JACOBS
IDOM

Technical Note

Project:	METROLINK– DUBLIN METRO
Doc No:	ML1-JAI-GEO-ROUT_XX-RP-Y-00036
Subject:	Preliminary Phase-3 – Ground Movement Induced Damage Assessment - Arthur Cox Building (B238)
Revision No.	P01.1
Prepared by:	Alberto Arizmendi	**Date:**
Checked by:	Arirajasingham Maheetharan	**Date:**
Reviewed by:	John Kinnear	**Date:**
Approved by:		**Date:**

1. Background and Purpose

The industry standard three-phased ground-movement-induced building damage assessment process is being applied for the Dublin MetroLink Project. As part of the Preliminary Design, the Phase-1 and Phase-2a (initial stage of Phase-2) assessments have now been completed. The details of the assessment process and the findings are reported in the Damage Assessment Report of Buildings and Other Assets [Ref. 1]. The Phase-1 and Phase-2 assessments are based on empirical methods, case history data and on conservative design assumptions. The appointed D&B Contractor will subsequently review and refine the Phase-2a assessment which will then form the Phase-2b (final stage of Phase-2) assessment. The buildings which show Damage Category-3 (DC-3) or above will be subject to a Phase-3 assessment. The Phase-3 assessment is building-specific and will utilise the detailed site-specific ground information and the proposed method of construction. This will therefore be carried out at the detailed design stage by the D&B Contractor. Phase-3 assessment will generally show improvement on the Phase-2 assessment results as detailed building-specific data being utilised for the assessment; i.e. resulting in reduction of the assessed Damage Category. At the end of the Phase-3 assessment, if the Damage Category is still unacceptable (DC-3 or above), appropriate mitigation measures would be required to those buildings. Although the above process is strictly applicable for masonry buildings on shallow foundations, for the initial assessment phases (Phases 1 & 2), the same process is adopted for concrete framed structures as well.

Arthur Cox Building is located in Dublin 2 (site also known as 10 Earlsfort Terrace and shown in Photo A and Photo B below) between chainages 18+920 and 18+980. It is a concrete framed structure with large-glazed windows and with two-level basement. The standard Phase-2a assessment results show Damage Category-2 (Slight) for this building. Despite, due to the form of construction of the building and the presence of the deep basement, it has been qualified for a Phase-3 detailed assessment to be carried at the detailed design stage.

A preliminary Phase-3 assessment has been undertaken at this stage and reported in this Technical Note following the concerns raised by the Building Owner (Ref. 5) during the Railway Order process. The primary purpose of this assessment is to demonstrate that the level of anticipated damage at the end of the final Phase-3 assessment to be carried out by the D&B Contractor would be within the acceptable limits.

2. Details and features of Arthur Cox Building

Two images of Arthur Cox Building are shown in Photo-1 and Photo-2. It is a 7-storey modern glass clad building with 8.6m deep two-level basement. The watertight basement heavily relies on the structural integrity of the concrete to prevent groundwater ingress. The glass façade and part of the columns are supported on a perimeter secant pile wall around the basement raft slab.

This class of foundation system makes this building more resilient to withstand the construction induced ground movements compared to a conventional concrete-framed structures. In particular, the basement raft slab is very effective in restraining the lateral ground movements applied to the building. Further, the raft slab is also effective in smoothing out the greenfield differential settlement imposed on the building. The presence of load bearing secant pile walls along the lines of the glazing facades further dampen the greenfield differential settlement applied to the facades.

Due to the above features, the damage assessment has been carried out using both the methods developed for Masonry Buildings and the method described in CIRIA C796 for framed buildings.

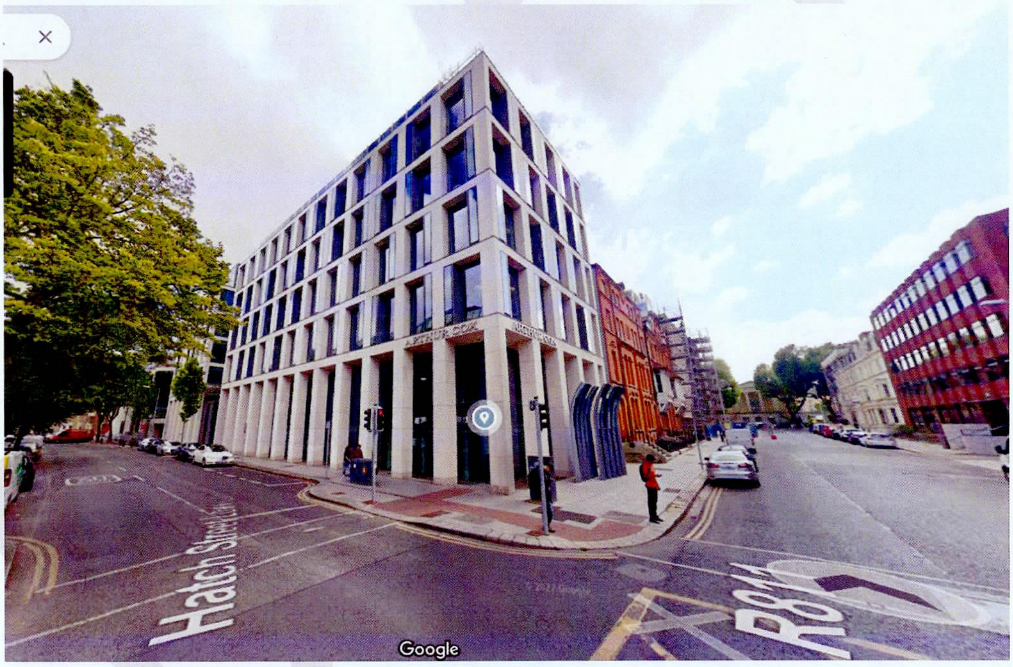

Image A: Arthur Cox Building (Earlsfort Terrace with Hatch Street Lower)

Image B: Arthur Cox Building (Hatch Pl with Hatch Street Lower)

3. Methodology of Phase-3 Assessment

The Arthur Cox building (B-238) lies entirely within the tunnelling zone (i.e. away from the proposed station boxes and other excavations). The Phase-2a assessment for the buildings has been based on a semi-empirical method and assumes that the shape of the settlement trough above a single tunnel follows a Gaussian (bell-shaped) distribution, and the volume of the settlement trough is assumed to be equal to the total volume of lost ground during tunnelling. The method is based on the previous experience in TBM tunnelling and requires only empirical parameters.

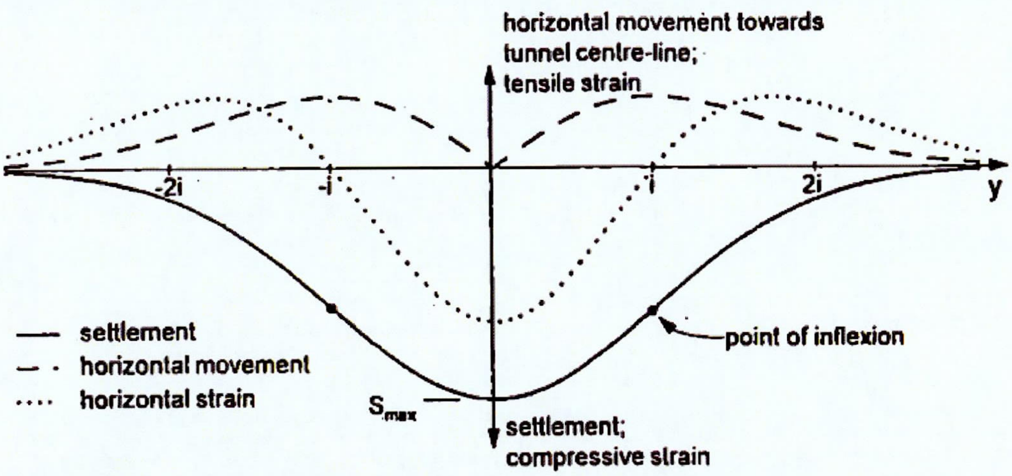

Figure 1: Transverse settlement trough due to tunnelling (After Mair, Taylor & Burland, 1996)

The green-field settlement trough immediately after a tunnel has been constructed is well described by a Gaussian distribution curve (See Figure 1) as

$$S_V = S_{max} \exp\left(\frac{-y^2}{2i^2}\right) \quad [1]$$

$$i = Kz_0 \quad [2]$$

where	Sv	is settlement;
	Smax	is the maximum settlement on the tunnel centre line;
	y	is the horizontal distance from the centre line;
	i	is the horizontal distance from the tunnel centre line to the point of inflexion on the settlement trough;
	K	is the trough width parameter depending on the ground type; i.e. clay or sand;
	zo	is the depth of tunnel axis below ground level.

and the volume of the settlement trough per metre length of tunnel (Vs) is evaluated as

$$V_s = \sqrt{2\pi}\, i\, S_{max} \quad [3]$$

Volume loss V_l is usually expressed as a percentage of the volume of the tunnel and will vary depending on the strata and is related to V_s by the following equation:

$$V_l = V_s / \frac{\pi D^2}{4} \quad [4]$$

where D is the tunnel diameter.

In this approach, the trough width parameter 'K' and the volume loss parameter $\mathbf{V_l}$ have to be selected based on the ground conditions. At this particular location, the tunnel is fully within the rock but the rock cover (above the crown level) is less than half the tunnel dimeter; the ground above the rock cover consists of superficial materials. For the Phase 2a assessment, the 'K' and 'V_l' values have been selected conservatively based on that used for the superficial deposits (ignoring the rock cover); i.e. 'K' has been taken as 0.4 and 'V_l' as 1%. The resulting settlement trough has been used to the assess of the Damage Category using the method proposed by Burland (1995) [Ref. 2] which gave DC-2 for the Arthur Cox building (B-238).

For the preliminary Phase-3 assessment carried out and reported in this TN, a detailed PLAXIS-3D finite element analysis has been undertaken to assess the greenfield settlement trough at building's raft slab level and at the toe level of the secant pile wall due to the tunnelling works. In the PLAXIS-3D analysis, the site-specific ground conditions (including the rock strata) and the detailed method of tunnel construction have been modelled in order to predict the settlement trough more accurately. The PLAXIS analysis does not require any input assumption regarding the trough width parameter 'K' nor the volume loss parameter 'V_l'. For the settlement trough obtained from the PLAXIS analysis, the value of equivalent volume loss V_l and the trough width parameter 'K' have been derived adopting the industry recognised Gaussian distribution curve.

As mentioned earlier in the report, due to the structural arrangement and form of construction, the Phase-3 Damage Category assessment for this building will be carried out following two approaches:

- Method A: using the method developed for Masonry Buildings [Ref. 2]
- Method B: using the method described in CIRIA C796 for framed buildings [Ref. 6]

In both cases, the greenfield ground movements for the damage assessment have been obtained from the equivalent volume loss and trough width parameter derived from the PLAXIS-3D analysis.

4. Basis of Phase-3 Assessment

4.1 Ground Model

The ground stratigraphy at the location of the Arthur Cox building is shown in Figure 2a together with the proposed tunnel position. The figure shows that the proposed tunnel will be entirely in the rock strata and the superficial material up to 15m overlies the Limestone rock strata. The superficial material consists of 1.5-3m of Made Ground, 1.5-8m of Brown Boulder Clay and 4-5m of Base of Drifts deposits. Groundwater is taken at around 3m below ground level.

The idealised ground model used for assessment in the PLAXIS analysis is shown in Figure 2b. In this assessment, conservatively, the maximum depth of superficial material has been modelled considering the variation of the rockhead level; i.e. rock cover has been taken as 2.5m.

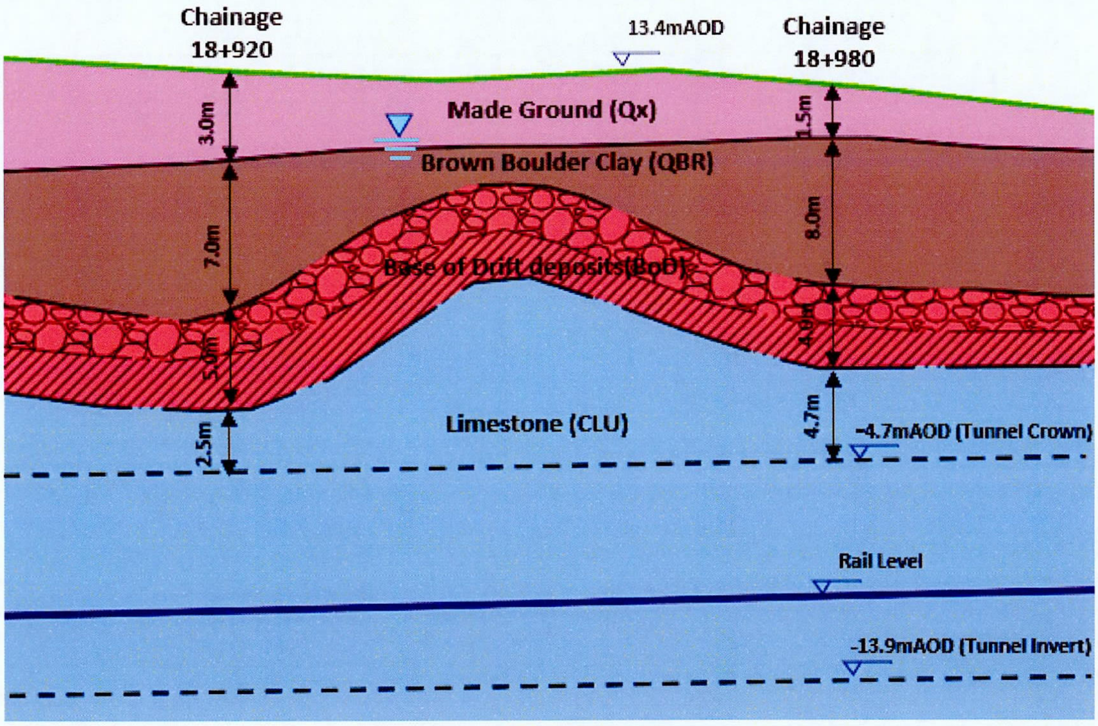

Figure 2a: Ground Stratification

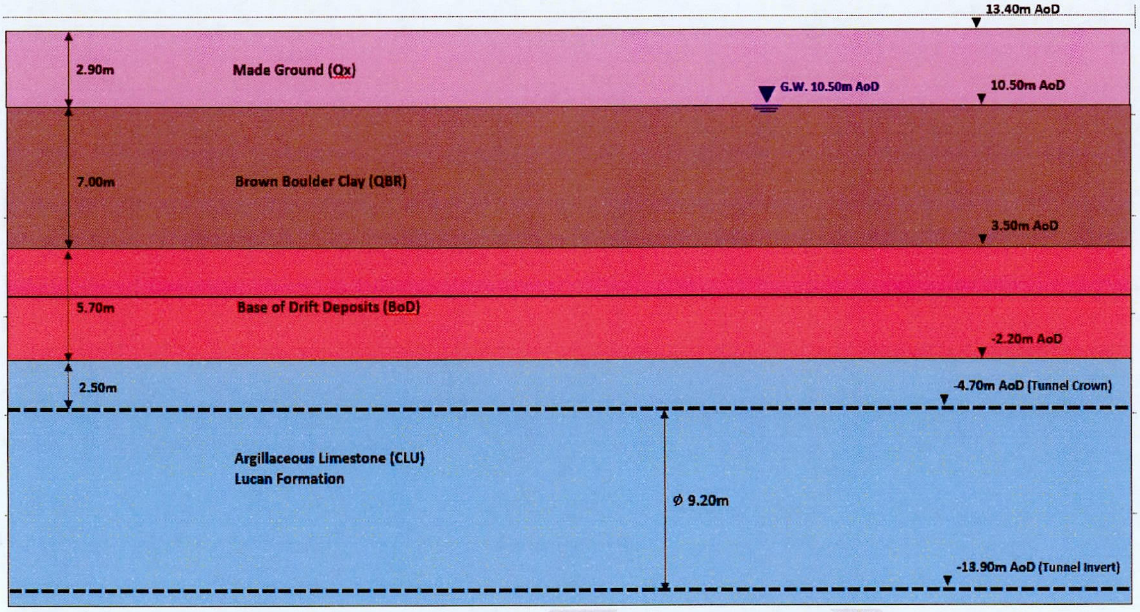

Figure 2b: Idealised Ground Model for PLAXIS Modelling

4.2 Ground Parameters

The ground parameters for various layers have been derived using the information available in the GIR [Ref. 3] and tabulated in Table 1. For the Made Ground and the rock strata, elasto-plastic soil model with Mohr-Coulomb failure criteria has been adopted. For the Brown Boulder Clay and the Base of Drifts strata, 'hardening-soil' model available in PLAXIS has been utilised. Hardening-soil model has the ability to model the stress dependency of ground stiffness and is therefore considerate appropriate for the region near the tunnel excavation. Further, it can model the unloading/reloading behaviour with increased stiffness, so it is an appropriate model to represent the behaviour of the ground due to excavation and/or tunnelling works.

Table 1: Ground Parameters

Strata	Description	Unit Weight (KN/m^3)	c' (kPa)	φ' (°)	E' (MPa)	ν (-)	Hardening-Soil Model Parameters (HS)				K_0
							E_{50}^{ref} (MPa)	E_{ur}^{ref} (MPa)	m (-)	p_{ref} (kPa)	
Made Ground (Qx)	Heterogeneous materials (sand, gravel, clay, cobbles and boulders)	20.0	0	28	6	0.2	-	-	-	-	0.53
Brown Boulder Clay (QBr)	Stiff to very stiff sandy Clay	22.5	10	30	-	0.2	35	105	0.9	100	1.5
Base of Drift Deposits (BoD)	Soft to firm gravelly Clay interbedded with loose to dense Sand	22.0	0	35	-	0.2	35	105	0.9	100	1.5
Limestone (CLU)	Fined grained Limestone with interbedded calcareous Shale	26.0	25	40	1600	0.3	-	-	-	-	1.0

Notes:
E_{50}^{ref} is the secant stiffness modulus for a reference confining pressure (p_{ref}).

4.3 Tunnel Geometry and Construction Parameters

The tunnel alignment consists of a single bi-directional tunnel constructed by means of a tunnel boring machine (TBM) which will be driven in a manner that provides maximum control of the resulting settlements. The tunnel has been designed with an internal diameter of 8.5m, determined by the rolling stock kinematic clearance, and railway services requirement. From a review of the geological and geotechnical properties of the ground along the tunnel alignment, project constraints, and TBM operational procedures, it is likely a Variable Density TBM or Mix shield machine will be selected as the most suitable TBM for this Project. The main characteristics of the TBM required to meet the tunnel requirements are listed below:

- Diameter of the cutter head: 9.53m
- Diametrical gap (outer diameter of excavation): 0.33m

The main characteristics of the segments are:

- Typology: Universal ring
- Thickness: 350 mm
- Concrete class: C40/50
- Reinforcement: Steel bars class C + steel fibres

4.4 Tunnel Construction Details

The following key features have been considered in the tunnel construction sequence adopted in the PLAXIS model (See Figure 3):

- the length of the front shield is 14m; this represents the maximum unlined length of the tunnel during the tunnelling works;
- the slurry pressure at the cutting head and the shield zone is maintained at the hydrostatic pressure at that level (see details below);
- the tunnel is advanced in stages and the lining installed behind the shield and back grouted; this procedure is repeated until the full development of the settlement trough at the ground level.

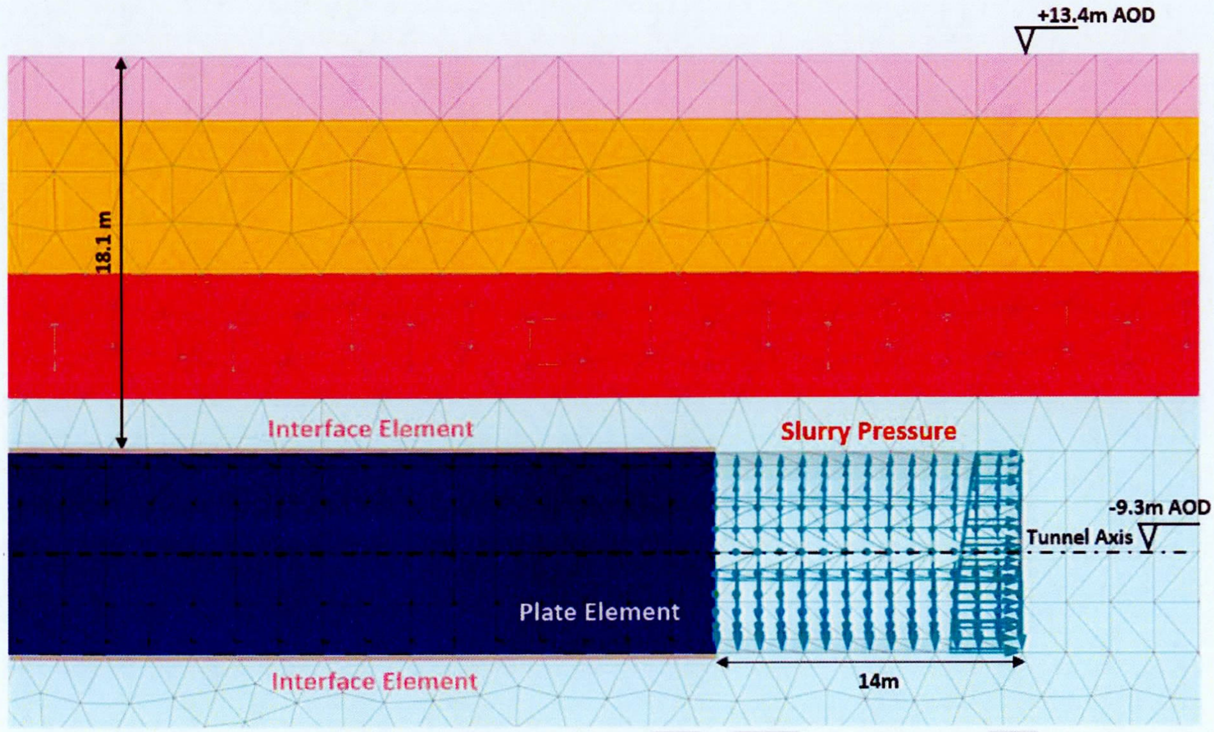

Figure 3: PLAXIS Model used for the Assessment

5. PLAXIS Modelling

5.1 General

PLAXIS3D is a 3D finite element program capable of modelling the ground and geotechnical construction including the tunnelling works. Considering the line of vertical plane symmetry, only half the tunnel has been modelled, see Figure 4a. The longitudinal section of the PLAXIS model is shown in Figure 4b which shows the shield cutting head of the TBM and the erected lining behind. The schematic 3D view of the PLAXIS model is shown in Figure 4c.

5.2 Modelling Stages

The following modelling stages have been simulated in the PLAXIS analysis:

- set up existing in-situ stress conditions; initially, the vertical and horizontal in-situ stress conditions have been assigned to the model;
- the tunnel construction then commenced from one end with the full shield zone (including tunnel face) being applied with the design slurry pressure;
- the tunnel advanced in 2m stages and lining erected simultaneously at the rear of the shield;
- the process continued until 50m length of tunnel is completed to ensure the full development of the settlement trough.

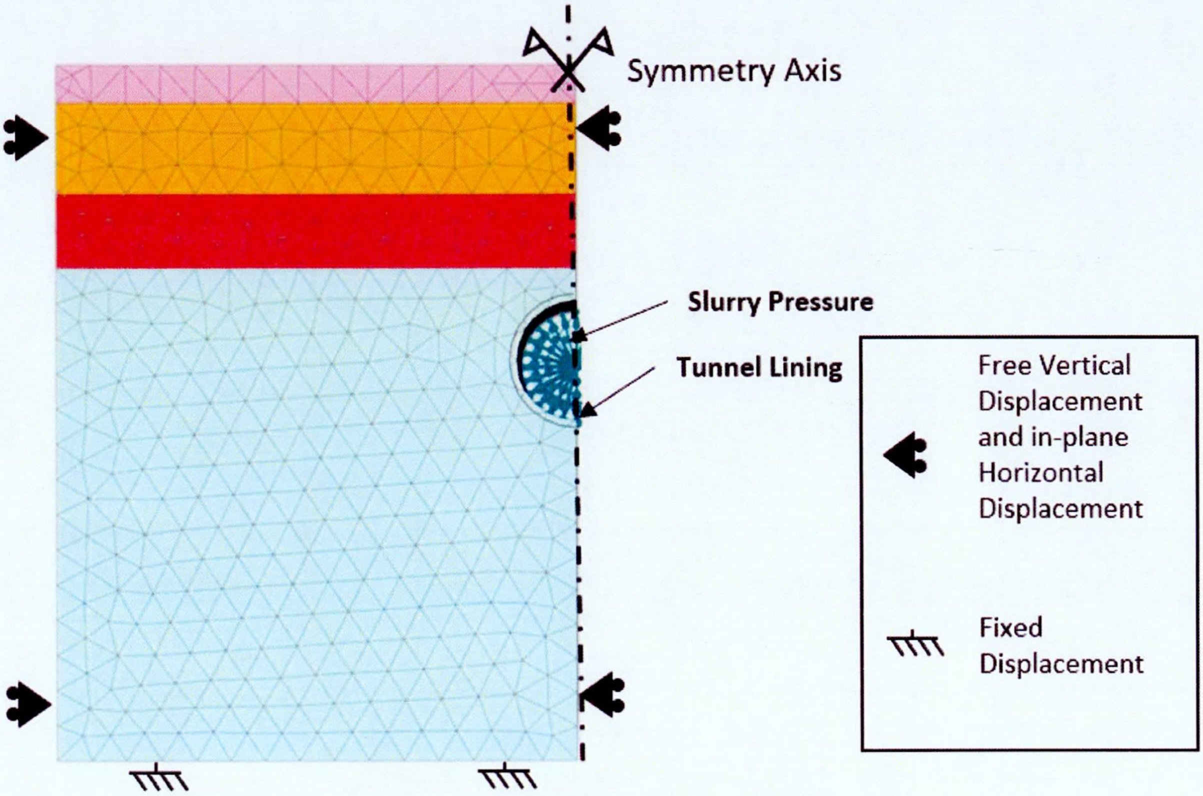

Figure 4a: PLAXIS model – Transverse Section

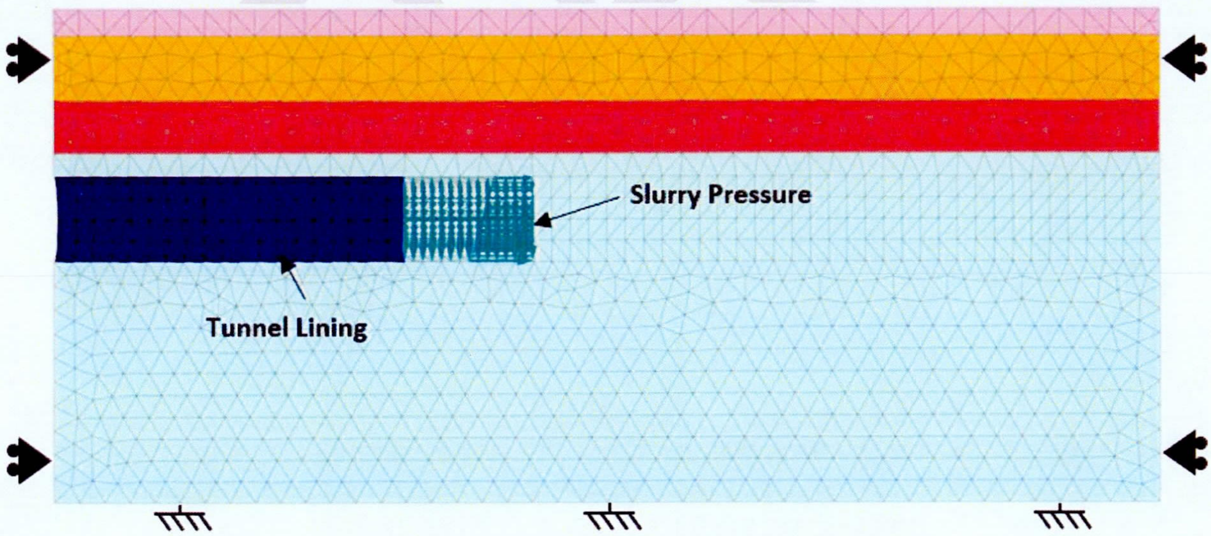

Figure 4b: PLAXIS model – Longitudinal Section

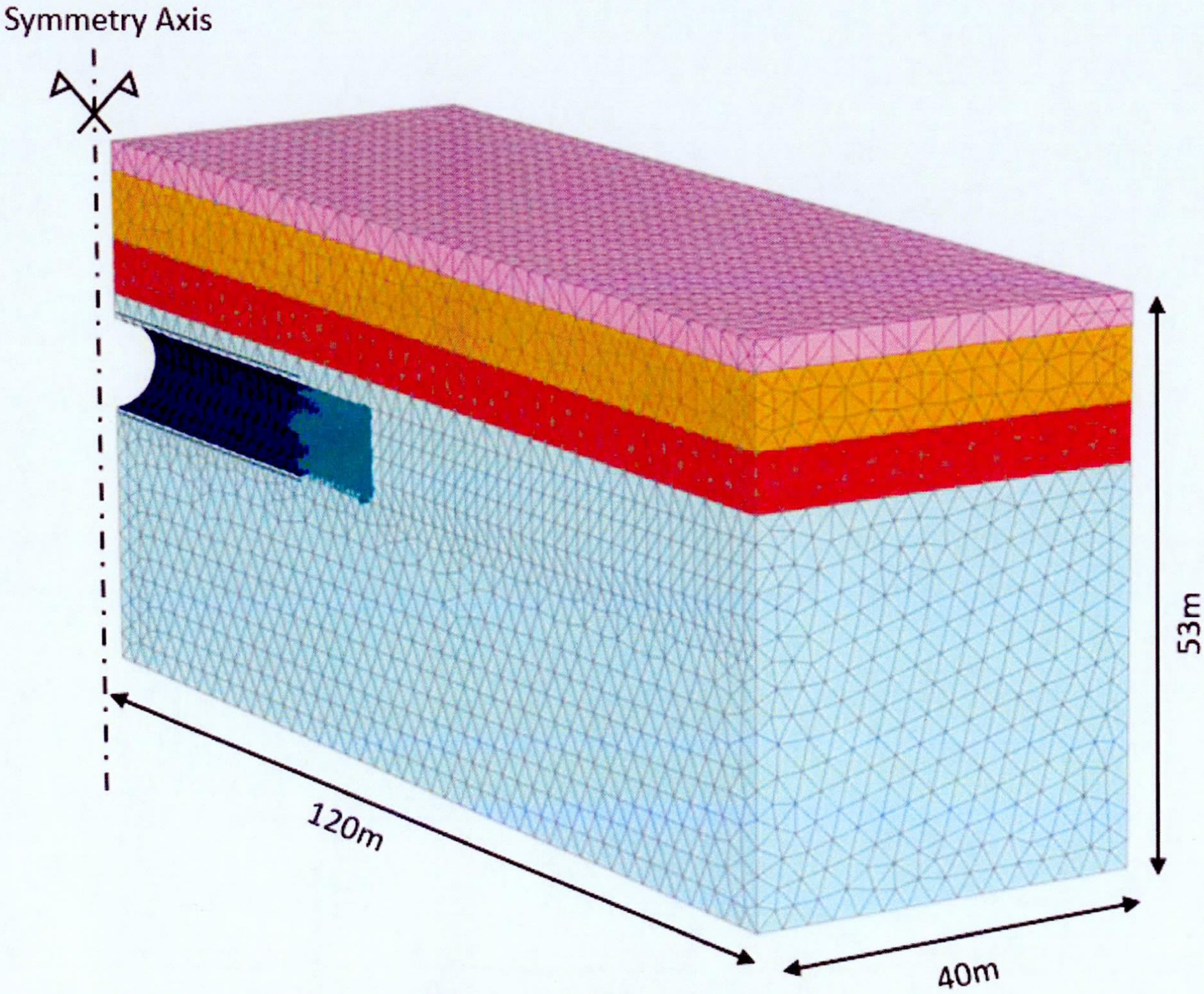

Figure 4c: PLAXIS model – Model Extensions

5.3 Calibration of the PLAXIS model

The first stage of the PLAXIS analysis involves the calibration of the model. In this analysis, the rock strata in the ground model is completely replaced with the superficial material immediately above (Drift deposits). In other words, the tunnel is assumed to be entirely in the superficial ground. The settlement trough at ground level obtained for this case is used to assess the equivalent volume loss and the trough width parameter by fitting with the Gaussian distribution curve. The slurry pressure at the tunnel head is adjusted until the volume loss for this case is of the order of 1.0% adopting an iterative procedure.

5.4 Assessment of Volume Loss for the Site-Specific PLAXIS Model

The calibrated PLAXIS model discussed above is then used to predict the volume loss, with the site-specific ground model, adopting the same modelling process and slurry pressure; i.e. rock strata reintroduced as per the idealised ground model (see Figure 2b) and the slurry pressure is maintained at hydrostatic level at the tunnel axis. The volume loss and the trough width parameter derived from the analysis are then used for the Phase-3 assessment as explained in Section 2.

6. Results and Interpretation of PLAXIS Analysis

6.1 Calibration/Validation Check

The settlement trough obtained from the calibration analysis is shown in Figure 5a. As stated in Section 4, these results correspond to the hypothetical case with the tunnel entirely in the superficial material. Also shown in the figure are the Gaussian distribution curves corresponding to the following parameters:

- Profile 1: K=0.40 and V_l=0.6%
- Profile 2: K=0.50 and V_l=0.8%
- Profile 3: K=0.65 and V_l=1.0%

The above profiles encompass the settlement trough obtained from the PLAXIS model (Figure 5a) and the equivalent volume loss is in the range of 0.6-1.0% which is considered show good agreement with the measured volume loss from recent tunnelling projects in soft ground (see Appendix A). Further, the corresponding trough width parameter (0.4-0.65) also falls within the range reported for tunnelling in soft ground (see Appendix A). The slurry pressure adopted in this calibration analysis is 25kPa above the water pressure at the tunnel axis level and this is evaluated iteratively. The transverse settlement contours obtained from the PLAXIS model is shown in Figure 5b. The corresponding longitudinal settlement results are shown in Figure 6.

The above modelling process and the results effectively demonstrate a successful calibration/validation of the PLAXIS model.

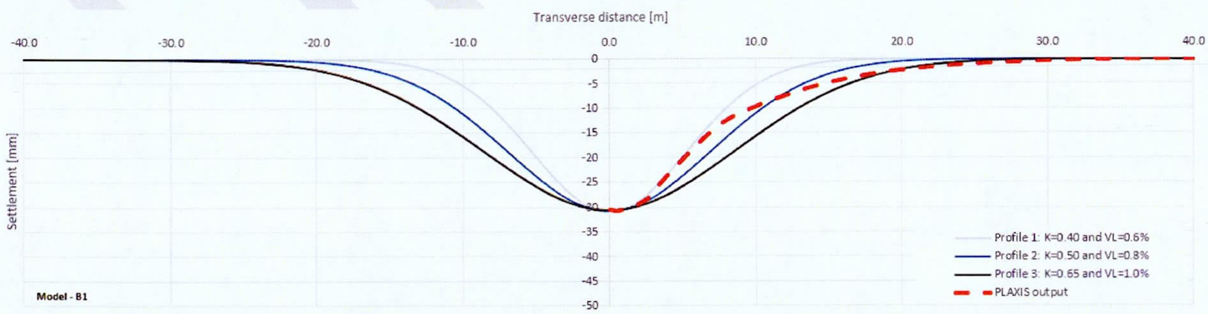

Figure 5a: Transverse settlement at ground level due to tunnel construction (calibration analysis)

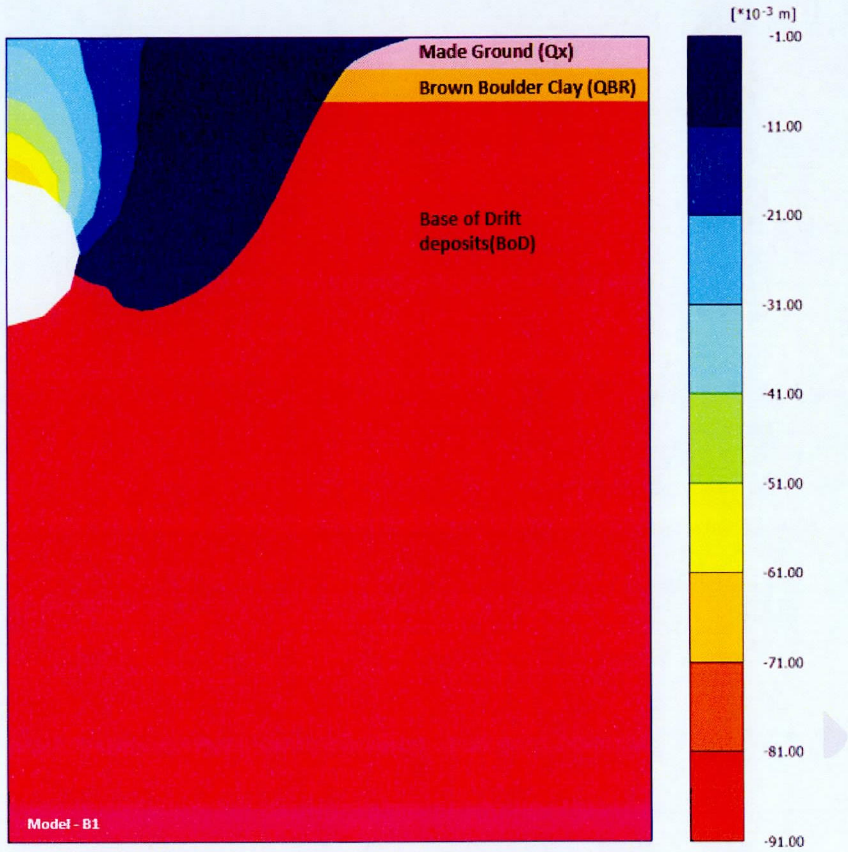

Figure 5b: Transverse Settlement Contour (Calibration analysis)

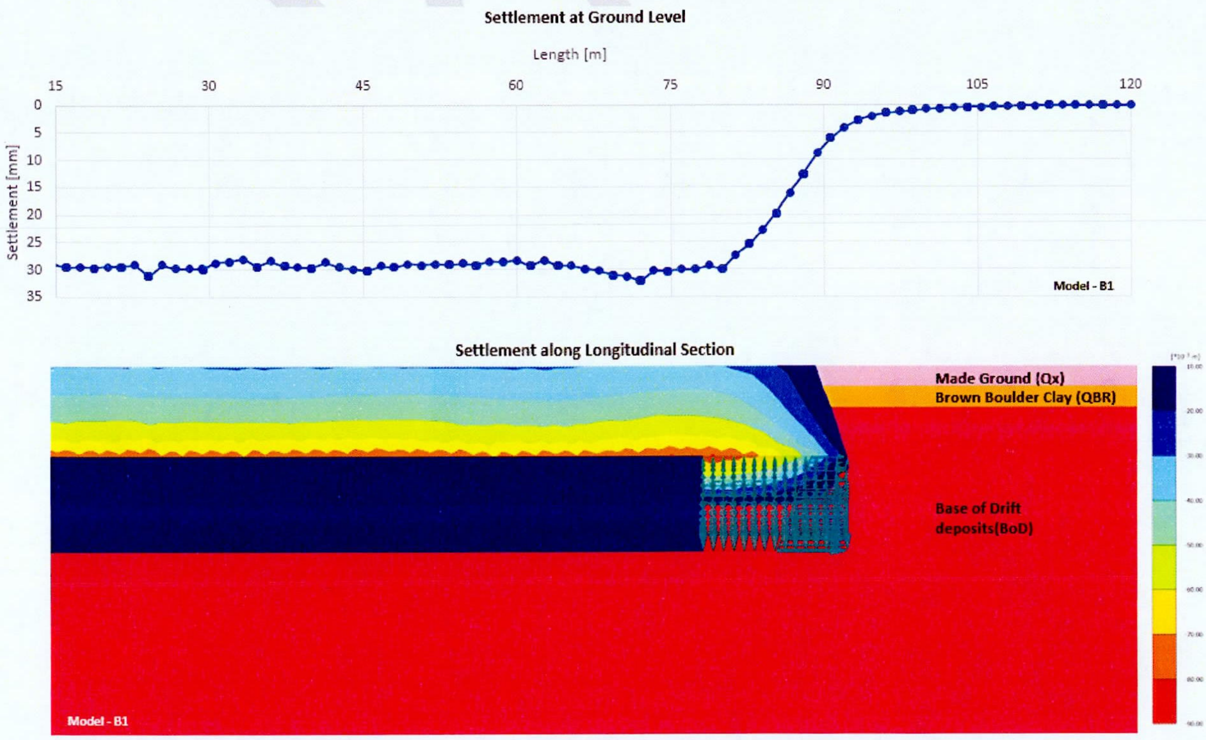

Figure 6: Settlement due to tunnel construction along the longitudinal axis (Calibration analysis)

6.2 Prediction of Tunnel Volume Loss with Site-Specific Ground Model

As noted in Section 4, the calibrated/validated PLAXIS model has then been used to predict the settlement trough but with the site-specific ground model shown in Figure 2b. In this analysis, slurry pressure has been taken as equals to the hydrostatic pressure at the tunnel axis level. The resulting settlement trough at raft slab level obtained from the PLAXIS analysis is shown in Figure 7a. The Gaussian Distribution curve with K=0.60 and V_l=0.18% fits reasonably well with the PLAXIS results..

Similar settlement trough output at the toe level of secant pile wall is presented in Figure 7b. The Gaussian Distribution curve with K=0.50 and V_l=0.20% fits reasonably well with the PLAXIS results for this case.

The transverse settlement contours obtained from the PLAXIS model is shown in Figure 7c. The corresponding longitudinal settlement results are shown in Figure 8.

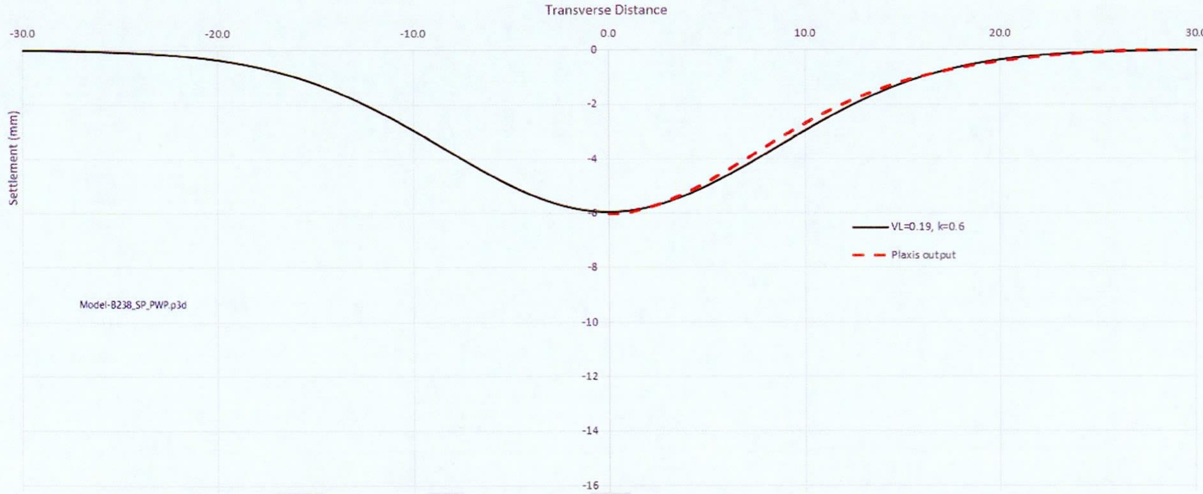

Figure 7a: Transverse settlement at 4.85m AoD (Basement Level) due to tunnel construction

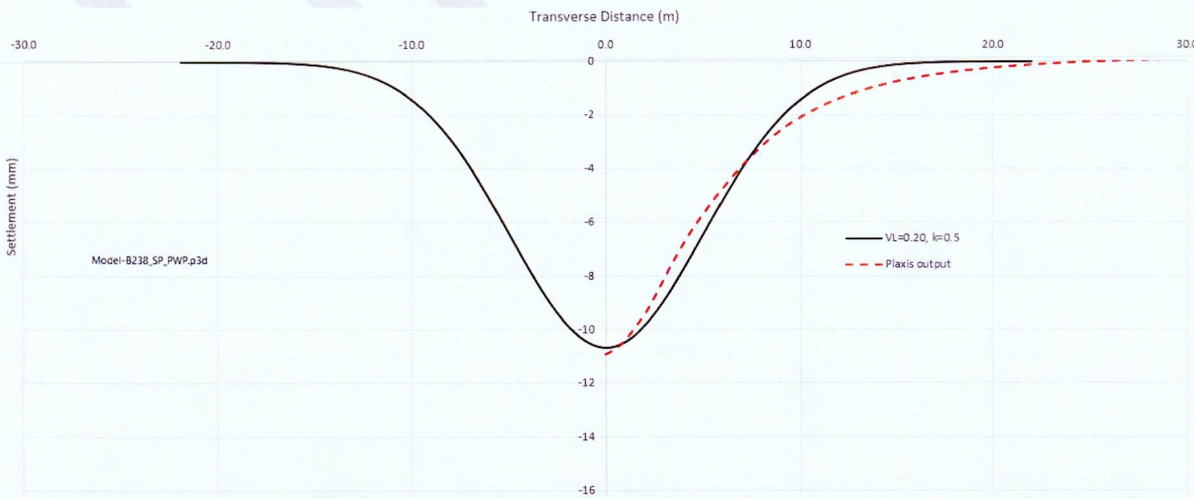

Figure 7b: Transverse settlement at 0.65m AoD (toe of secant pile wall level) due to tunnel construction

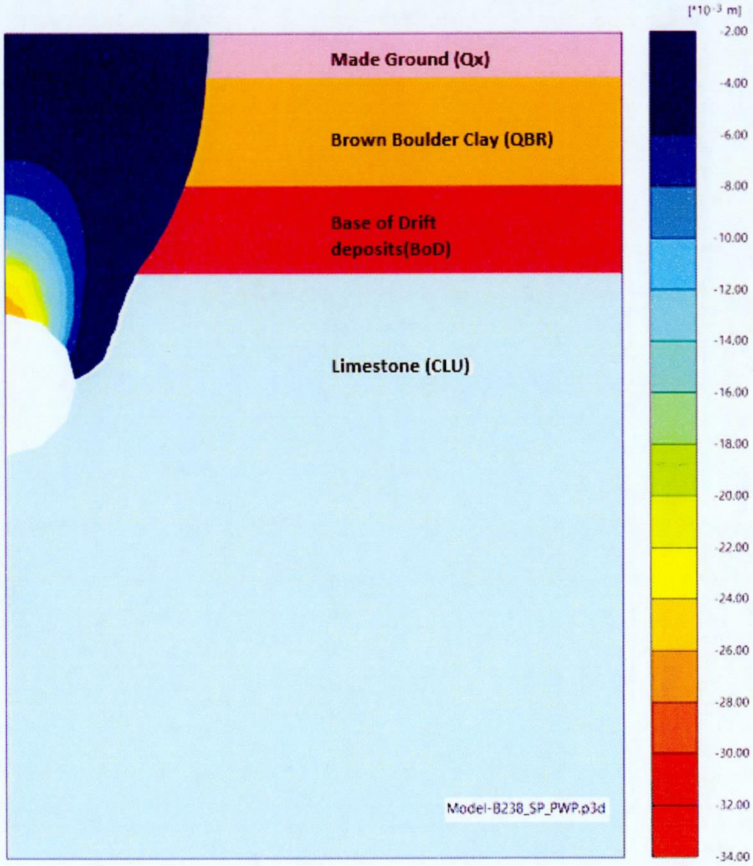

Figure 7c: Transverse Settlement Contour (PLAXIS Model)

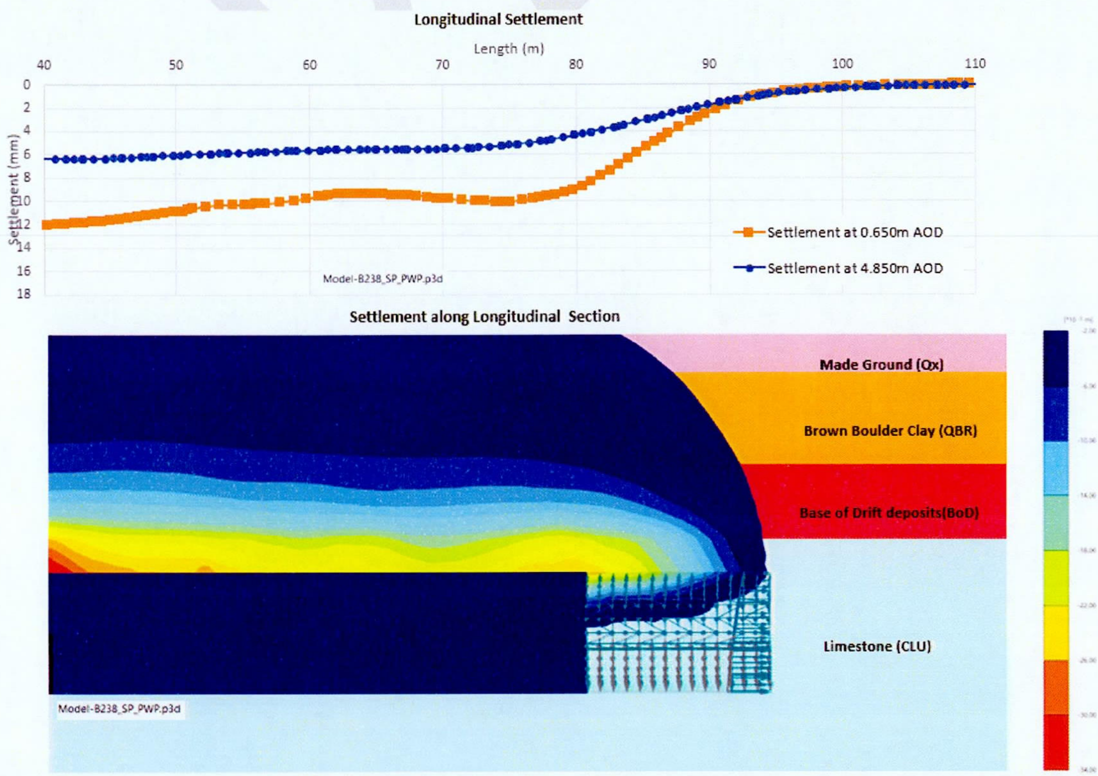

Figure 8: Settlement due to tunnel construction along the longitudinal axis (PLAXIS Model)

7. Phase 3 Assessment

The trough width parameter (K) and the volume loss value (V_l) based on the results obtained from the PLAXIS model (see section 6.2) have been used to for the damage assessment of the Arthur Cox Building. Settlement contours obtained at the raft slab level from XDisp are shown in Figure 9.

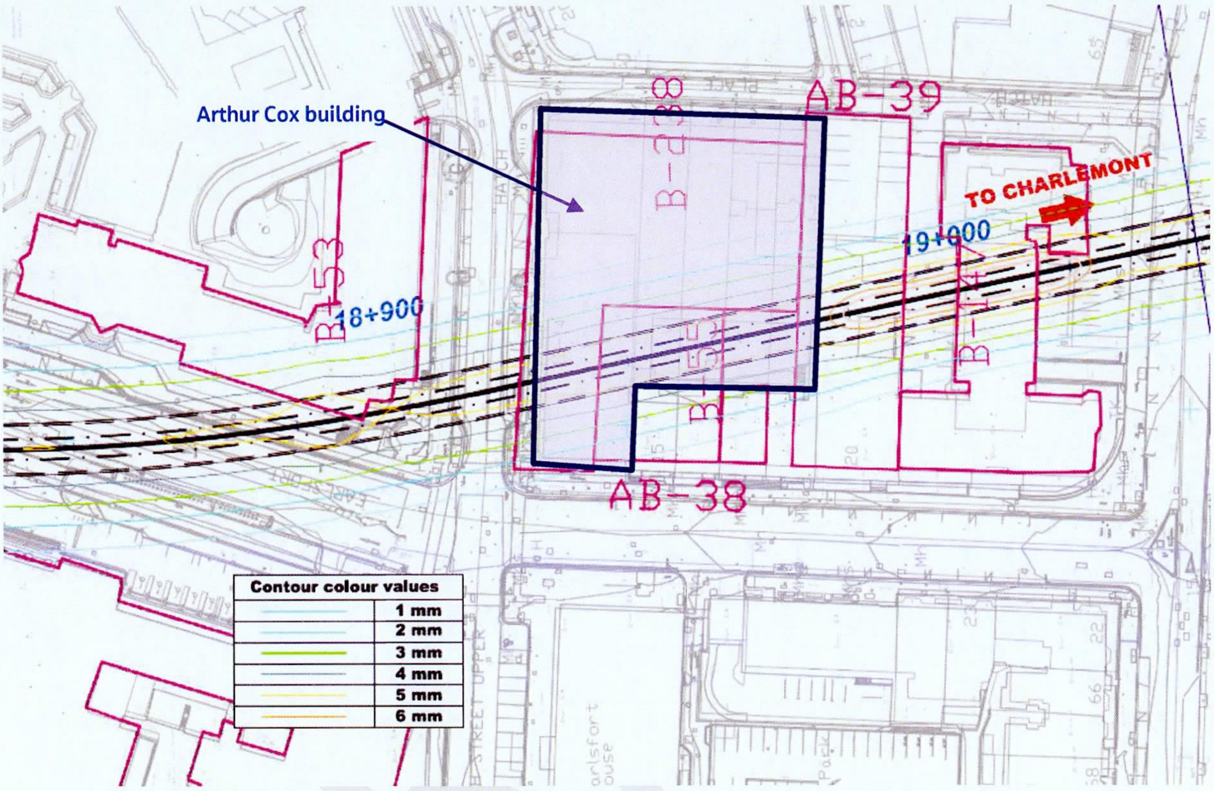

Figure 9: Settlement Contour at Basement Level around Arthur Cox Building

Method A: Using the method developed for Masonry Buildings

This method of assessment has been carried using XDisp Software [Ref. 4]. The assessment has been carried out at the basement slab level and the results show that the building falls into Damage Category 0 (Negligible). The assessment has also been done at the pile toe level along the direction of each secant pile wall and again the results show that the building falls into Damage Category 0 (Negligible).

Method B: using the method described in CIRIA C796 for Framed Buildings

In accordance with this method, if the imposed greenfield settlements are less than 10mm and the imposed differential settlement ratio is less than 1 in 500, then the impacts of ground movement are negligible and no further evaluation is required.

If the above conditions are not met then the shear/bending stiffness of the building could be utilized to modify the greenfield ground movements in accordance with the published literature. Subsequently, if the modified settlement profile complies with the above requirements, then the impacts of ground movement are negligible and no further evaluation is required.

The Figure 7a shows that the peak greenfield settlement at the basement level is 6mm (<10mm) and the maximum differential settlement gradient is of the order of 1 in 3000 (<1 in 500). The impacts of ground movement on the building are therefore negligible and no further evaluation is required.

The Figure 7b shows that the peak greenfield settlement at the pile toe level is 11mm and the maximum differential settlement gradient is of the order of 1 in 800 (<1 in 500). Although the maximum settlement is slightly above the 10mm threshold specified in the CIRIA C796, it is our judgement that the presence of the raft slab/capping beam will assist in reducing the peak settlement to below 10mm. The impacts of ground movement on the building are therefore negligible and no further evaluation is required.

8. Summary and Conclusions

The Phase-2a assessment (initial stage of Phase 2) of the industry standard three-phased ground-movement-induced building damage assessment process, indicates Damage Category-2 (DC-2) for the Arthur Cox Building (B-238). Only those buildings falling on DC-3 or above would be subjected to a Phase-3 assessment.

As Arthur Cox Building is a concrete framed structure with deep basement, the method of damage assessment relevant to masonry buildings is not strictly applicable. On the other hand, the provision of the raft slab foundation makes the structure more resilient to resist the construction-induced ground movements and therefore the method of damage assessment relevant to framed buildings is not directly applicable either. The Arthur Cox Buildings can be considered some what in between the above cases. As a result, damage assessment for the building has been done using both methods.

Using the above two methods, the assessment for the building has been carried out using the greenfield settlement profile derived from the Plaxis3D model. In the Plaxis3D, the detailed tunnel construction process has been modelled utilising the site-specific ground model and with the tunnel head/shield slurry pressure maintained the same as the hydrostatic (in-situ water pressure at the tunnel axis level). Based on the 'K' factor and the volume loss derived from the PLAXIS analysis results, the greenfield settlements at the basement slab level and at the secant pile wall toe level have been derived and utilized for the damage assessment.

The assessment results show that the building will undergo negligible damage or fall into damage category 0 (DC-0). It is therefore concluded that no further mitigation works are required to protect this building other than maintaining the slurry pressure slightly above the hydrostatic pressure level at the tunnel level. It should be noted that this Phase-3 preliminary ground movement assessment is based on the currently available ground investigation information which will be further reviewed as more information becomes available during the detail design phase.

9. References

[Ref. 1] Jacobs-Idom. Damage Assessment Report of Buildings and other Assets: ML1-JAI-GEO-ROUT_XX-RP-Y-00036.

[Ref. 2] Burland J B. (1995). Assessment of risk of damage to building due to tunnelling and excavation. Proc. 1st Int. Conf. Earthquake Geotechnical Engineering, Ishihara(ed.), Balkema, 1189-1201.

[Ref. 3] Ground Investigation Report (GIR); ML1-JAI-GEO-ROUT_XX-RP-Y-00003.

[Ref. 4] Oasys XDisp Tutorial Manual – Ground Movement Analysis Software.

[Ref. 5] 79 ABP-314724-22 – Submission – Earldev Properties Unlimited Company.

[Ref. 6] CIRIA C796 (2021) Assessing the impacts of construction-induced ground movements on framed buildings.

Appendix A. Reported measured values from recent tunnelling projects

Table A-1: Monitored Volume Loss of recent tunnelling projects

Project names		Excavation Diameter (ft)	Excavation Completion	Excavation Method	Geologic Conditions	Typical Ground Losses (%)	References
Sao Paulo Metro Line 4 – Lot 1, Sao Paulo, Brazil		31.2	2009	EPBM	Three different geologic formations: soil derived from the alteration of gneiss, interbedded high to medium plasticity clay and sandy clay with gravel, and interbedded medium stiff to hard clay with fine to coarse sands	< 0.4	Pellegrini and Perruzza, 2009
Barcelona Metro Line 9, Barcelona, Spain[1]	Mas Blau to San Cosme Segment	30.8	2008	EBPM	Submerged fine silty sands and clayey silts	0.4 to 0.8	Mignini et al., 2008
	Segment IV-B (San Adria)	39.2	2007	EPBM	Sands, clay, and silts overlying gravels with sands	0.7 to 1.0	Della Valle, 2007
	Segment IV-C (Trajana)	39.2	2007	EPBM	Mixed face of silts and sands or gravels in a sandy clay matrix overlying highly to completely weathered granodiorite	0.2 to 0.6	Della Valle, 2007
	Fira to Park Logistic Segment	30.8	2006	EPBM	Silty sands with sandy silts, silts and silty clays	0.3 to 0.4	Orfila et al., 2007, Della Valle, 2007
Madrid South Bypass M-30 Tunnels, Madrid, Spain[1]		50.0	2007	EPBM	Mixed face of sandy clay overlying hard clay with gypsum	0.1 to 0.4	Universidade da Coruña, 2008, Fernandez, 2005
MTA Gold Line Eastside Extension, LA, USA[2]		21.4 (twin tunnels)	2007	EPBM	Mix of stiff to hard silt, lean clay, sandy clay, and loose to very dense sand and gravel, both above and below groundwater	< 0.3	Choueiry et al., 2007
Channel Tunnel Rail Link, London, UK[1]		26.7 (twin tunnels)	2004	EPBM	London clay: Stiff to hard clay	0.3 to 0.8	Bowers et al., 2005, Mair and Borghi, 2008
					Fine and medium silty sand	0.3 to 0.8	
Docklands Light Railway Lewisham Extension, London, UK[1]		19.2 (twin tunnels)	1998?	Slurry TBM	Stiff to hard clays with gravels	0.7 to 1.0	Sugiyama et al., 1999
					Mixed face of stiff to hard clays and silty fine dense sand	0.5 to 0.9	

(1) Achieved ground losses in combination with careful control of bentonite injection around TBM and tail-skin grouting. Higher ground losses were reported for locations where ground movement control measures were not implemented or were or poorly implemented, or along the tunnel excavation learning curve.

(2) Ground loss values back-calculated from the settlements reported in the paper.

Table A-2: Reference values for K and Vs on different projects

Values of K and Vs	K		Vs(%)	
Considered IDOM/JACOBS	0,500	Boulder clay /QTR	0,500	Section completely in rock or ground with Hb/D>2
	0,800	BedRock	0,750	Section in Mixed face or 2>Hb/D>1.5
			1,000	Section with Hb/D<1.5
Document Evaluation of Risk Assesment	0,415	Averaged	0,690	Averaged
Paper Findlater's Church-J.Murphy.	0,400		0,760	Taken from Dublin Port
Dublin Port	0.47-0.51	Boulder clay	0.21-0.64	(1.66 locally as an exception)
Mair and Taylor(1997)	0.4-0.6	Clays	1-2	Open face tunnels London Clay
	0.25-0.45	Gravels&sands	0.5-2	Closed face tunnel, EPB, slurry shield
Proof of evidence. Professor John Burland	0.3	Fluvio glacial deposits	1,500	Mixed Face fluvio glacial deposits
	0.4	Limestone bedrock	0,600	Glacial Till
	0.6	Glacial Till	0,200	Limestone bedrock