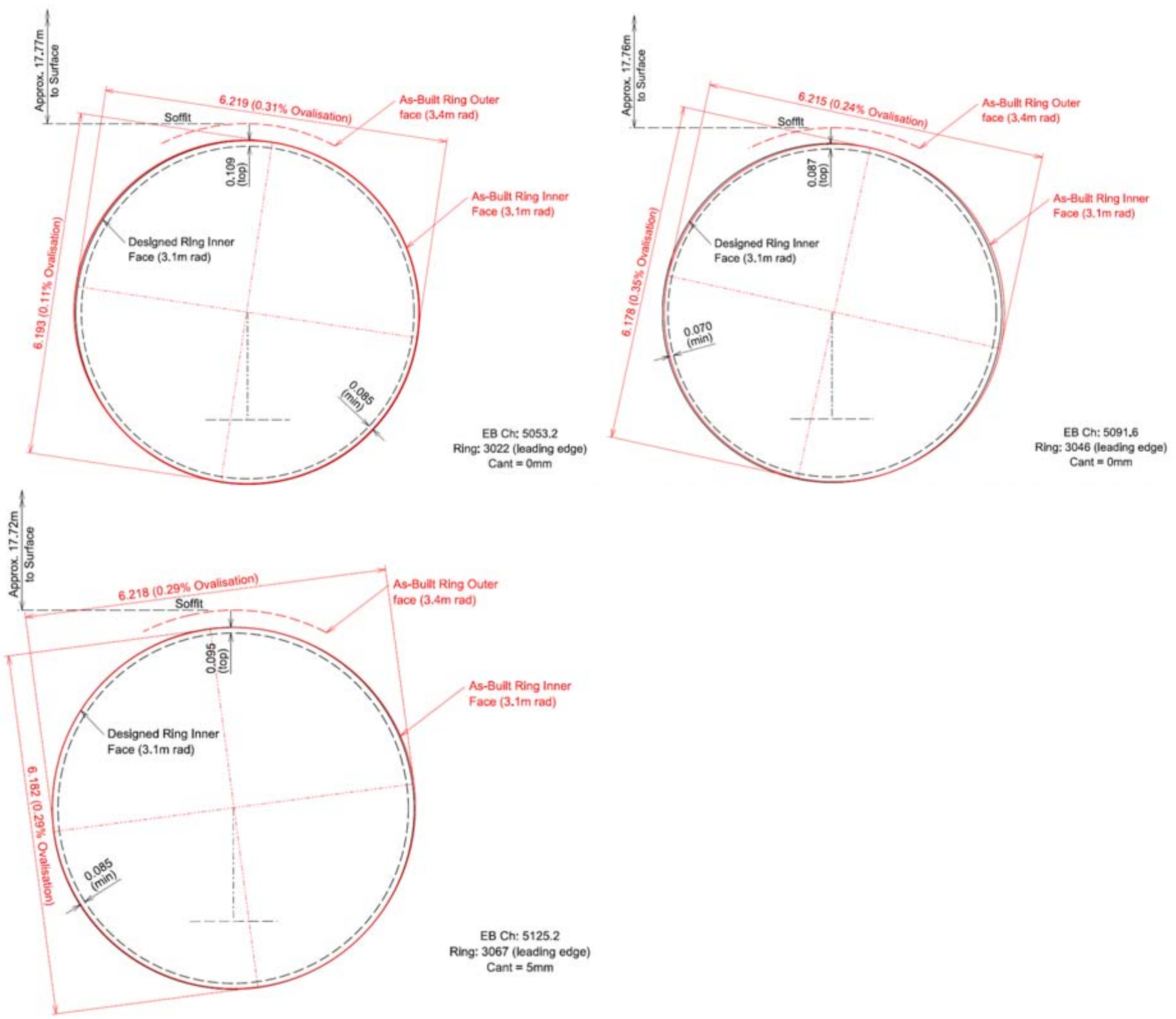


Figure 20 – As built position of the Crossrail Eastbound tunnel under the St Giles Circus footprint.

Tunnel ovalisation is well within the maximum allowable ovalisation (1%). In addition, the tunnel is ‘squatting’, meaning that the calculated ovalisation induced by the St Giles Circus works will counter the existing distortion and bring the cross-section back towards an undistorted shape.

The tunnel position is also within tolerance, resulting in a minimum of 70mm of the lining construction tolerance remaining available as additional space for the internal fit out and the kinematic envelope of the train. The values of ovalisation calculated for the St Giles Circus analysis in Section 3 are within this additional space gained through unused construction tolerance.

4.3 Structural lining capacity

A check of the capacity of the structural components of the lining has been carried out with reference to the effects of the excavation of the St Giles Circus’ basement on the segmental lining in both cross section and over the longitudinal profile.

The assessment has focused on the following aspects:

- The change in load in the segmental lining during excavation and in the long term conditions, including the effects of the imposed diametrical deformations.
- The effects of the change of level of the tunnel in longitudinal direction with reference to induced strains, possible opening of the joints and effects on the waterproofing of the tunnel.

The most onerous loading conditions of the tunnel during excavation and in the long term case have been exported from the PLAXIS model and included in Table 7. Conservatively, the minimum axial force along the ring has been associated to the highest bending moment.

	Excavation to 113.5mATD	Excavation to 109.9mATD	Long Term Conditions
Minimum Axial Force [kN/m]	534	525	781
Bending Moment [kNm/m]	62	36	57

Table 7 – Summary of loading conditions in the Crossrail tunnel (factored ULS loads).

The critical loading conditions within the lining have been plotted in the capacity curve for a 300mm lining. Conservatively, the capacity has been checked assuming a plain concrete without the benefits of the steel fibres. The graph in Figure 21 shows that all points are within the capacity of the lining.

The Crossrail tunnel has also been assessed for the effects of the change in longitudinal geometry as presented in Section 3. The induced movement produces a small change of alignment of the tunnel and the radius of direction of the segmented tunnel.

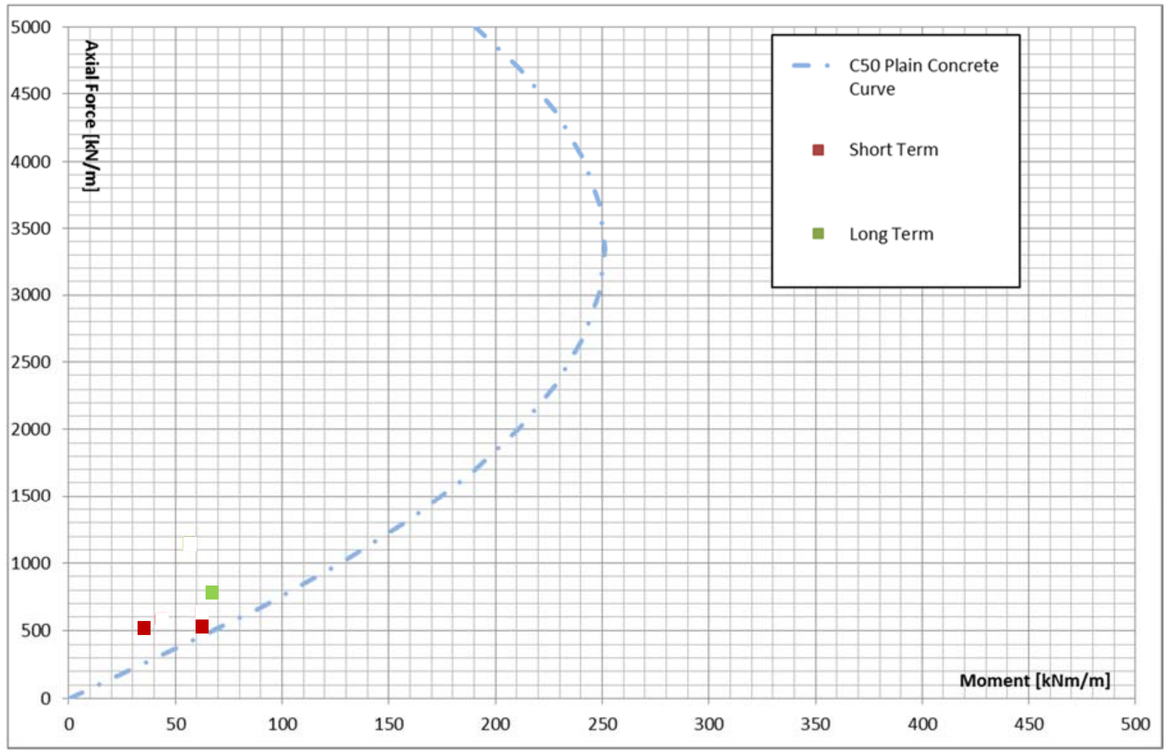
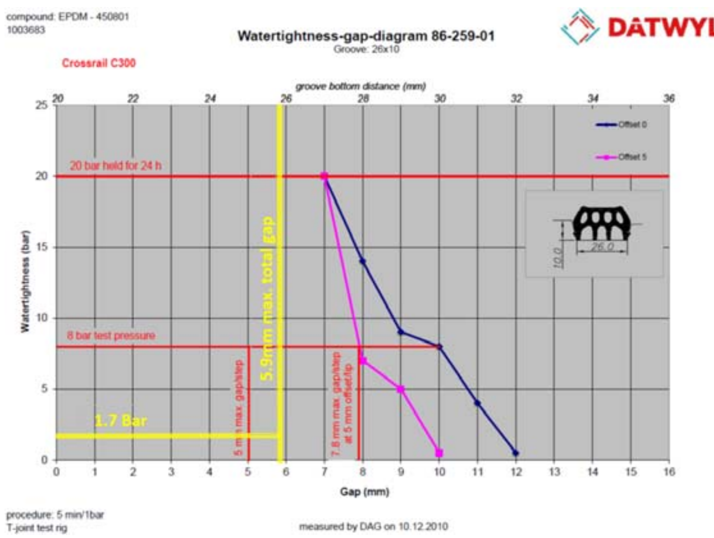


Figure 21 – Eurocode 2 capacity curve for the Crossrail segmental lining (ULS).

The extent of the joint opening has been checked against the performance requirements of the gasket system that provides waterproofing of the Crossrail segments and it has been demonstrated that the induced opening does not affect the serviceability of the gasket in the design conditions at this section of the tunnel (Figure 22).

The assessment shows that the imparted stress in longitudinal directions and the opening of the joints as imparted by such movements are within the allowable limits. In particular, the opening of the joints does not impart excessive stresses to the existing connector elements. The deformation calculated in Section 3 is assessed against the capacity of the dowels assuming either pure shear (Figure 23) or pure bending (Figure 24) mode of deformation. In both cases the results are found to be within the capacity of the dowels.



Highest tunnel axis level	104.1	mATD
Maximum GWL	121.0	mATD
Maximum water head	16.9	m
Maximum water pressure	169	kPa
Maximum water pressure	1.7	Bar
Crossrail tolerances:		
Construction gap/step	5	mm
Construction offset	5	mm
Gap + Additional opening	5.9	mm

Figure 22 – Capacity of gaskets against opening induced by the St Giles Circus basement.

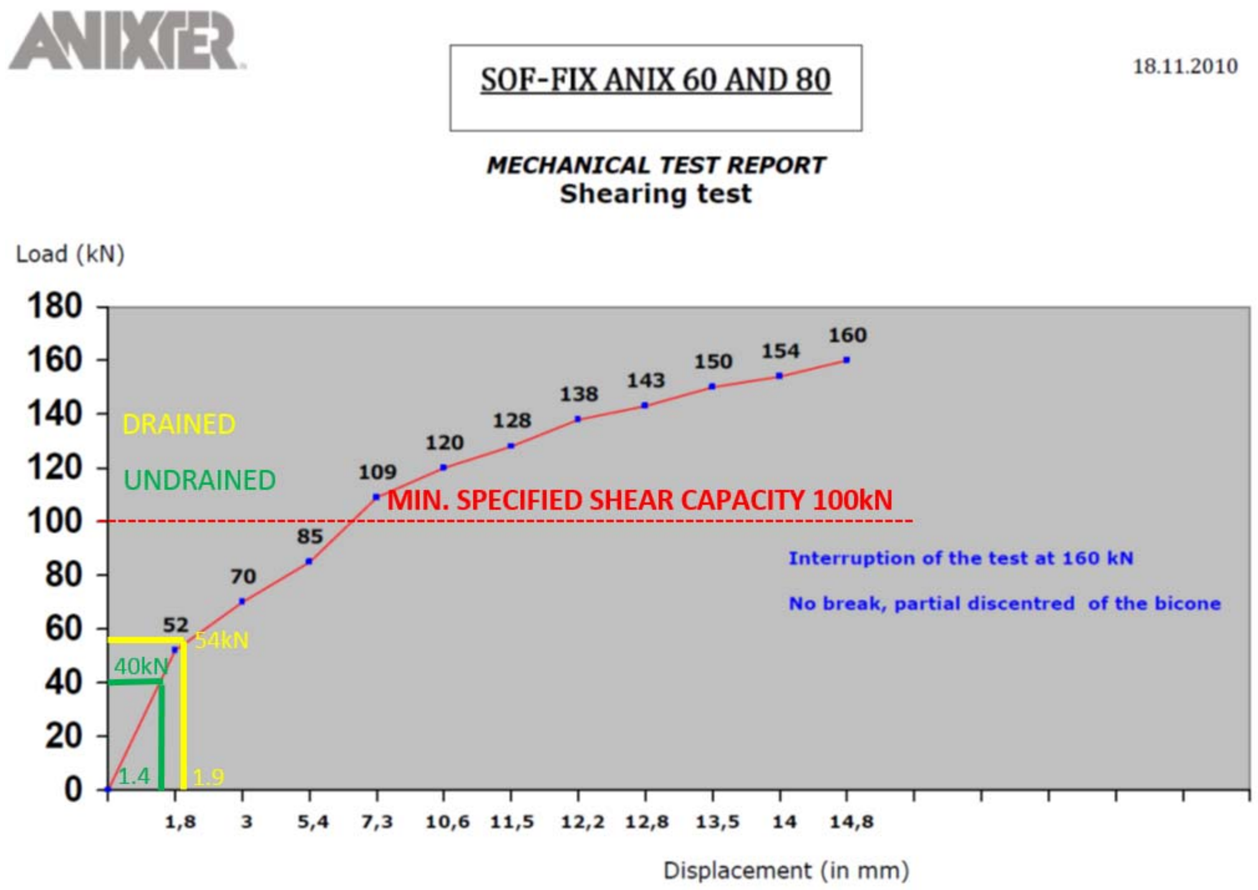


Figure 23 – Calculated shear force (ULS) against capacity of the Crossrail dowels.

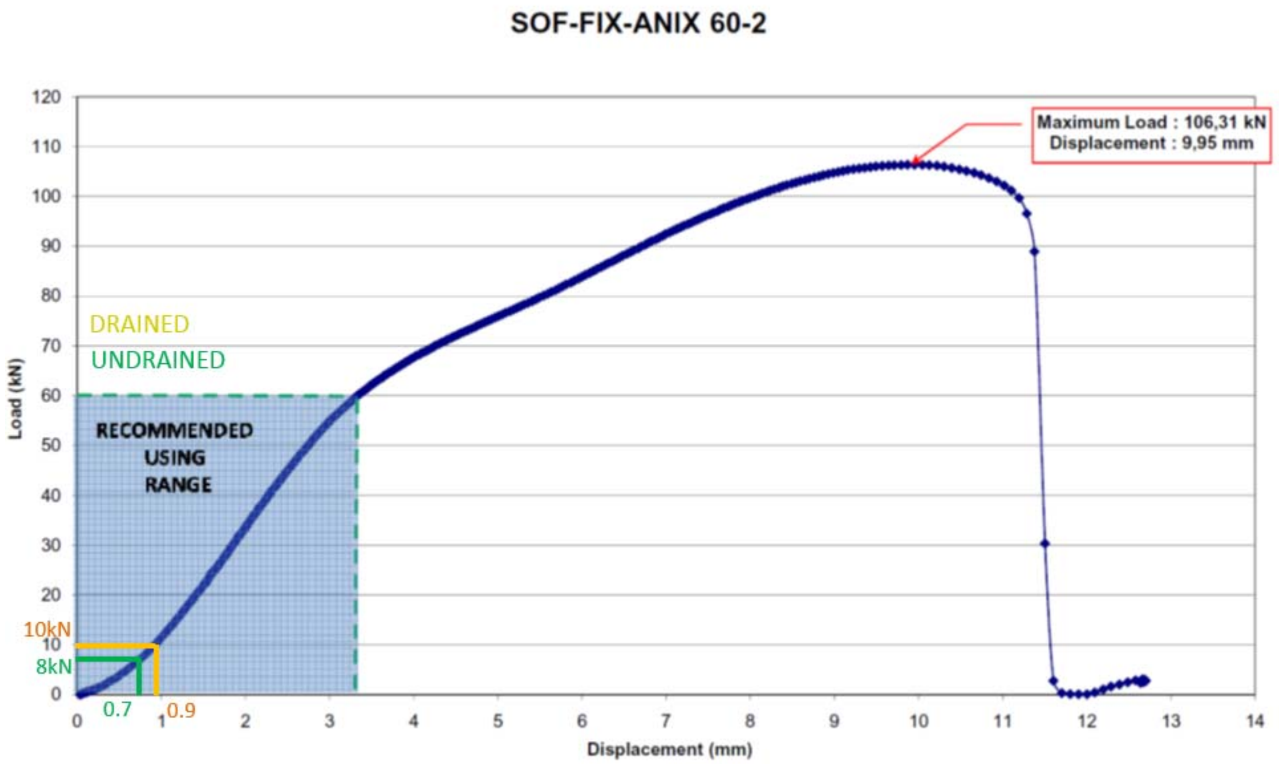


Figure 24 – Calculated tension force (ULS) against capacity of the Crossrail dowels.

4.4 Conclusions

A review of the as-built and design information for the Crossrail Eastbound tunnel has been carried out. The review has highlighted the following key points:

- The tunnel is constructed well within construction tolerances. The values of ovalisation calculated for the St Giles Circus analysis counteract the existing tunnel squatting, and are within the additional space gained through unused construction tolerance.
- The calculated structural capacity of the lining is likely to withstand heave caused by the alternative St Giles Circus basement construction analysed in this report.
- The waterproofing of the joints is not impaired by the longitudinal curvature caused by the alternative St Giles Circus basement construction analysed in this report.

As a result, it is concluded that the segmental lining and the associated details are capable to withstand the effects caused by the construction works of the St Giles Circus development.

5 Other Crossrail infrastructure

5.1 Introduction

Additional information has been sought through Crossrail with regard to what can be sensitive items of infrastructure within the tunnel, namely the floating slab track, the track alignment and the overhead line equipment. In addition to the criteria in the Developer / Third Party Interface document for 'St Giles Court' issued by Crossrail on 31/10/2011 and the Addendum to the Crossrail Safeguarding Guide: Information to Developers January 2014, location-specific technical and programme information has been obtained informally; this information should not be relied upon unless formally confirmed by Crossrail.

5.2 Programme

The programme of the St Giles Circus and Crossrail works determines which element of the Crossrail tunnels will be affected by the bulk of the heave (short term).

Enabling works for the St Giles Circus development are ongoing. Demolition and piling are planned to occur in 2016, and the critical excavation of the basement is planned for 2017 (based on information provided by Skanska, October 2015).

Informal information from Crossrail places the installation of the track slab and rails in 2016. The overhead line equipment is planned to be installed through 2017 and 2018.

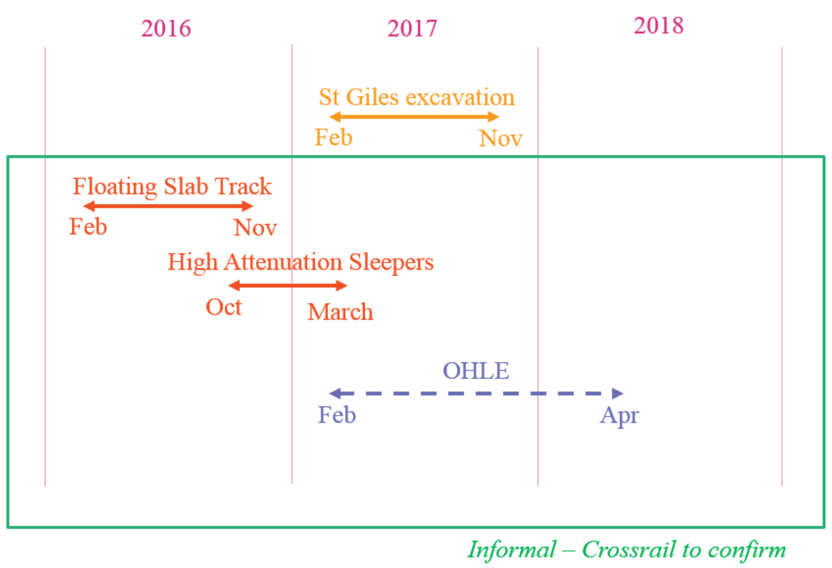


Figure 25 – Indicative programme.

5.3 Track Slab

The trackform in the Crossrail Eastbound tunnel under the St Giles Circus development consists of standard floating slab track to the west and high attenuation sleepers to the east (Figure 26 and Figure 27).

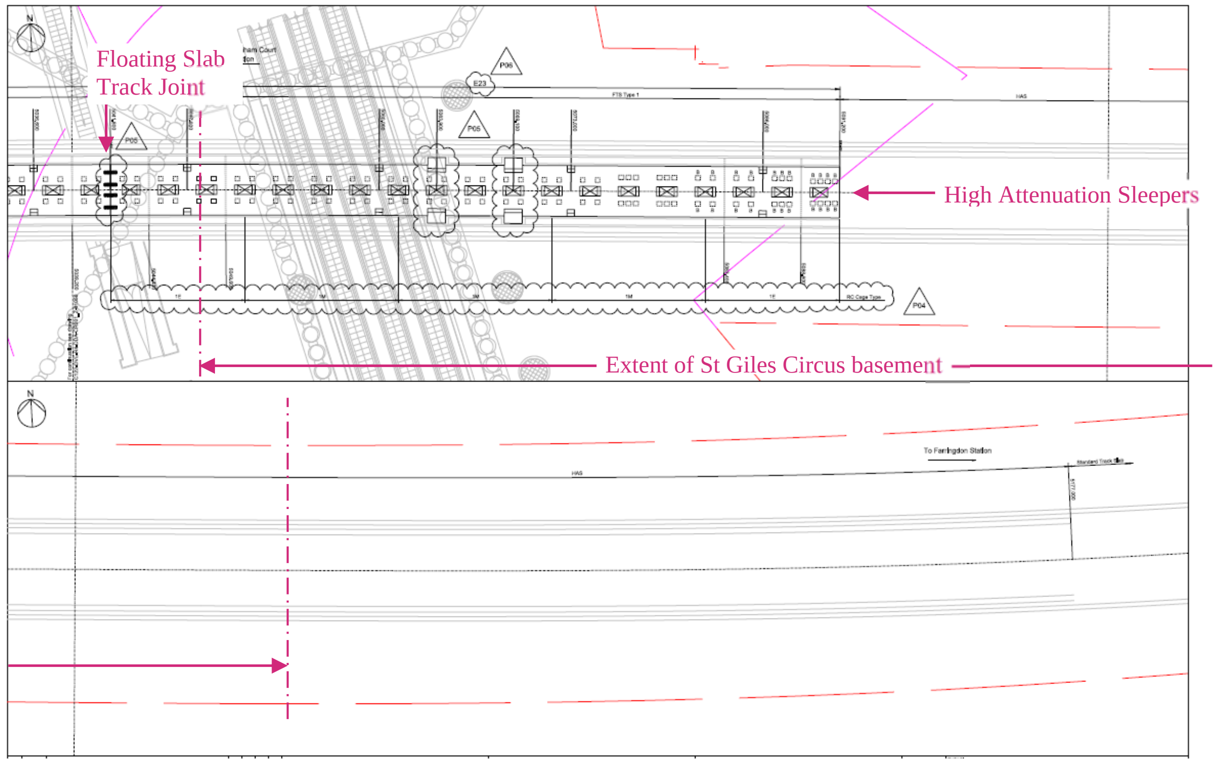


Figure 26 – Trackform layout under St Giles Circus development, extract from C122-OVE-R4-DDA-CR001_Z-81059 rev C05.

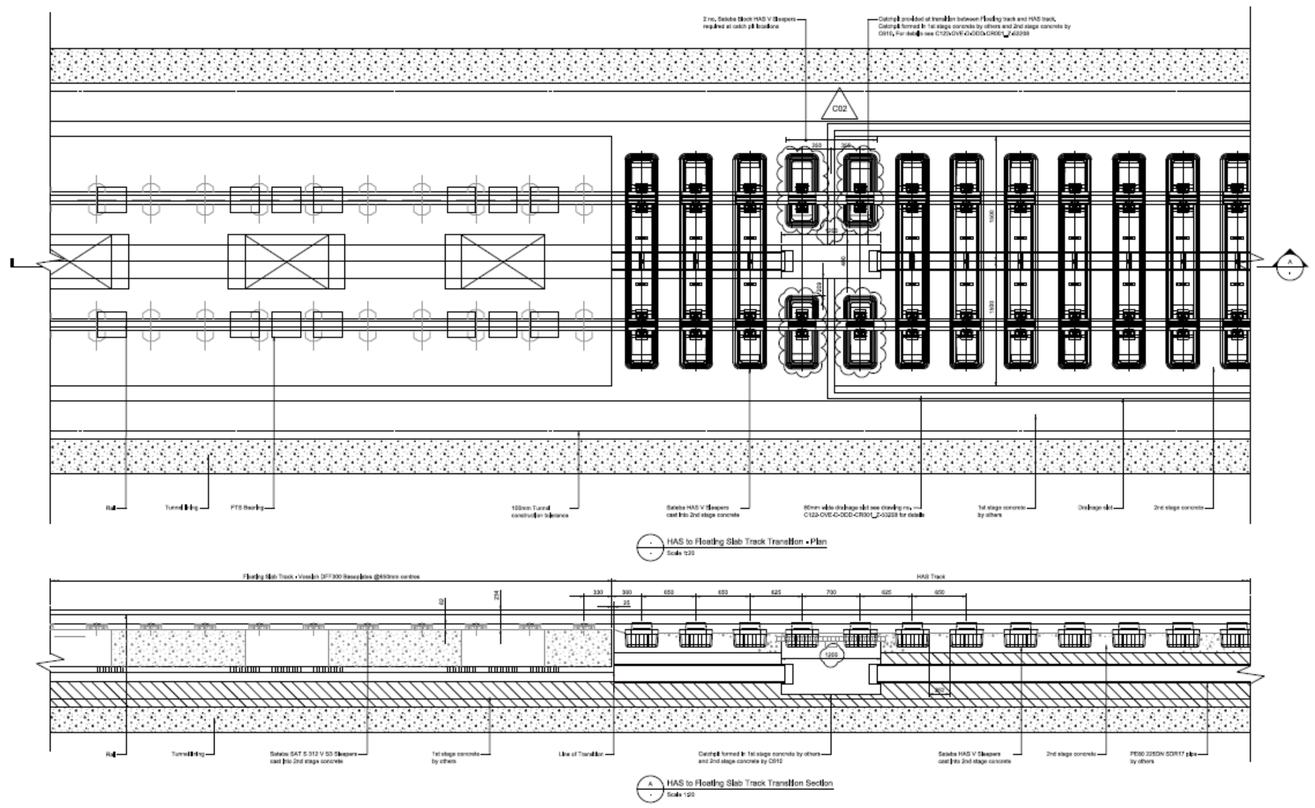


Figure 27 – Plan and section of Floating slab track and high attenuation sleepers, extract from C122-OVE-R4-DDA-CR001_Z-82209 rev C02).

The standard floating track slab consists of a 400mm thick reinforced concrete slab supported on elastomeric bearings. The slab is continuous for approximately 50m in length, with a joint located immediately to the west of St Giles Circus. The effects of the curvature imposed by the St Giles development (a minimum of 21.2km at invert level) is less than the normal operational deflections of the standard floating track slab, and it is therefore considered to have no detrimental impact on the Crossrail operations. This conclusion is based on a study carried out by Crossrail (ref. C122-OVE-R4-ASM-CRG01-50001 Rev.1) on acceptable movement limits for track slab structures along the Crossrail route.

The structural support of the section with High Attenuation Sleepers consists of mass concrete. It is therefore not particularly sensitive to ground movements, which may be relieved by local cracking.

5.4 Track

The design alignment of the track is illustrated in Figure 28, and is based on Crossrail drawings C122-OVE-R4-DDA-CR001_Z-11117 and 11118 rev. C03. It is assumed that the as-built position of the tunnel does not affect the design alignment.

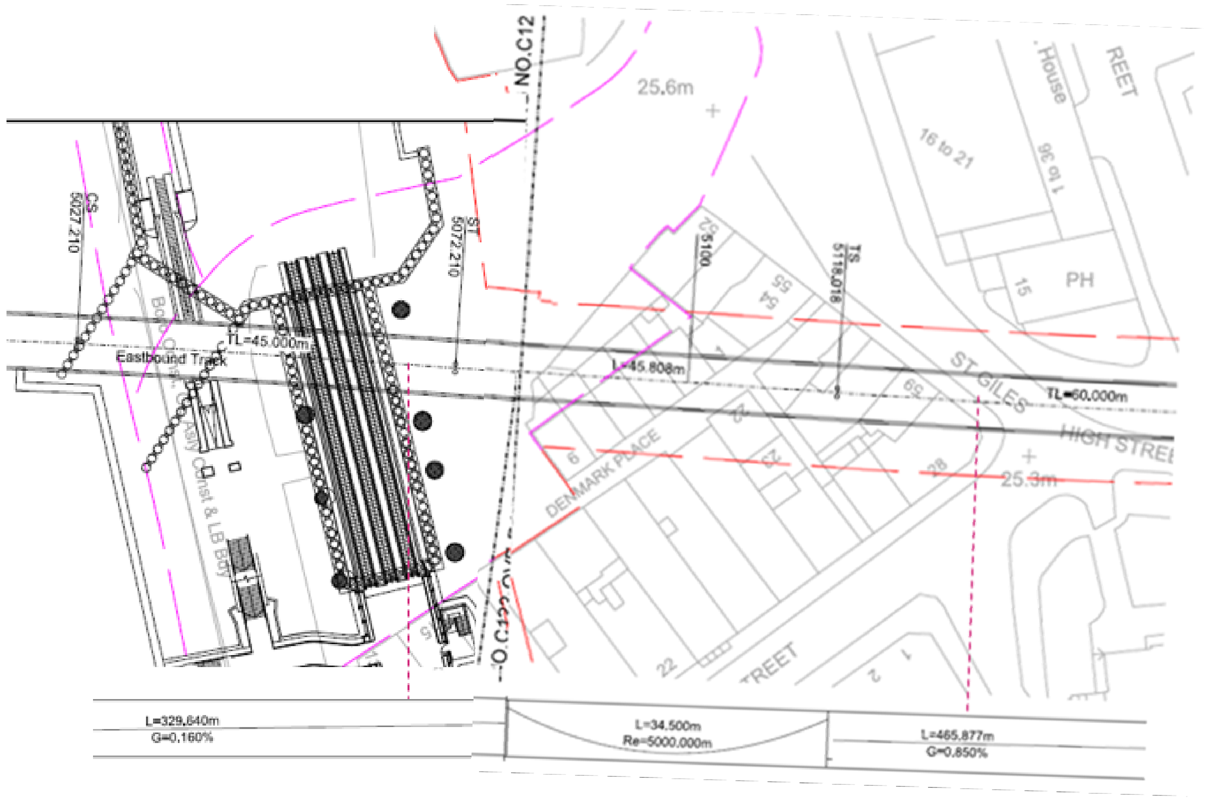


Figure 28 – Design track alignment.

The calculated heave along the invert of the tunnel (Section 3.6) is superimposed to the design alignment. Figure 29 and Figure 30 show the short and long term position of the track with the additional heave calculated for the St Giles Circus basement alternative proposal analysed in Section 3. The as-built tunnel position is also shown on the same Figures. The tunnel has been constructed within the required tolerances, therefore it is not anticipated that any changes in design alignment will be required and minor asperities in the profile will be smoothed out at the time the first stage concrete is cast.

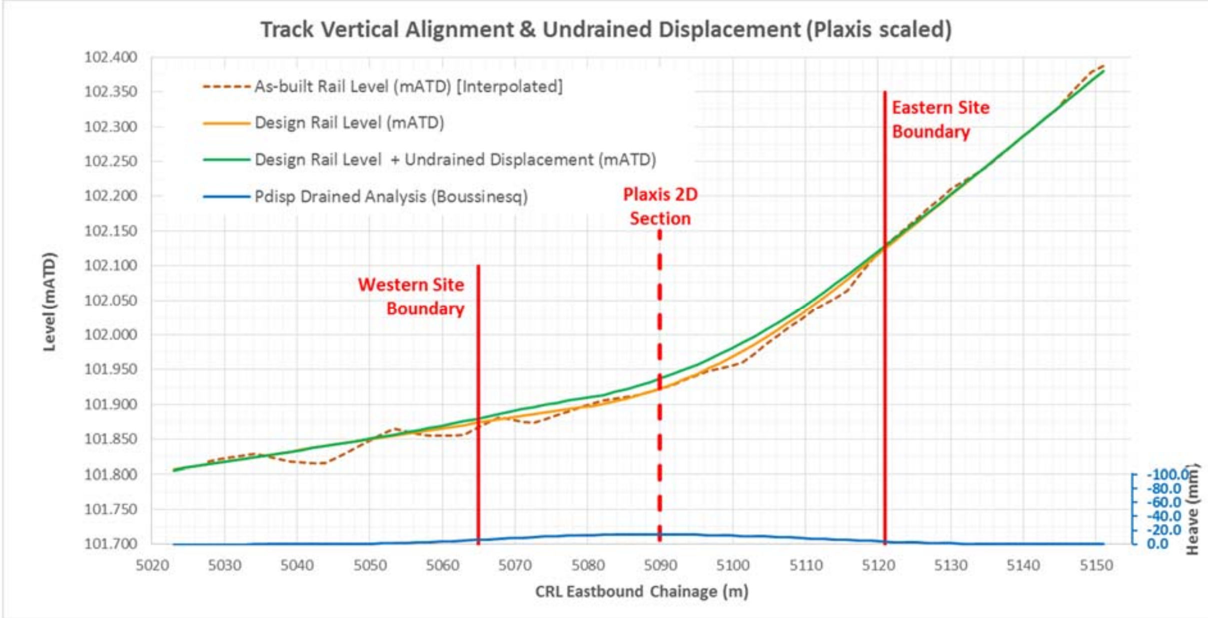


Figure 29 – Short term heave at track level.

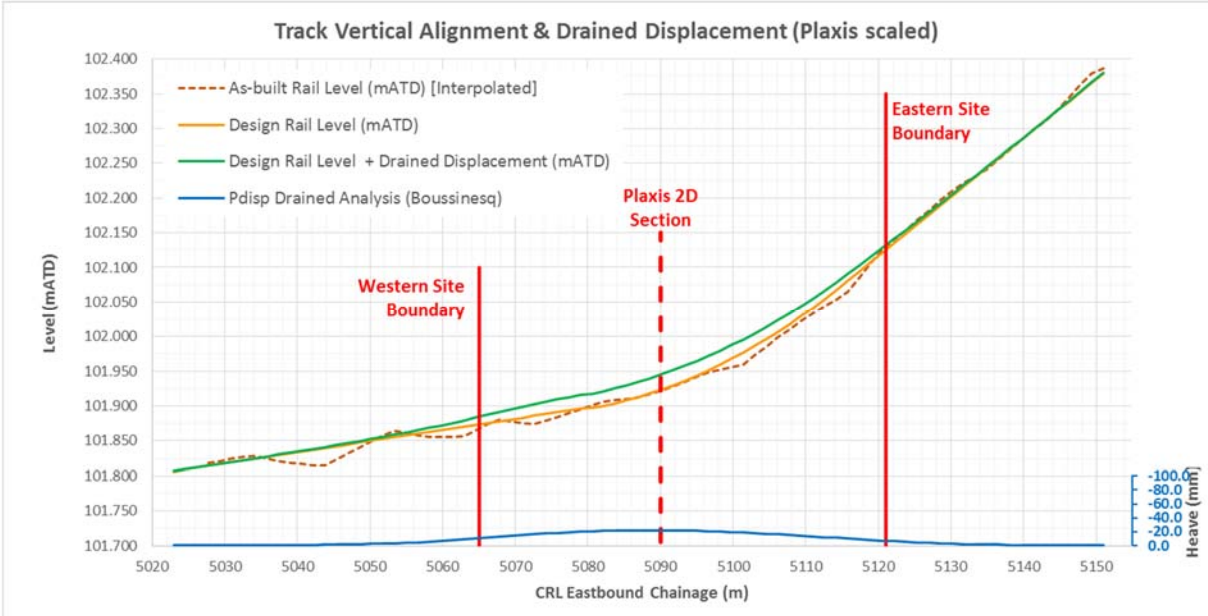


Figure 30 – Long term heave at track level.

The calculated maximum heave of the track alignment ranges from 14mm to 22mm in the short and long term respectively. The maximum radius of curvature of the track alignment is unaffected or reduced in absolute terms from the design value of 5km. However, the heave generated by the St Giles Circus excavation generates a change of gradient in the alignment.

Crossrail requests developers to comply with the Network Rail ‘no mandated action’ track maintenance threshold. For a track speed of 70kph in this area, the vertical alignment threshold is 20mm (the latest applicable standard reference is NR/L2/TRK/001/mod11 issue 8). Whilst the maximum calculated long term heave marginally exceeds this criteria by 2mm, the absolute vertical movement is on its own of no consequence to the track. What will affect the performance of the track is the imposed radius of curvature. The maximum alignment curvature is not worsened at this location, and the greenfield curvature imposed by the St Giles Court development is greater than 20km. In addition, the maximum calculated long term heave may be refined at a later stage (by refining the analysis or by determining the exact number and length of adit piles) in order to achieve no more than 20mm calculated maximum heave.

In order to mitigate the potential effects of track movements, consideration could be given to the proposed construction setting out the track, which could absorb part of the calculated heave movement, and the introduction adjustable rail fixings that could be used to return the track to its current design alignment after the St Giles Circus basement excavation has occurred.

5.5 Overhead line equipment

It is assumed that the overhead line equipment consists of rigid overhead conductors fixed to guide beams, in turn supported by drop tubes attached to the tunnel lining.

Crossrail have advised Engenuiti (minutes of Engenuiti / Crossrail meeting on 31st October 2011) that the nominal tolerance of the overhead line equipment to movement is -0/+10mm (positive for upward movement). The reason for the limited tolerance to upward movement is not fully understood. This tolerance should be clarified by Crossrail as it appears to be tighter than standard tolerances for overhead line equipment.

The total ovalisation for the revised St Giles Circus analysis will result in relative movement between the overhead line equipment and the track of 14mm. Should the overhead line equipment be installed after the excavation of the basement, the net ovalisation is calculated to be 4mm, which is well within the 10mm criterion set by Crossrail. Should the overhead line equipment be installed before the excavation of the St Giles basement, the 10mm criterion will be exceeded by 4mm. In this case, the justification for the 10mm criterion should be fully investigated, as preliminary considerations would suggest that it is overly restrictive.

5.6 Conclusions

A review of in-tunnel infrastructure potentially sensitive to ground movement has been carried out. The review has highlighted the following key points:

- The track slab will not be unduly affected by the revised sequence proposed for the St Giles Circus basement excavation works.
- The track will heave following the invert movements (14mm and 22mm vertical movement, 28.6km and 21.2km of curvature for short and long term respectively). The criterion indicated by Crossrail is the ‘no maintenance threshold’ in the Network Rail track standards, which is 20mm vertical movement in this area. Whilst the maximum calculated long term heave marginally exceeds this criteria by 2mm, the absolute vertical movement is, on its own, of no consequence to the track. What will affect the performance of the track is the imposed radius of curvature. The maximum alignment curvature is not worsened at this location, and the greenfield curvature imposed by the St Giles Court development is greater than 20km. Should it be considered that heave movement exceed the design tolerances, this could be mitigated by revising the design alignment or intervening on the track. In the latter case, it should be ensured that track fastenings with suitable adjustment availability are installed.
- The overhead line equipment should be capable of adjustment beyond the 10mm originally suggested by Crossrail. If the conduction rail is installed after the excavation of the St Giles Circus basement, the short term movements will be avoided altogether, and the criterion complied with. Programme and actual tolerances should be confirmed by Crossrail.

The information used in this review should be formally confirmed by Crossrail.

6 Conclusions and recommendations

The purpose of this report is to assess the feasibility of an alternative construction sequence for the St Giles Circus basement, and the implications of reducing the number or size of heave-restraining elements. A fully assured design will be required in order to implement the alternative solution examined in this report.

To give confidence in the modelling methods and to review the actual impact of the excavation above the Crossrail tunnels, the case of Paddington Station, where the station box was excavated above the Crossrail tunnels, has been analysed. There is good agreement between the 2d FE model analysed as part of this study and the tunnel monitoring data collected during the excavation of Crossrail Paddington Station. Therefore, the modelling method which is used for the purpose of this feasibility study for the analysis of the St Giles Circus basement can be considered validated. In addition, a set of case history data has been presented illustrating a construction sequence which will be similar to the proposed St Giles Circus basement excavation, and in similar ground conditions. In the case of Crossrail Paddington Station, excavation proceeded to the crown of the tunnels whilst the tunnels remained fully operational (for the purpose of the Tunnel Boring Machine operations) and behaved in accordance with calculations.

Subsequently, the St Giles Circus basement excavation has been modelled using the same analysis methods adopted for Paddington. Simple analytical methods have also been adopted to extrapolate 2d results to the third dimension. The results of the analysis are summarised in Table 8, in terms of maximum vertical movement at the crown and invert of the tunnels and maximum ovalisation, and in Table 9, in terms of calculated longitudinal radii of curvature.

ST: short term LT: long term	Revised sequence, ground slab, reduced adit piles stiffness	
	ST	LT
Max movement (invert)	14	22
Max movement (crown)	24	36
Ovalisation	10	14

Table 8 – Summary of St Giles Circus alternative basement vertical movement (all in mm).

ST: short term LT: long term	Revised sequence, ground slab, reduced adit piles stiffness	
	ST	LT
Max curvature (invert)	28.6	21.2
Max curvature (crown)	7.2	6.5

Table 9 – Summary of St Giles Circus alternative basement radii of curvature (all results in km).

A review of the as-built and design information for the Crossrail Eastbound tunnel has been carried out. The review has highlighted the following key points:

- The tunnel is constructed within construction tolerances. The values of ovalisation calculated for the St Giles Circus analysis counteract the existing tunnel squatting, and are within the additional space gained through unused construction tolerance.
- The calculated structural capacity of the lining is likely to withstand heave caused by the alternative St Giles Circus basement construction analysed in this report.
- The waterproofing of the joints is not impaired by the longitudinal curvature caused by the alternative St Giles Circus basement construction analysed in this report.

As a result, it is concluded that the segmental lining and the associated details are capable to withstand the effects caused by the construction works of the St Giles Circus development.

In addition, we have reviewed a number of internal tunnel systems which can be susceptible to ground movements (track slab, track alignment, overhead line equipment) and considered the potential impact of the calculated movements. The review has highlighted the following:

- The track slab structure will not be unduly affected by the St Giles Circus basement excavation works analysed in Section 3.
- The track will heave following the invert movements (14mm and 22mm vertical movement, 28.6km and 21.2km of curvature for short and long term respectively). The criterion indicated by Crossrail is the ‘no maintenance threshold’ in the Network Rail track standards (20mm vertical movement). Whilst the maximum calculated long term heave marginally exceeds this criterion by 2mm, it is the imposed radius of curvature and not the vertical displacement which will affect the performance of the track. The design alignment curvature (5km) is not worsened at this location, and the greenfield curvature imposed by the St Giles Court development is greater than 20km.

  In addition, the maximum calculated long term heave may be refined at a later stage (by refining the analysis or by determining the exact number and length of adit piles) in order to achieve no more than 20mm calculated maximum heave.

  Finally, it would be advisable to consider active mitigation of track heave by revising the design alignment or intervening on the track. In the latter case, it should be ensured that track fastenings with suitable adjustment availability are installed. These mitigation measures would have the advantage to remove the risk to the track in any scenario under consideration.
- The overhead line should be installed after the excavation of the St Giles Circus basement. In this case, the short term movements will be avoided altogether, and the 10mm criterion will be complied with for the long term movement. In any case, it is likely that the 10mm criterion currently set by Crossrail is overly restrictive for this area of tunnel.

  Installation programme and actual tolerances of the overhead line equipment should be confirmed by Crossrail.

The alternative construction sequence for the St Giles Circus basement illustrated in this report presents obvious advantages in terms of health and safety and programme risk reduction against the originally proposed partial basement and tunnelled adit beams sequence. By doing away with the tunnelled adit beams, the alternative presented in this report also provides a more standard basement construction solution, which is more amenable to calculation and validation (as shown through the Paddington case study) and therefore inherently posing a lower risk to the Crossrail infrastructure.

Provided that the sensitivity of in-tunnel infrastructure is confirmed, the alternative construction sequence and foundations arrangement analysed in this report appear feasible and will be withstood by the Crossrail tunnel lining without undue effects.

A programme of in-tunnel monitoring, as well as a commitment to make good of any occurrence of damage during the basement construction works, is expected to be required by Crossrail for any construction sequence under consideration.