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AGL
CONSULTING
GEOTECHNICAL ENGINEERS

TECHNICAL NOTE

To: **Robert Coughlan, Punch Consulting**

From: Conor O'Donnell

Re: **Project Metrolink - Refined Phase IIa Building Damage Assessment for Arthur Cox Building at 13-14 Earlsfort Terrace**

Date: 26/2/2024 **Ref: 22-232A-TN01**

1.0 INTRODUCTION

This technical note presents the results of the Phase 2a assessment of building damage that could occur due to tunnelling-induced ground movements during the construction of the Metrolink Tunnel under the Arthur Cox Building at 13-14 Earlsfort Terrace in Dublin City Centre.

The assessment has been carried out in accordance with the criteria and methodology set out for a refined Phase 2a assessment of subsidence damage in Section 4 of the Building Damage Report ("the BDR") produced by Jacobs/IDOM, which is included as Appendix A5.17 of the Environmental Impact Assessment Report ("the EIAR").

The analysis has been carried out to assess the potential tunnelling settlements and associated building damage that could occur at the Arthur Cox building based on the specific ground conditions, tunnel geometry and building characteristics at the site.

The tunnel rises slightly from north to south across the width of the building. Therefore, analyses have been carried out at 3 No. locations across the width of the building - at the building façade on Hatch St. (Ch. 18+945), at the centre of the building (Ch.18+970), and at the south façade to the rear of the building (Ch. 18+995).

At Ch. 18+945 the potential damage to the building façade on Hatch St. has been assessed based on the tunnelling settlements that could occur at the toe level of the perimeter secant pile wall, which supports the façade and internal structure.

At Ch. 18+970 and 18+995 the damage to the interior reinforced concrete structure of the building and basement floor slab, respectively, have been assessed based on the settlements that could occur at subgrade level for the slab. The tunnel is shallowest on the south side of the structure.

Analyses have been carried out for the design tunnel profile shown on the drawings in the EIAR, and for a raised and lowered profile within the proposed vertical Limits of Deviation, which are up to 5.0m above and 10.0m below the design profile.

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2.0 STATEMENT OF EXPERTISE

Conor O'Donnell is the Senior Geotechnical Consultant and Managing Director of AGL Consulting with more than 25 years' experience as a Geotechnical Engineer in Ireland and the United States. He is a Chartered Engineer with Bachelors Degree in Civil, Structural and Environmental Engineering from Trinity College Dublin, and a Masters Degree in Geotechnical Engineering and Structural Mechanics from Cornell University, Ithaca, NY.

Prior to 2001, Conor worked for Mueser Rutledge Consulting Engineers, a specialist geotechnical engineering consulting firm in New York City. At MRCE, Conor specialised in the geotechnical design of foundations, excavation support systems and ground improvement schemes, including deep soil mixing, grouting and ground freezing for tunnelling projects. He worked on a number of landmark tunneling and underground mass transit projects, including the NATM tunnel for the MBTA South Boston Transitway under Russia Wharf, and Contract C09A4 of the Boston Central Artery Project, which involved tunnel jacking under the railway lines at the approach to South Station in Boston, Massachusetts.

At AGL Conor has been involved in a number of major civil, infrastructure and commercial building projects across Ireland at planning, detailed design and construction stage. He was the lead geotechnical consultant for the detailed ground investigation and preliminary design of the basement excavation and perimeter secant piling works for the Dublin Central development off O'Connell St. in Dublin City Centre. He prepared the hydrogeological impact assessment for the project and a report on ground movements related to basement excavation and dewatering. He was also the geotechnical specialist adviser to An Bord Pleanála for the oral hearing into the planning application for the onshore Corrib Gas Pipeline, which included a long microtunnel crossing of Sruwaddacon Bay in Co. Mayo.

Mr. O'Donnell has extensive experience in assessing ground movements related to tunnelling, micro-tunnelling and underground excavation works. His postgraduate studies and Masters thesis involved forensic analyses and numerical modelling of ground movements adjacent to deep excavations for a cut and cover section of the Boston Central Artery tunnel project. Related papers were subsequently published in the ASCE Journal of Geotechnical and Geoenvironmental Engineering which were co-authored by Prof. Tom O'Rourke, who is a leading international expert on ground movements and related building damage adjacent to excavations. In Ireland Mr. O'Donnell was the geotechnical consultant for a large-diameter micro-tunnelling section of the North Docklands Sewerage Scheme in Dublin Port. He also advised on the specification and scope of work for the ground investigation for the Blanchardstown Regional Drainage Scheme, which involved large diameter microtunnelling and deep caissons. Mr. O'Donnell carried out numerical modelling to assess the impact of microtunnelling behind the masonry abutments of Sarsfield Bridge for the Limerick Main Drainage project.

AGL Consulting have been involved in most of the large tunnelling projects in Ireland. We were geotechnical advisers to Dublin City Council on temporary works designs involving soil nailing for the cut and cover section of the Dublin Port Tunnel along the M1 in Swords. We have also developed a 3D model of ground and groundwater conditions along the alignment of the tunnel in AutoCAD Civil 3D for Transport Infrastructure Ireland, which collates all the available ground investigation information on the project. We recently used this ground model to assess the impact of multi-story apartment buildings on the tunnel at Hartfield Place in Swords by advanced 3D finite element modelling.

AGL were also temporary works designers for the casting basin of the immersed tube sections of the Limerick Tunnel, and for the launch shaft and reception pit for the Tunnel Boring Machine (TBM) used on the 4.0m dia. Corrib Gas Pipeline tunnel in Co. Mayo.

3.0 ANALYSIS PROFILES FOR ARTHUR COX BUILDING

The proposed alignment and vertical profile of the tunnel are shown on the following drawings in Book 2 of the Railway Order (RO) Alignment Details (Area ML304 to ML307 - Balbutcher Lane to Ranelagh Road):

- ML1-JAI-ARD-ROUT_XX-DR-Y-03095: Metrolink General Arrangement – Hatch Street Lower to Grande Parade;
- ML1-JAI-ARD-ROUT_XX-DR-Y-01018: Metrolink Alignment – Long Section 18

Copies of the drawings are included in Appendix A. Figure 3-1 shows an excerpt from the general arrangement alignment drawing with the location of the Arthur Cox building highlighted. Figure 3-2 shows an excerpt from the long-section profile drawing which shows the design tunnel profile and top of rail level under the building. The chainage of the tunnel is not shown on the alignment drawings. Therefore, it has been determined from the long-section drawings, which identify where the tunnel passes under Hatch St.

Based on these drawings, the tunnel crosses under the Arthur Cox Building for approximately 50m between Ch. 18+945 and 18+995, which is measured from north to south across the width of the building. Ground level on Hatch St. is at **+13.20mOD (Malin)**. To the south of the street the top of rail level in the tunnel rises by 0.90m across the width of the Arthur Cox Building from **-11.05mOD** at Ch. 18+945 to **-10.15mOD** at Ch. 18+995.

Figure 3-3 shows the proposed tunnel alignment superimposed on a plan drawing of the basement and perimeter secant pile wall of the building. The figure identifies where there are load-bearing piles in the perimeter wall (shaded) which support concentrated loads from the building façade and internal reinforced concrete (RC) structure. It also shows where the basement slab has been locally thickened to create integral pad foundations for the internal columns of the building. A copy of the drawings is included in Appendix A.

The Building Damage Assessment has been carried out at 3 No. profiles across the width of the building:

- Section 1 @ Ch. 18+945: Building north façade on Hatch St.
- Section 2 @ Ch. 18+970: Center of building
- Section 3 @ Ch.18+995: South side of building

The locations of these sections is shown on Figure 3-3.

The Limits of Deviation (LoD) on the vertical profile that are proposed in the Railway Order are **5.0m upwards** and **10.0m downwards** from the design profile shown on the drawings. This could have a significant impact on the building and has therefore been considered in our assessment. The LoD proposed for the horizontal alignment are **±15.0m** from the design alignment. However, this has not been considered in our assessment.

Figure 3-4 shows a profile of the basement floor slab and perimeter secant pile wall on Hatch St. The basement slab is 600mm thick and subgrade level is at **+4.80mOD**. The slab is locally 150mm thicker at the integral pad foundations for the internal columns and basement wall. Toe level for the secant piles on this side of the building is **+0.65mOD**.

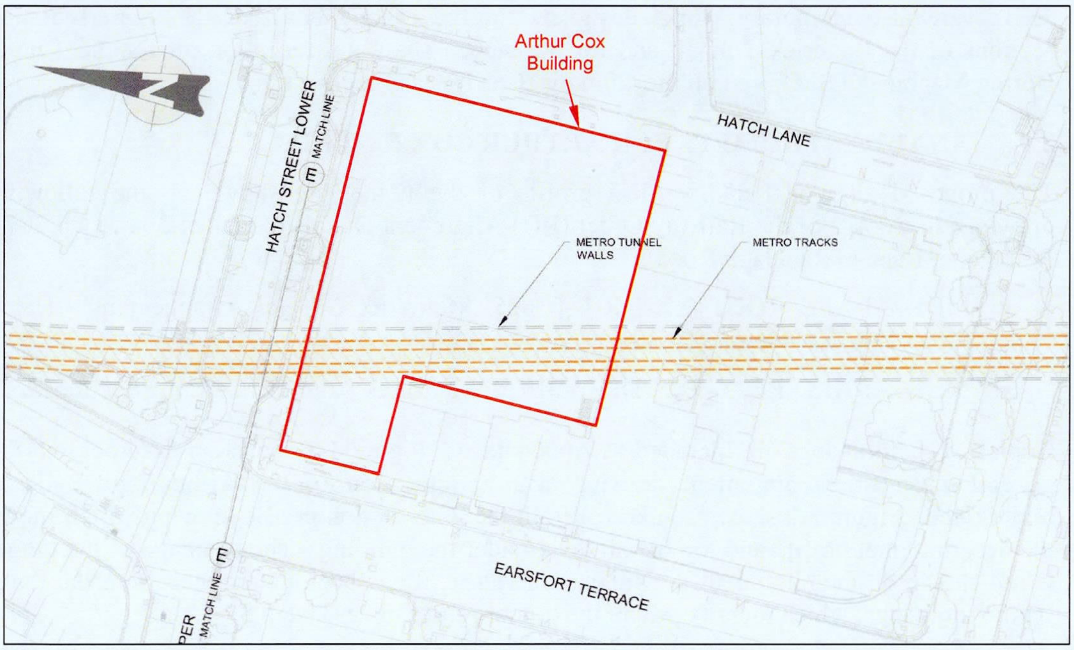


Figure 3-1 – Design tunnel alignment from RO Alignment Drawings

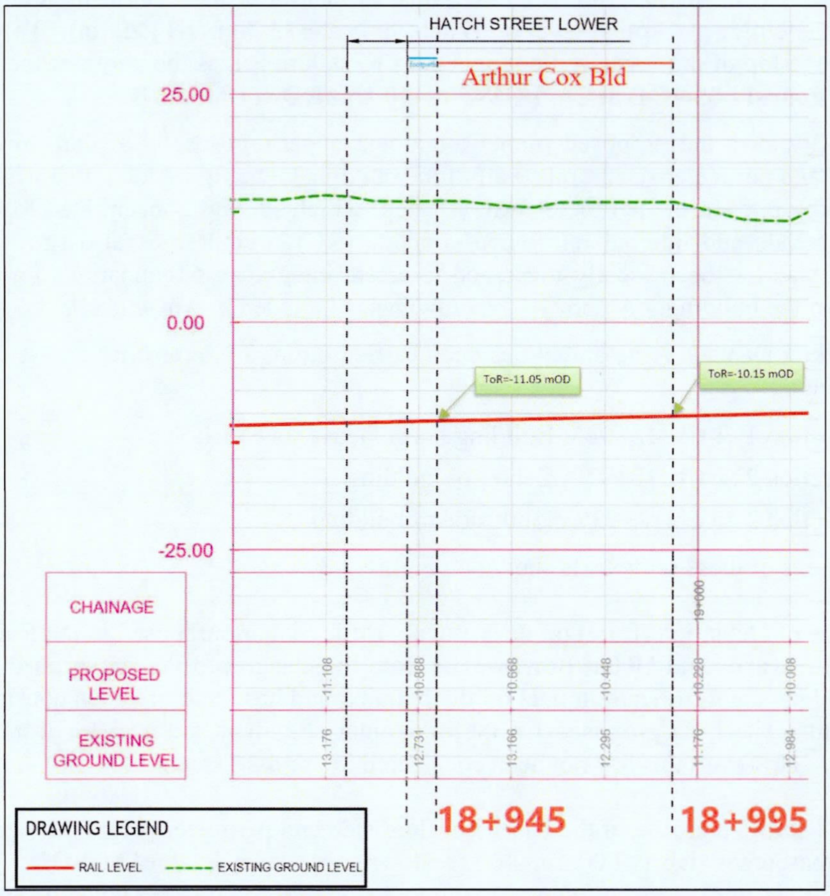


Figure 3-2 Design tunnel profile (top of rail level) from RO Long-Section Drawings

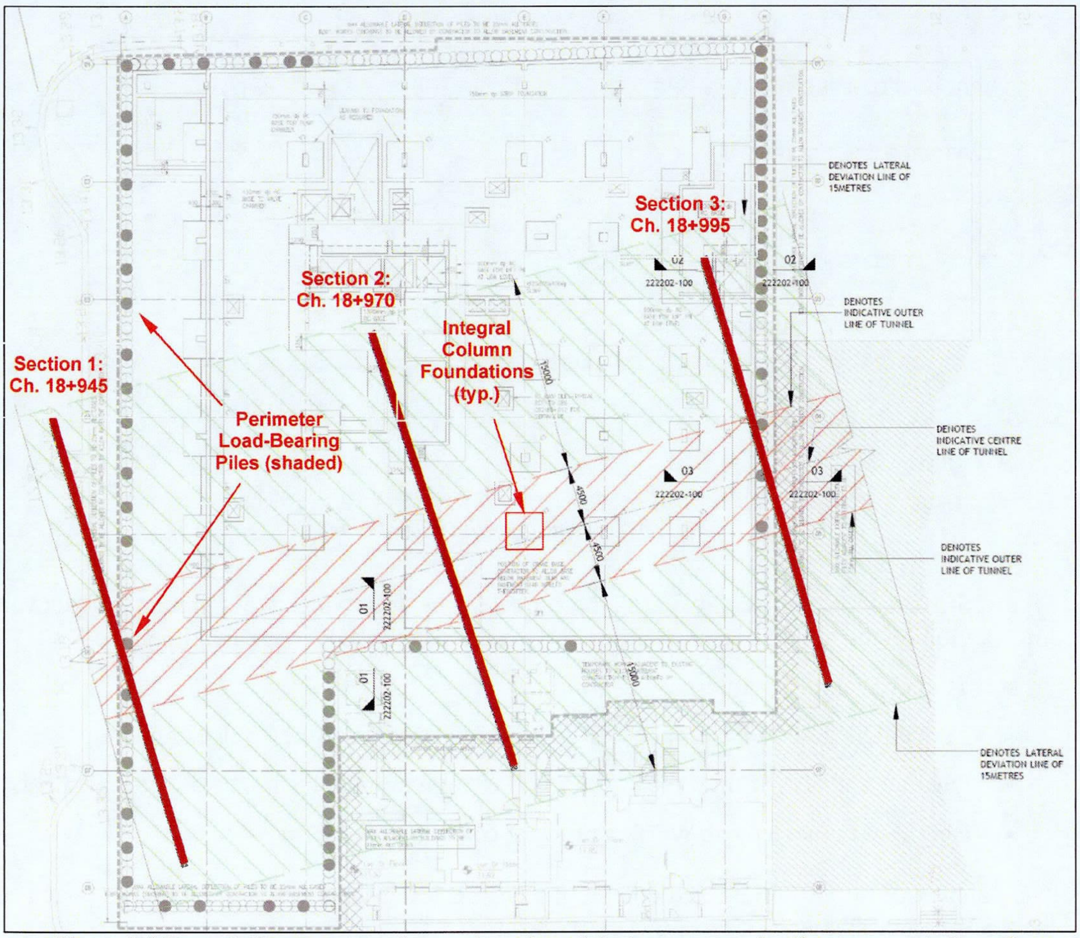


Figure 3-3 Tunnel alignment superimposed on plan of the basement and perimeter secant pile wall.

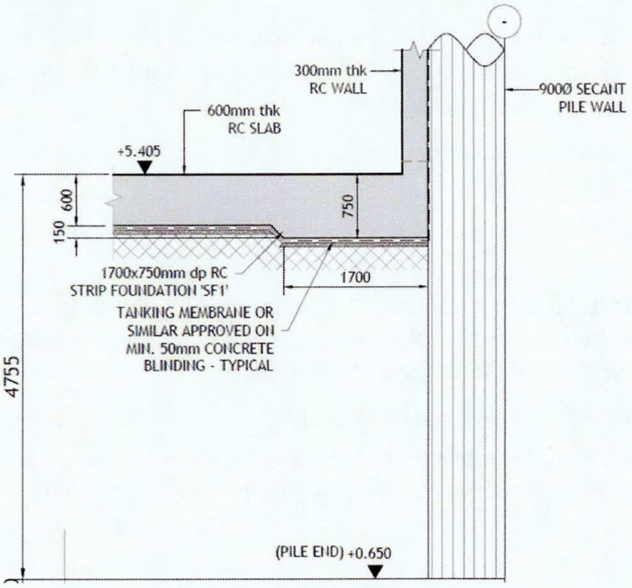


Figure 3-4 Profile of basement floor slab and 900mm diameter perimeter secant pile wall on Hatch St.

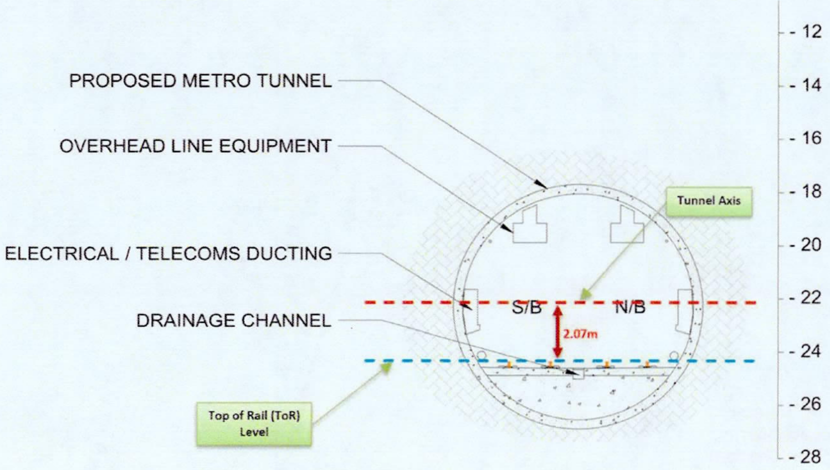


Figure 3-5 – Typical profile of the tunnel

Figure 3-5 shows a typical profile of the tunnel. The following is a summary of relevant information on the tunnel geometry from Section 2.1 of the BDR (copy in Appendix A):

- Tunnel Diameter – Internal = 8.50m
- Tunnel Diameter – External = 9.20m (350mm thick concrete lining segments)
- Diameter of TBM Cutter Head = 9.53m (165mm annular clearance outside segments)
- Height of tunnel axis above Top of Rail (ToR) level = **2.07m**

The calculation of tunnelling settlements for the Building Damage Assessment is based on the **9.53m** outer diameter of the TBM cutter head.

The Building Damage Assessment has been carried out for **9 No. cases** as follows:

- **Section 1 (Ch.18+945):** Below the perimeter secant pile wall on Hatch St. to assess the potential impact of tunnelling on the basement walls and building façade based on tunnelling settlements at pile toe level (+0.65mOD):
    - Case 1A: for the design tunnel profile
    - Case 1B: for a raised tunnel profile (+3.9m from design level – ***see Note 1***)
    - Case 1C: for the lowered tunnel profile (-5.0m from design level).

- **Section 2 (Ch.18+970):** Below the centre of the building to assess the potential impact of tunnelling on the internal reinforced concrete structure based on tunnelling settlements at slab subgrade level (+4.80mOD):
    - Case 2A: for the design tunnel profile
    - Case 2B: for a raised tunnel profile (+5.0m from design level)
    - Case 2C: for the lowered tunnel profile (-5.0m from design level).

- **Section 3 (Ch.18+995):** Below the basement slab and side walls on the south side of the building to assess the potential impact of tunnelling on the basement floor slab based on tunnelling settlements at slab subgrade level (+4.80mOD):
  - Case 3A: for the design tunnel profile
  - Case 3B: for a raised tunnel profile (+5.0m from design level – ***see Note 2***)
  - Case 3C: for the lowered tunnel profile (-5.0m from design level).

The relevant levels for the calculation of the tunnelling settlements for the design level at each section are presented in Table 3-1.

Notes:

1. *At Ch.18+945, on the north side of the building, the clearance between the crown of the tunnel bore (TBM Cutter Head) and the toe level of the secant pile wall at the design profile is **4.9m**. If the tunnel is raised by 5.0m, which is the maximum proposed Vertical Limit of Deviation (VLoD), **then the TBM will hit the toe of the piles**. Therefore, for Case 1B, to illustrate the impact that raising the level of the tunnel has on the building façade we have only raised the tunnel profile by **3.9m** so that it is at least 1.0m below the toe of the piles.*
2. *At Ch.18+995, on the south side of the building, the clearance between the crown of the tunnel bore (TBM Cutter Head) and the toe level of the secant pile wall at the design profile reduces to **4.0m**. If the tunnel is raised by 5.0m on this side **the TBM will hit the bottom 1.0m of the piles**. However, for Case 3B we have assessed the impact that raising the tunnel could have on the basement floor slab, which is at a higher level (+4.80mOD). Therefore, to illustrate this we have raised the tunnel profile by the max VLoD of **5.0m** in our calculations. The impact of hitting the piles with the TBM is addressed separately in the report.*

Table 3-1 Profile geometry and levels at each analysis section for the design tunnel profile in the EIAR

	Section 1 **Ch. 18+945**	**Section 2** **Ch. 18+970**	**Section 3** **Ch. 18+995**
Top of Rail (ToR) Level (mOD)	-11.05mOD	-10.60mOD	-10.15mOD
Tunnel Axis Level (mOD)	-8.98mOD	-8.53mOD	-8.08mOD
Foundation Level (mOD)	+0.65mOD (Pile Toe Level)	+4.80mOD (Slab Subgrade Level)	+4.80mOD (Slab Subgrade Level)
Depth to Tunnel Axis from Foundation Level, z_o (m)	9.63m	13.33m	12.88m
Tunnel Crown Level (TBM Cutter Head) (mOD)	-4.22mOD	-3.77mOD	-3.32mOD
Clearance to Foundation Subgrade from Tunnel Crown (m)	4.87m	8.57m	8.12m

4.0 GROUND CONDITIONS

4.1 Interpretation of Ground Conditions at the Arthur Cox Building in the EIAR

Figure 4-1shows the location of the boreholes that were used by Jacobs/IDOM to interpret the ground conditions along the tunnel in the vicinity of the Arthur Cox Buildling. This is from Figure 20.6 (Sheet 7 of 8) in Chapter 20 of the EIAR (Soils & Geology).

The corresponding interpreted geological cross-section at this location from Appendix A20.9 of the EIAR is shown in Figure 4-2. The outline of the Arthur Cox Building, basement and perimeter secant pile wall has been added to the profile over the tunnel.

The following is a summary of the relevant information on the assessment of the ground and groundwater conditions at the Arthur Cox Building in the EIAR:

- The most relevant boreholes used for the interpretation of the ground and groundwater conditions in the area are NBH92, NBH221 and NBH93. Borehole NBH221 is located at the building, as shown on Figure 4-1.
- None of these boreholes are identified on the geological cross section in Figure 4-2 . All of the site investigation points that are shown on the profile were terminated above the level of the tunnel and were located 115-165m to the right (west) of the tunnel alignment.
- None of the logs for the investigation points shown on the location plans or geological sections were included in the EIAR so it is not possible to verify the ground conditions interpreted by Jacobs/IDOM.
- The interpreted geological section in Figure 4-2 would indicate that the subgrade for the basement floor slab at +4.8mOD is in the glacial till deposits of Boulder Clay and Sand & Gravel, possibly encountering the top of the Weathered Rock layer in the centre of the building at about Ch. 18+975.
- The profile would also indicate that the toe of the perimeter secant pile wall, at +0.65mOD, is embedded into the Weathered Rock or Sand & Gravel layer at the base of the Glacial Till and does not penetrate into the underlying Limestone bedrock.
- The top of the Limestone Rock is shown to be undulating between +2.5mOD and -2.5mOD, which is approximately 2.5 to 7.5m below the basement subgrade level.
- The tunnel profile is shown to be in the Limestone bedrock under the building.
- Based on the interpreted geological section in Figure 4-2 Jacobs/IDOM have assumed the following ground loss parameters for the Building Damage Assessment along section of the tunnel under the Arthur Cox Building:
    - **0.75%** between Ch. 18+960 and 18+980, where the tunnel is in rock and the cover of rock over the tunnel is ≥0.5D, where D is the tunnel diameter (9.5m).
    - **1.50%** to the north (<Ch.18+960) and south (>Ch.18+980) of this zone, where the cover of rock over the tunnel is <0.5D.

  These parameters will be discussed in more detail in Section 5.2.
- A groundwater level of +11.0mOD (≈2.5mBGL) is shown in BH-RC01 at Ch. 18+800, approximately 150m north of the Arthur Cox Building.

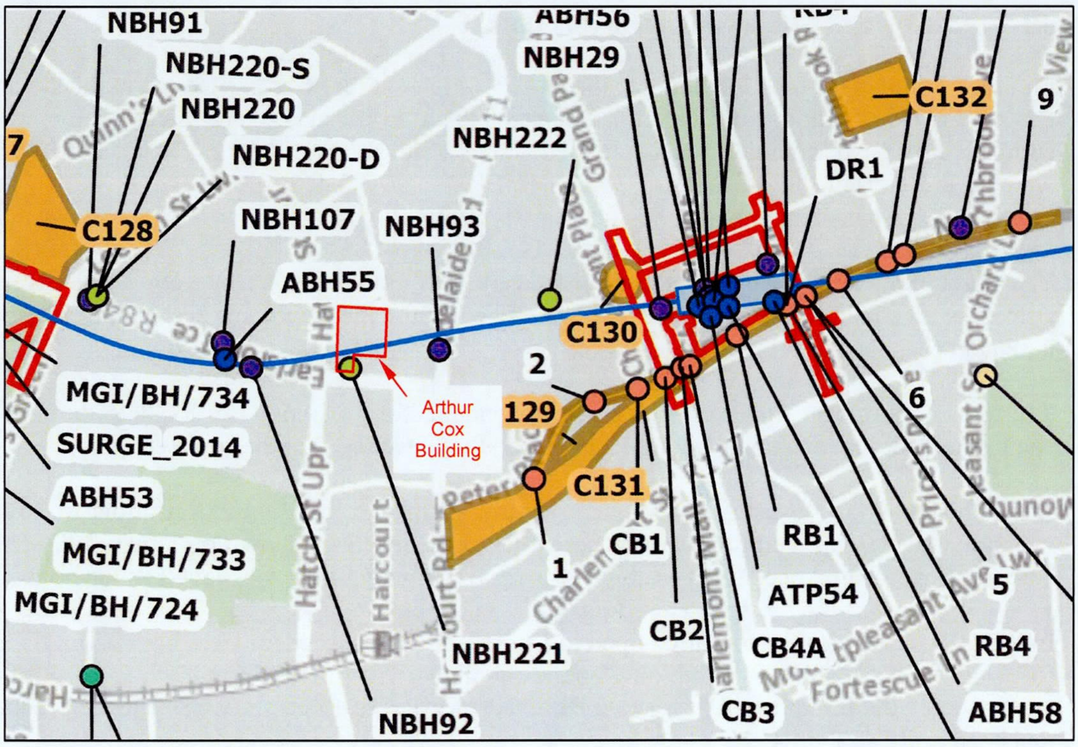


Figure 4-1 Site Investigation Location Plan [from Figure 20.6 (Sheet 7 of 8) in Chapter 20 of the EIAR]

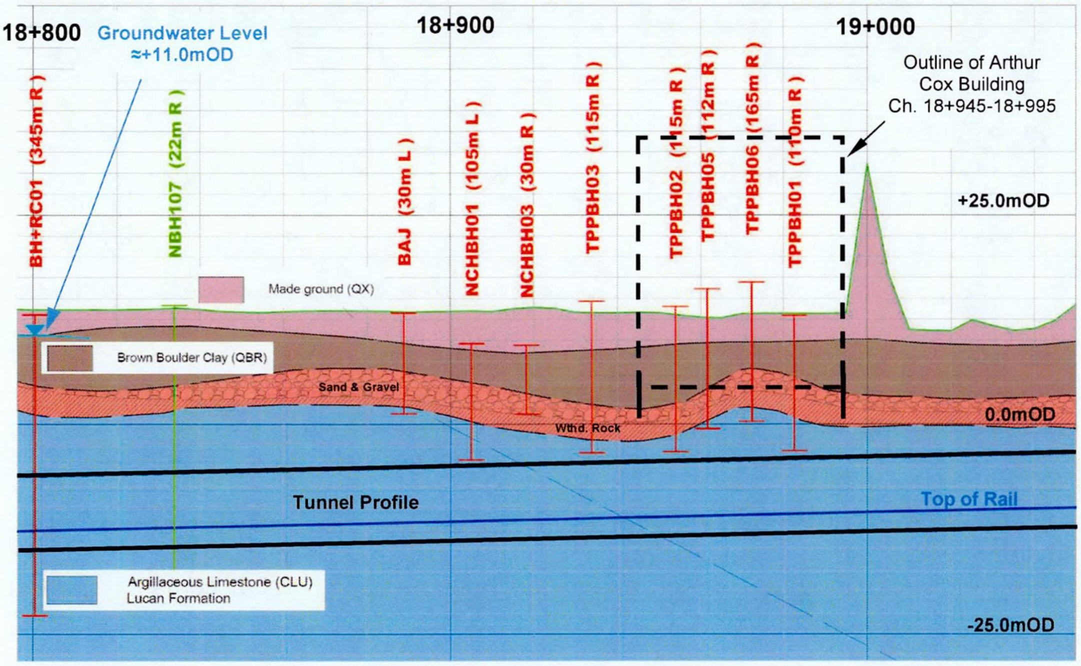


Figure 4-2 Geological Cross-Section [Sheet 26 of 28 from Appendix A20.9 to Chapter 20 of the EIAR]

4.2 Site Specific Site Investigation (SI) Data

Figure 4-3 shows the location plan for the site investigation that was carried out at the site of the Arthur Cox Building in 2008 for Michael Punch & Partners. The investigation was comprised of 4 No. boreholes (BH-1 to BH-4) and 2 No. rotary coreholes, RC-1 and RC-4, which were carried out adjacent to boreholes BH-1 and BH-4, respectively, as shown on Figure 4-3. Copies of the logs are included in Appendix B.

The boreholes were advanced to refusal in very stiff Boulder Clay or very dense sandy Gravel at depths of 5.6 to 8.2mBGL, which is within the depth of excavation for the basement (i.e. above +4.8mOD).

The top of competent Limestone rock was encountered at +4.50mOD in RC-1 at the north end of the building, and at the higher level of +5.90mOD in RC-2 at the south end.

A supplemental site investigation was carried out on the site by Punch Consulting in 2014 which included 3 No. additional rotary coreholes at the locations shown on Figure 4-4. The corehole logs are in Appendix B. Table 4-1 gives a summary of the rock levels in the holes.

In the 2014 coreholes the top of competent Limestone rock was encountered at +4.1mOD in RC-1 on the north side of the building and at the higher level of +7.35mOD in RC-3 on the south side of the building. A layer of weathered rock 0.6 to 1.4m thick was encountered at rockhead in RC-1 and RC-2.

Table 4-1 – Summary of rock levels in rotary coreholes

	Ground Level $^{(Note\ 1)}$**(mOD)**	**Top of Wthd. Rock (mOD)**	**Top of Competent Rock (mOD)**	**End of Corehole (mOD)**
RC-1 (2008)	+13.30m		+4.50m	+1.50m
RC-4 (2008)	+12.70m		+5.90m	+1.30m
RC-1 (2014)	+13.20m	+5.40m	+4.10m	-1.40m
RC-2 (2014)	+12.60m	+5.60m	+5.00m	-2.35m
RC-3 (2014)	+12.35m	-	+7.35m	-2.75m

Notes:

1. *The ground levels are not report on the logs and have been determined from the ground levels shown on Figure 4-3.*

The rock encountered in the coreholes is classified as a strong to medium strong or very strong, grey to dark grey, fine-grained, thinly to medium or thickly bedded argillaceous LIMESTONE with dark grey/black thinly bedded to laminated Mudstone/Shale seams. This is consistent with the typical characteristics of the Calp Limestone of the Lucan Formation.

The rock is described as fresh to slightly weathered, and locally moderately weathered in the Mudstone/Shale seams. Total core recovery (TCR) in the competent rock was 100%. The quality of the rock increased with depth with RQD (Rock Quality Designation) of 17-36% in the more fractured rock at rockhead, increasing to 65-85% below this level.

The coreholes were terminated in competent rock at levels between +1.30mOD and -2.75mOD, which is below the basement floor slab (+4.8mOD) and generally below the toe level for the perimeter secant pile wall (+0.65mOD). However, they did not reach the design level of the tunnel, which is below -3.3 to -4.2mOD.

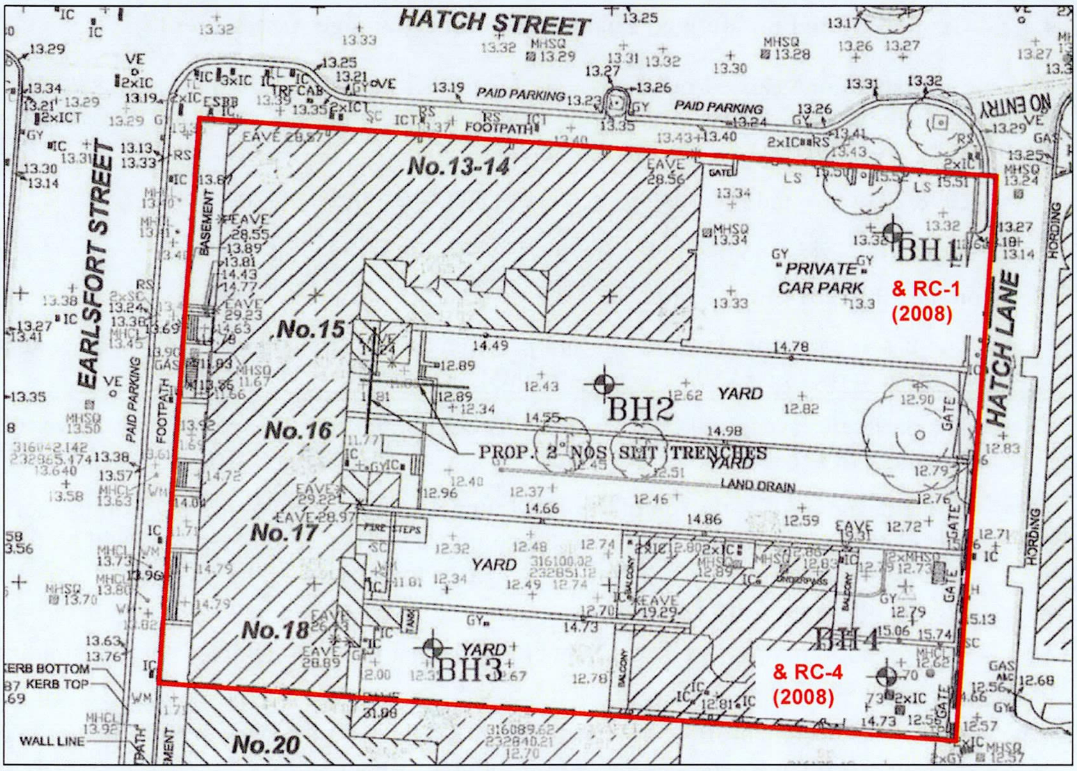


Figure 4-3 SI Location plan for 2008 Ground Investigation for Michael Punch & Partners

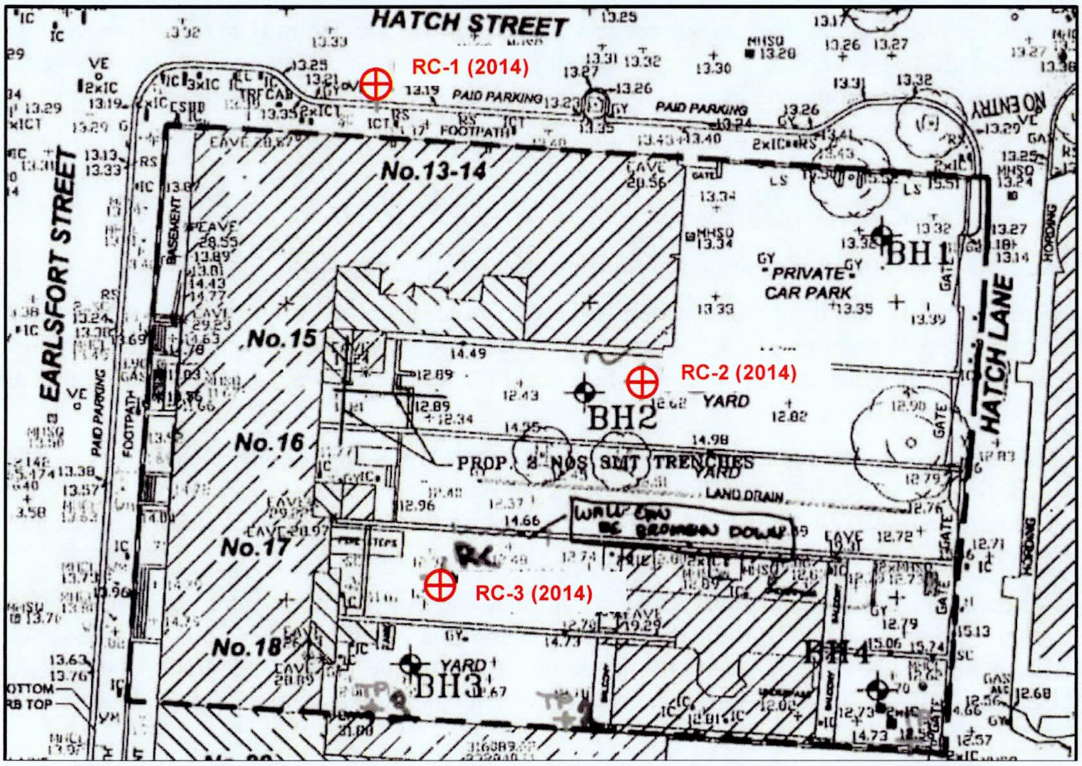


Figure 4-4 SI Location plan for 2014 Supplemental Ground Investigation for Punch Consulting

4.3 Ground Model for Refined Phase 2a Building Damage Asssessment

The site investigations carried out on the site of the Arthur Cox Building in 2008 & 2014 indicate that the top of rock is at a higher level than shown on the geological cross section produced by Jacobs/IDOM for the EIAR (Figure 4-2) i.e.:

- 2008/2014 Ground Investigations: +4.5mOD to +7.35mOD
- Jacobs/IDOM Cross Section: +2.50mOD to -2.50mOD

Based on the 2008/2014 investigations:

- The basement floor slab and internal pad foundations are supported on weathered or competent rock at +4.80mOD to +4.65mOD, respectively.
- The perimeter secant pile wall is embedded 3.5-4.0m into competent rock below the basement to a toe level of +0.65mOD.
- At the design profile the top of the TBM tunnel bore rises from -4.2mOD on the north side of the building to -3.3mOD on the south side. Therefore, the tunnel will be fully in rock and there will be 8.1 to 8.3m cover of rock between the basement floor slab and the top of the tunnel.

This is the ground, building and design tunnel profile that has been adopted for the Building Damage Assessment in this report.

Note that, at the design profile there will be >0.5D cover of rock over the tunnel (i.e. >4.75m), which would mean that the lower bound volume loss of 0.75% assumed by Jacobs/IDOM for their Phase 2a BDA would apply across the full width of the building.

However, the Railway Order includes proposed Limits of Deviation (LoD) to allow changes to be made to the vertical and horizontal alignment of the tunnel at detailed design stage to accommodate engineering design and construction constraints. The following LoD are proposed for the vertical alignment:

- **+5.0m** upwards
- **-10.0m** downwards.

An LoD of **±15.0m** is also proposed for the horizontal alignment.

If the tunnel is raised by 5.0m, which is the maximum proposed upward Limit of Deviation (LoD), **then the depth of rock cover under the basement reduces to 3.1-3.3m, which is <0.5D**, in which case the upper limit of ground loss should apply across the full width of the building (1.50%).

This is not recognised in the Building Damage Report (BDR) by Jacobs/IDOM. It is also not identified in the Wider Effects Report (WER) in Appendix 5.19 of the EIAR, which assesses whether the power to deviate the tunnel alignment within the LoD would alter the predicted significant impacts reported in the EIAR.

Furthermore, if the tunnel is raised by 5.0m, then the crown of the tunnel bore for the TBM cutter head will be at **+0.8mOD** on the north side of the building and **+1.7mOD** on the south side, which is above the toe level of the perimeter secant pile wall (+0.65mOD). **This means that the TBM will hit the base of the piles**, which has also not been recognised in the BDR or WER reports by Jacobs/IDOM.

These are notable omissions to the EIAR as they could have significant impacts on the building damage assessment for the Arthur Cox Building.

5.0 BUILDING DAMAGE ASSESSMENT METHODOLOGY

5.1 Building Risk Category and Damage Classification

The risk category and building damage for each building model and tunnel profile has been classified using the criteria set out in Table 5-1, which is presented as Table 4-4 in Section 4 of the Building Damage Report by Jacobs/IDOM (EIAR Appendix A5.17).

Table 5-1 – Criteria for Building Risk Category and Damage Classification (Table 4-4 in Building Damage Report by Jacobs/IDOM – Appendix A5.17 of the EIAR)

Building and Structure Damage Classification (after Burland et al (1977) and Boscarding and Cording (1989))					Approximately Equivalent Ground Settlements and Slopes (after Rankin 1988)	
Risk Category	**Degree of Damage**	**Description of Typical Damage and Likely Forms of Repair for Typical Masonry Buildings**	**Approx. Crack Width (mm)**	**Limiting Max Tensile Strain (%)**	**Max Slope of Ground**	**Maximum Settlement of Building (mm)**
0	Negligible	Hairline cracks	<0.1	Less than 0.05		
1	Very Slight	Fine cracks easily treated during normal redecoration. Perhaps isolated slight fracture in building Cracks in exterior brickwork visible upon close inspection	0.1 to 1	0.05 to 0.075	Less than 1:500	Less than 10
2	Slight	Cracks easily filled. Redecoration probably required. Several slight fractures inside building. Exterior cracks visible some re-pointing may be required for weather tightness. Doors and windows may stick slightly	1 to 5	0.075 to 0.15	1:500 to 1:200	10 to 50
3	Moderate	Cracks may require cutting out and patching. Recurrent cracks can me masked by suitable linings. Re-pointing and possibly replacement of a small amount of extent brickwork may be required. Doors and windows sticking. Utility services may be interrupted. Weather tightness often impaired	5 to 15 or a number of cracks greater than 3	0.15 to 0.3	1:200 to 1:50	50 to 75
4	Severe	Extensive repair involving removal and replacement of sections of walls, especially over doors and windows required. Windows and frames distorted. Floor slopes noticeably. Walls lean or bulge noticeably, some loss of bearing in beams. Utility services disrupted.	15 to 25 but also depends on number of cracks	Greater than 0.3	1:200 to 1:50	Greater than 75
5	Very Severe	Major repair required involving partial or complete reconstruction. Beams lose bearing, walls lean badly and require shoring. Windows broken by distortion Danger of instability	Greater than 25 but also depends on number of cracks	Greater than 0.3	Greater than 1:50	Greater than 75

For this assessment the Risk Category and potential Building Damage have been classified as a function of the max. building settlement, ground slope and limiting maximum tensile strain that could occur due to ground loss and settlement when tunnelling under the building.

The maximum building settlement and ground slope have been calculated from the estimated profile of vertical settlements over the tunnel. The limiting maximum tensile strain has been calculated as a function of the corresponding horizontal, bending and diagonal strains that could occur in the building.

The following sections give details of the calculations that were involved.

5.2 Settlements & Maximum Ground Slope

As described in Section 4.2.2 of the BDR, the shape of the settlement trough above the tunnel has been assumed to follow a Gaussian distribution curve centred over the centreline of the tunnel, as illustrated in Figure 5-1 and Figure 5-2.

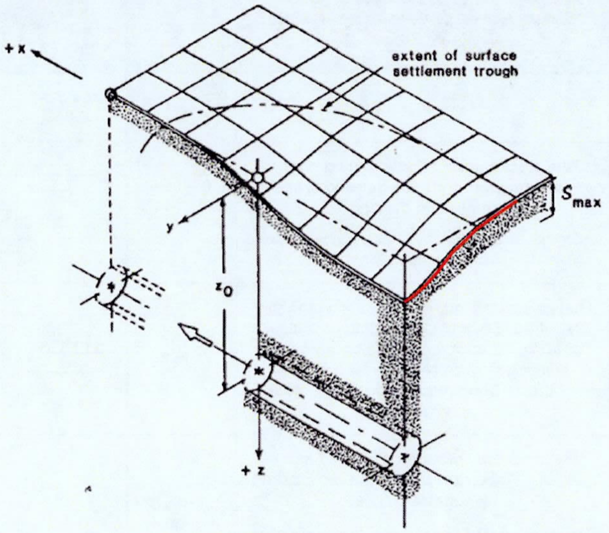


Figure 5-1 Profile of settlements over an advancing tunnel (Mair et al, 1996)

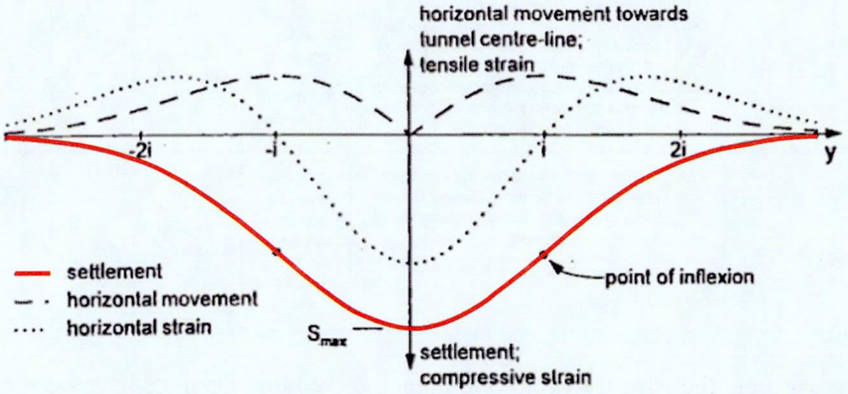


Figure 5-2 Profile of vertical and horizontal movements over the tunnel centreline and the corresponding horizontal strains (Figure 4-3 of the BDR in Appendix 5.17 of the EIAR)

The settlement (S_v) is defined as a function of the distance from the tunnel centreline, **y**, by the equation:

$$\mathbf{S_v = S_{max}exp(-y^2/2i^2)}$$

Where:

- $\mathbf{S_{max}}$ = maximum settlement over the centreline of the tunnel
- **y** = horizontal distance from the tunnel centreline
- **i** = the horizontal distance to the point of inflection on the settlement trough, which is defined as:

  $$\mathbf{i = Kz_o}$$

  Where:

  - **K** = the trough width parameter
  - $\mathbf{z_o}$ = depth to tunnel axis below ground level

The trough width parameter, **K**, is an empirical parameter that is defined by the ground conditions along and above the tunnel horizon.

At the Arthur Cox building the tunnel will be wholly in rock with at least half a tunnel diameter (>4.75m) of rock above the crown of the tunnel. Therefore, as described in Section 4.2.3 of the BDR, a value of **K=0.4** has been adopted for this Phase 2a assessment.

The basement of the Arthur Cox Building is supported on the rock at +4.80mOD, which is approximately 8.4m below ground level on Hatch Street (+13.2mOD). Also, the building façade is supported on a 900mm diameter perimeter secant pile retaining wall which has a toe level of +0.65mOD under the main façade on Hatch St. Therefore, for this Phase 2a assessment the depth to the tunnel axis, z_o, has been calculated relative to the level at the underside of the floor slab (Section 2 & 3) or to pile toe level (Section 1) rather than street level to get a more representative assessment of the ground movements that could impact the building.

The maximum settlement, $\mathbf{S_{max}}$, is calculated as a function of the volume of the settlement trough per metre length of tunnel, **Vs**, using the equation:

$$\mathbf{S_{max} = V_s/(i\sqrt{2\pi})}$$

The volume of the settlement trough is assumed to be equal to the total volume of ground loss during tunnelling, i.e.:

$$\mathbf{Vs = V_l.A}$$

Where:

- $\mathbf{V_l}$ = the ground loss due to tunnelling expressed as a percentage of the cross-sectional area of the tunnel bore; and
- **A** = cross-sectional area of the tunnel = $\pi D^2/4$, where D is the outer diameter of the TBM tunnel bore.

The following ground loss parameters were assumed for the *refined* Phase 2a assessment methodology in Section 5.2.1 of the BDR:

- **V_l = 0.5%** where the tunnel is in rock and there is at least half a tunnel diameter (i.e. ≥0.5D) of rock cover above the crown; and
- **V_l = 1.0%** in mixed soil/rock strata with <0.5D cover, or in superficial material (clay/granular soil).

These are considered by Jacobs/IDOM to be compatible with the values experienced using the modern tunnelling equipment and control systems that are expected to be used on the Metrolink project. The value of 0.5% for ground loss related to tunnelling in rock is also consistent with experience on the Dublin Port Tunnel (Gillarduzzi, 2014). Therefore, we have adopted these values for the building damage assessment in this report rather than the more conservative values of 0.75%/1.50% used by Jacobs/IDOM for the Phase 1 and Phase 2a assessments for the Arthur Cox Building in the BDR.

At the Arthur Cox building the tunnel will be in rock with at least half a tunnel diameter of rock cover. Therefore, the lower bound value of 0.5% should apply for calculating ground movements due to ground loss due to tunnelling.

However, these parameters are used to assess "greenfield" settlements that do not account for concentrated building loads from the secant pile wall or interior pad foundations. Therefore, we have also calculated settlements for a higher ground loss of 1.0% to calibrate the sensitivity of the analysis.

For this refined Phase 2a assessment, the tunnel diameter, D, has been taken as the diameter of the TBM cutter head (9.53m – BDR Section 2.1).

The calculated settlement trough profiles are included in Appendix C. Table 5.2 gives a summary of the upper and lower bound values of S_{max} for each analysis case.

The maximum ground slope across the settlement trough, $\mathbf{m_{max}}$, has been calculated using the following equation that was derived by differentiating the equation for S_v with respect to y at the point of inflection of the settlement trough, i.e. @y=i.

- $\mathbf{m_{max}} = [dS_v/dy \ @ \ y=i] = \mathbf{(-S_{max}/i).e^{-0.5}}$

The corresponding values for each analysis case are also included in Table 5.2.

Table 5-2 – Max settlement (S_{max}) and maximum ground slope (m_{max}) for each analysis

Analysis	Profile Details	Depth to tunnel axis, z_o	Cover to Fndn. Subgrade (m)	Lower Bound (V_l = 0.5%)		Upper Bound (V_l = 1.0%)	
				S_{max}	m_{max}	S_{max}	m_{max}
Case 1A	Ch.18+945 (Hatch St.) Secant Pile Wall/Bldg. Façade **Design Vertical Alignment**	9.6m	4.9m	37mm	0.58%	74mm	1.16%
Case 1B	Ch.18+945 (Hatch St.) Secant Pile Wall/Bldg. Facade Raised Vertical Alignment (+ 3.9m)	5.7m	1.0m	62mm	1.63%	124mm	3.25%
Case 1C	Ch.18+945 (Hatch St.) Secant Pile Wall/Bldg. Facade Lowered Vertical Alignment (- 5.0m)	14.6m	9.9m	24mm	0.25%	49mm	0.50%
Case 2A	Ch.18+970 (Centre) Internal Building RC Frame **Design Vertical Alignment**	13.3m	8.6m	27mm	0.30%	53mm	0.61%
Case 2B	Ch.18+970 (Centre) Internal Building RC Frame Raised Vertical Alignment (+ 5.0m)	8.3m	3.6m	43mm	0.78%	85mm	1.55%
Case 1C	Ch.18+970 (Centre) Internal Building RC Frame Lowered Vertical Alignment (- 5.0m)	18.3m	13.6m	19mm	0.16%	39mm	0.32%
Case 3A	Ch.18+995 (South Side) Basement Floor Slab **Design Vertical Alignment**	12.9m	8.1m	28mm	0.32%	55mm	0.65%
Case 3B	Ch.18+995 (South Side Basement Floor Slab Raised Vertical Alignment (+ 5.0m)	7.9m	3.1m	45mm	0.87%	90mm	1.74%
Case 3C	Ch.18+995 (South Side Basement Floor Slab Lowered Vertical Alignment (- 5.0m)	17.9	13.1m	20mm	0.04%	40mm	0.07%

5.3 Horizontal Movement (S_h) & Horizontal Ground & Building Strain (ε_h)

The horizontal movement of the ground within the settlement trough, S_h, has been calculated from the settlement profile using the following equation from Section 4.3.4 of the BDR:

$$S_h = (y/z_o)S_v = (y/z_o)S_{max}.\exp(-y^2/2i^2)$$

Figure 5-2 shows a typical profile of horizontal movement across the settlement trough. The resultant vectors of ground movement are directed towards the tunnel axis. The calculations for each analysis case are presented in Appendix C.

The horizontal ground strains, ε_h, were calculated using the following equation that was derived by differentiating the equation for horizontal ground movements with respect to y:

$$\varepsilon_h = dS_h/d_y = (S_{max}/z_o)[1-(y^2/i^2)].\exp(-y^2/2i^2)$$

Figure 5-2 shows a typical profile of horizontal ground strains across the settlement trough. The calculations for each analysis case are presented in Appendix C.

As described in Section 4.3.4 of the BDR, to assess the potential building damage it is assumed that the building behaves as an ideal beam of height **H** that deforms to the profile of the ground movements at the foundation level (i.e. at the tip of the secant pile wall or at basement subgrade level). This creates sagging and hogging zones of building movements, as illustrated in Figure 5-3, which are analysed separately to determine the maximum limiting tensile strain on the building.

Where the Metrolink tunnel passes under the Arthur Cox building the basement and perimeter walls extend across the full width of the settlement trough. Therefore, the building response has been assessed over one half of the trough with the maximum settlement centred over the centreline of the tunnel.

The extent of the hogging and sagging zones are as follows:

- Sagging Zone: y=0 (tunnel centreline) to y=i (point of inflection of settlement trough)
- Hogging Zone: y=i (point of inflection of settlement trough) to y = 2.5i (practical limit of settlement trough)

Therefore:

- Length of sagging zone, $\mathbf{L_s = i}$ (i.e. from y=0 to y=i), and
- Length of hogging zone, $\mathbf{L_h = 1.5i}$ (i.e. from y=i to y=2.5i).

The average horizontal strain in each zone has been calculated by subtracting the horizontal movement at either end by the corresponding length of the zone.

The calculations for each analysis case are presented in Appendix C and summarised on Table 5-3. Horizontal strain within the sagging zone is compressive (+ive), whereas horizontal strain in the hogging zone is tensile (-ive). Calculations are included for lower and upper bound displacements corresponding to the assumed volume loss parameters of 0.5% and 1.0% of the tunnel volume.

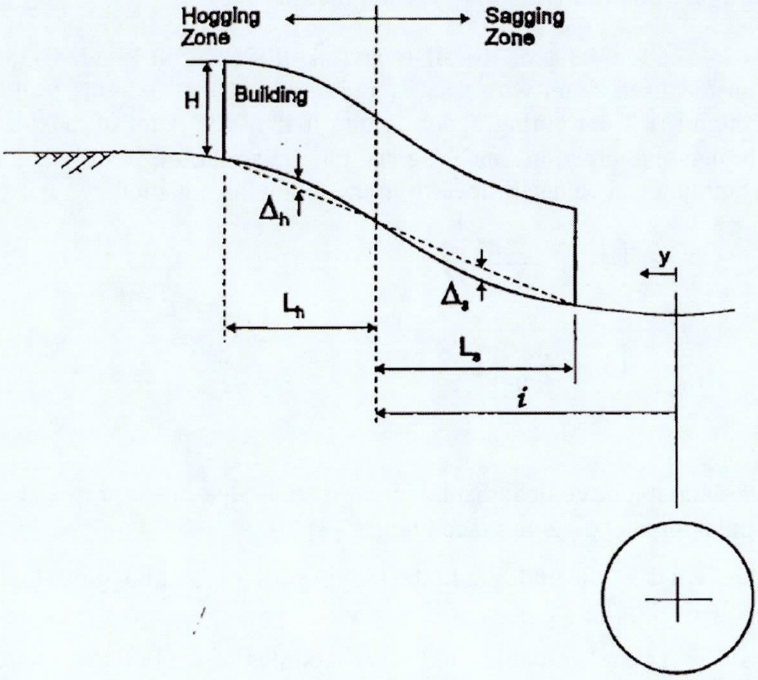


Figure 5-3 – Theoretical profile of building deformation (Figure 4-5 in the BDR)

Table 5-3 Horizontal movements (S_h) & horizontal building strains (ε_h)

Analysis	Details	Lower Bound (V_l = 0.5%)							Upper Bound (V_l = 1.0%)						
		S_h	S_h	S_h	Sagging		Hogging		S_h	S_h	S_h	Sagging		Hogging	
		@y=0	@y=i	@y=2.5i	L_s	ε_{hs}	L_h	ε_{hh}	@y=0	@y=i	@y=2.5i	L_s	ε_{hs}	L_h	ε_{hh}
		(mm)	(mm)	(mm)	(m)	[%]	(m)	[%]	(mm)	(mm)	(mm)	(m)	[%]	(m)	[%]
Case 1A	Ch. 18+945 (Hatch St.) Secant Pile Wall/Bldg. Façade **Design Vertical Alignment**	0	9.0	1.6	3.85	0.23%	5.78	-0.13%	0.0	17.9	3.2	3.85	0.47%	5.78	-0.25%
Case 1B	Ch. 18+945 (Hatch St.) Secant Pile Wall/Bldg. Façade Raised Vertical Alignment (+3.9m)	0	15.0	2.7	2.30	0.65%	3.46	-0.36%	0.0	30.0	5.4	2.30	1.30%	3.46	-0.71%
Case 1C	Ch. 18+945 (Hatch St.) Secant Pile Wall/Bldg. Façade Lowered Vertical Alignment (-5.0m)	0	5.9	1.1	5.85	0.10%	8.78	-0.06%	0.0	11.8	2.1	5.85	0.20%	8.78	-0.11%
Case 2A	Ch. 18+970 (Centre) Internal Building RC Frame **Design Vertical Alignment**	0	6.5	1.2	5.33	0.12%	8.00	-0.07%	0.0	12.9	2.3	5.33	0.24%	8.00	-0.13%
Case 2B	Ch. 18+970 (Centre) Internal Building RC Frame Raised Vertical Alignment (+5.0m)	0	10.4	1.9	3.33	0.31%	5.00	-0.17%	0.0	20.7	3.8	3.33	0.62%	5.00	-0.34%
Case 2C	Ch. 18+970 (Centre) Internal Building RC Frame Lowered Vertical Alignment (-5.0m)	0	4.7	0.9	7.33	0.06%	11.00	-0.04%	0.0	9.4	1.7	7.33	0.13%	11.00	-0.07%
Case 3A	Ch. 18+995 (South Side) Basement Floor Slab **Design Vertical Alignment**	0	6.7	1.2	5.15	0.13%	7.73	-0.07%	0.0	13.4	2.4	5.15	0.26%	7.73	-0.14%
Case 3B	Ch. 18+995 (South Side) Basement Floor Slab Raised Vertical Alignment (+5.0m)	0	10.9	2.0	3.15	0.35%	4.73	-0.19%	0.0	21.9	4.0	3.15	0.69%	4.73	-0.38%
Case 3C	Ch. 18+995 (South Side) Basement Floor Slab Lowered Vertical Alignment (-5.0m)	0	4.8	0.9	7.15	0.07%	10.73	-0.04%	0.0	9.7	1.7	7.15	0.13%	10.73	-0.07%

5.4 Bending Strain and Diagonal (Shear) Strains

As described in Section 4.3.4 of the BDR and as illustrated in Figure 5-3, by treating the building as an idealised beam with span L and height H that deforms to the profile of the settlement trough (as if deforming under a point load at the point of maximum settlement), the maximum bending strain, $\boldsymbol{\varepsilon_b}$, and diagonal (shear) strain, $\boldsymbol{\varepsilon_d}$, in the sagging and hogging zones of the building can be determined from the following equations:

$$\frac{\Delta}{L} = \left\{\frac{L}{12t} + \frac{3I\,E}{2tLH\,G}\right\}\varepsilon_b$$

$$\frac{\Delta}{L} = \left\{1 + \frac{HL^2G}{18IE}\right\}\varepsilon_d$$

Where:

- **Δ** is the maximum vertical displacement relative to a linear profile across the sagging (Δ_s) and hogging (Δ_s) zones (see Figure 5-3);
- **L** is the length of the building in the sagging ($L_s = i$) and hogging ($L_h = 1.5i$) zones of the settlement trough;
- **E** and **G** = Young's modulus and shear modulus of the building modelled as a beam of height H;
- **H** is the height of the building – from basement subgrade level (or base of secant pile wall) to roof level (Case 1/Case 3), or the thickness of the basement floor slab (Case 2);
- **t** is the furthest distance from the neutral axis to the edge of the beam; and
- **I** is the moment of inertia of the beam.

The strains were calculated using the following parameters for E & G that were used for the design of the concrete in the building frame (E/G = 2.0):

- $E = 20 \times 10^6$ N/mm^2
- $G = 10 \times 10^6$ N/mm^2

In the **sagging** zone the neutral axis is assumed to be at the centre of the beam representing the building. Therefore:

- $t_s = H/2$
- $I_s = H^3/12$

Bending in this zone will cause **compressive** (+ive) **and tensile** (-ive) bending and diagonal strains (ε_{bs} & ε_{ds}).

In the **hogging** zone the neutral axis is assumed to be at the base of the beam representing the building due to the restraining effect of the foundations. Therefore:

- $t_h = H$
- $I_h = H^3/3$

Bending in this zone will cause **tensile** (-ive) bending and diagonal strains (ε_{bh} & ε_{dh}).

The calculations for each analysis case are presented in Appendix C and summarised on Table 5-4 and Table 5-5 for the sections of the building in the sagging and hogging zones, respectively.

Calculations are included for lower and upper bound displacements corresponding to the assumed volume loss parameters of 0.5% and 1.0% of the tunnel volume (V_l = 0.5% & 1.0%).

Strains within the sagging zone are shown as compressive (+ive) but can also be tensile. Strains in the hogging zone are tensile (-ive).

Table 5-4 – Bending strains (ε_{bs}) and diagonal strains (ε_{ds}) in the sagging zone

Analysis	Details	Lower Bound (V_l = 0.5%)					Upper Bound (V_l = 1.0%)				
		H	Sagging Zone				H	Sagging Zone			
			L_s	Δ_s	ε_{bs}	ε_{ds}		L_s	Δ_s	ε_{bs}	ε_{ds}
		(m)	(m)	(mm)	Bending	Diagonal	(m)	(m)	(mm)	Bending	Diagonal
Case 1A	Ch. 18+945 (Hatch St.) Secant Pile Wall/Bldg. Façade **Design Vertical Alignment**	34.80	3.85	3.0	0.02%	0.08%	34.80	3.85	5.9	0.03%	0.15%
Case 1B	Ch. 18+945 (Hatch St.) Secant Pile Wall/Bldg. Façade Raised Vertical Alignment (+3.9m)	34.80	2.30	5.0	0.03%	0.22%	34.80	2.30	9.9	0.06%	0.43%
Case 1C	Ch. 18+945 (Hatch St.) Secant Pile Wall/Bldg. Façade Lowered Vertical Alignment (-5.0m)	34.80	5.85	2.0	0.01%	0.03%	34.80	5.85	3.9	0.02%	0.07%
Case 2A	Ch. 18+970 (Centre) Internal Building RC Frame **Design Vertical Alignment**	34.62	5.33	2.1	0.01%	0.04%	34.62	5.33	4.3	0.02%	0.08%
Case 2B	Ch. 18+970 (Centre) Internal Building RC Frame Raised Vertical Alignment (+5.0m)	34.62	3.33	3.4	0.02%	0.10%	34.62	3.33	6.9	0.04%	0.21%
Case 2C	Ch. 18+970 (Centre) Internal Building RC Frame Lowered Vertical Alignment (-5.0m)	34.62	7.33	1.6	0.01%	0.02%	34.62	7.33	3.1	0.02%	0.04%
Case 3A	Ch. 18+995 (South Side) Basement Floor Slab **Design Vertical Alignment**	0.60	5.15	2.2	0.03%	0.00%	0.60	5.15	4.4	0.06%	0.00%
Case 3B	Ch. 18+995 (South Side) Basement Floor Slab Raised Vertical Alignment (+5.0m)	0.60	3.15	3.6	0.12%	0.01%	0.60	3.15	7.3	0.24%	0.02%
Case 3C	Ch. 18+995 (South Side) Basement Floor Slab Lowered Vertical Alignment (-5.0m)	0.60	7.15	1.6	0.01%	0.00%	0.60	7.15	3.2	0.02%	0.00%

Table 5-5 – Bending strains (ε_{bh}) and diagonal strains (ε_{dh}) in the hogging zone

Analysis	Details	Lower Bound (V_l = 0.5%)					Upper Bound (V_l = 1.0%)				
		H	Hogging Zone				H	Hogging Zone			
			L_H	Δ_H	ε_{bh}	ε_{dh}		L_H	Δ_H	ε_{bh}	ε_{dh}
		(m)	(m)	(mm)	Bending	Diagonal	(m)	(m)	(mm)	Bending	Diagonal
Case 1A	Ch. 18+945 (Hatch St.) Secant Pile Wall/Bldg. Façade **Design Vertical Alignment**	34.8	5.78	-4.0	-0.01%	-0.07%	34.8	5.78	-8.0	-0.02%	-0.14%
Case 1B	Ch. 18+945 (Hatch St.) Secant Pile Wall/Bldg. Façade Raised Vertical Alignment (+3.9m)	34.8	3.46	-6.7	-0.02%	-0.19%	34.8	3.46	-13.4	-0.04%	-0.39%
Case 1C	Ch. 18+945 (Hatch St.) Secant Pile Wall/Bldg. Façade Lowered Vertical Alignment (-5.0m)	34.8	8.78	-2.6	-0.01%	-0.03%	34.8	8.78	-5.3	-0.02%	-0.06%
Case 2A	Ch. 18+970 (Centre) Internal Building RC Frame **Design Vertical Alignment**	34.62	8.00	-2.9	-0.01%	-0.04%	34.62	8.00	-5.8	-0.02%	-0.07%
Case 2B	Ch. 18+970 (Centre) Internal Building RC Frame Raised Vertical Alignment (+5.0m)	34.62	5.00	-4.6	-0.01%	-0.09%	34.62	5.00	-9.3	-0.03%	-0.18%
Case 2C	Ch. 18+970 (Centre) Internal Building RC Frame Lowered Vertical Alignment (-5.0m)	34.62	11.00	-2.1	-0.01%	-0.02%	34.62	11.00	-4.2	-0.01%	-0.04%
Case 3A	Ch. 18+995 (South Side) Basement Floor Slab **Design Vertical Alignment**	0.60	7.73	-3.0	-0.03%	0.00%	0.60	7.73	-6.0	-0.07%	-0.01%
Case 3B	Ch. 18+995 (South Side) Basement Floor Slab Raised Vertical Alignment (+5.0m)	0.60	4.73	-4.9	-0.13%	-0.02%	0.60	4.73	-9.8	-0.26%	-0.03%
Case 3C	Ch. 18+995 (South Side) Basement Floor Slab Lowered Vertical Alignment (-5.0m)	0.60	10.73	-2.2	-0.01%	0.00%	0.60	10.73	-4.3	-0.03%	0.00%

5.5 Total Bending and Diagonal Strains & Maximum Combined Tensile Strain

As described in Section 4.3.4 of the BDR, the maximum combined tensile strain that is used to assess the potential building damage with Table 5-1 is determined by combining the total horizontal building strain (ε_h) from Section 5.3 with the bending strains (ε_b) and diagonal strains (ε_d) from Section 5.4 using the following equations:

$$\varepsilon_{bt} = \varepsilon_h + \varepsilon_b$$

$$\varepsilon_{dt} = 0.35\varepsilon_h + \left[(0.65\varepsilon_h)^2 + \varepsilon_d^2\right]^{0.5}$$

The maximum value of the combined tensile strain obtained from these equations is used in the assessment of the potential building damage category in Table 5-1.

The calculations for each analysis case are presented in the appendices and summarised on Table 5-6 and Table 5-7 for the sections of the building in the sagging and hogging zones, respectively. Calculations are included for lower and upper bound displacements corresponding to the assumed volume loss parameters of 0.5% and 1.0% of the tunnel volume (V_l = 0.5% & 1.0%). Compressive strains are shown as positive and tensile strains are shown as negative.

In the **sagging** zone the horizontal strains are compressive (+ive) but the bending and diagonal (shear) strains can be either compressive (+ive) or tensile (-ive) because the neutral axis is assumed to be at the centre of the beam (H/2). The positive horizontal strains in the sagging zone are significantly larger than the tensile bending and diagonal strains. Therefore:

- For the bending strains, the total bending strain (ε_{bt}) has been calculated as the sum of the compressive (+ive) horizontal strain ($\varepsilon_{h\,+ive}$) and bending strains ($\varepsilon_{b\,+ive}$);
- However, for the diagonal strains we have calculated the maximum *compressive* diagonal strain ($\varepsilon_{dt\,+ive}$) using positive values for both the horizontal and bending strains ($\varepsilon_{h\,+ive}$ & $\varepsilon_{d\,+ive}$).

In the **hogging** zone, where the building is more susceptible to damage, the horizontal strains, bending strains and diagonal (shear) strains are tensile (-ive) because the neutral axis is assumed to be at the base of the beam. Therefore:

- For the bending strains, the total bending strain (ε_{bt}) has been calculated as the sum of the tensile (-ive) horizontal ($\varepsilon_{h\,-ive}$) and bending strains ($\varepsilon_{b\,-ive}$);
- For the diagonal strains a representative resultant total diagonal strain ($\varepsilon_{dt\,-ive}$), has been calculated using the *absolute* values of the tensile horizontal and diagonal strains ($\varepsilon_{h\,-ive}$ & $\varepsilon_{d\,-ive}$) because of the square functions in the equation. However, the calculated resultant has been reported as a maximum *tensile* diagonal strain ($\varepsilon_{dt\,-ive}$) for consistency with the sign convention in this report.

Only negative tensile strains are considered in the building damage assessment.

The maximum tensile (-ive) bending or diagonal strain from the sagging or hogging zone (typically hogging) is used in the building damage assessment. The relevant values are summarised in Table 5-8.

Table 5-6 – Total bending strains (ε_{bts}) and diagonal strains (ε_{dts}) in the sagging zone [Compressive]

Analysis	Profile Details	Combined Strains (Sagging Zone)							
		Lower Bound (V_l = 0.5%)				Upper Bound (V_l = 1.0%)			
		Horizontal	Bending	Combined (Bending)	Combined (Diagonal)	Horizontal	Bending	Combined (Bending)	Combined (Diagonal)
		ε_h (%)	ε_b (%)	ε_{bt} (%)	ε_{dt} (%)	ε_h (%)	ε_b (%)	ε_{bt} (%)	ε_{dt} (%)
Case 1A	Ch. 18+945 (Hatch St.) Secant Pile Wall/Bldg. Façade **Design Vertical Alignment**	0.23%	0.02%	0.25%	0.25%	0.47%	0.03%	0.50%	0.50%
Case 1B	Ch. 18+945 (Hatch St.) Secant Pile Wall/Bldg. Façade Raised Vertical Alignment (+3.9m)	0.65%	0.03%	0.68%	0.70%	1.30%	0.06%	1.36%	1.40%
Case 1C	Ch. 18+945 (Hatch St.) Secant Pile Wall/Bldg. Façade Lowered Vertical Alignment (-5.0m)	0.10%	0.01%	0.11%	0.11%	0.20%	0.02%	0.22%	0.22%
Case 2A	Ch. 18+970 (Centre) Internal Building RC Frame **Design Vertical Alignment**	0.12%	0.01%	0.13%	0.13%	0.24%	0.02%	0.27%	0.26%
Case 2B	Ch. 18+970 (Centre) Internal Building RC Frame Raised Vertical Alignment (+5.0m)	0.31%	0.02%	0.33%	0.34%	0.62%	0.04%	0.66%	0.67%
Case 2C	Ch. 18+970 (Centre) Internal Building RC Frame Lowered Vertical Alignment (-5.0m)	0.06%	0.01%	0.07%	0.07%	0.13%	0.02%	0.15%	0.14%
Case 3A	Ch. 18+995 (South Side) Basement Floor Slab **Design Vertical Alignment**	0.13%	0.03%	0.16%	0.13%	0.26%	0.06%	0.32%	0.26%
Case 3B	Ch. 18+995 (South Side) Basement Floor Slab Raised Vertical Alignment (+5.0m)	0.35%	0.12%	0.47%	0.35%	0.69%	0.24%	0.93%	0.69%
Case 3C	Ch. 18+995 (South Side) Basement Floor Slab Lowered Vertical Alignment (-5.0m)	0.07%	0.01%	0.08%	0.07%	0.13%	0.02%	0.16%	0.13%

Table 5-7 – Total bending strains (ε_{bth}) and diagonal strains (ε_{dth}) in the hogging zone [Tensile]

Analysis	Profile Details	Combined Strains (Hogging Zone)							
		Lower Bound (V_l = 0.5%)				Upper Bound (V_l = 1.0%)			
		Horizontal	Bending	Combined (Bending)	Combined (Diagonal)	Horizontal	Bending	Combined (Bending)	Combined (Diagonal)
		ε_h (%)	ε_b (%)	ε_{bt} (%)	ε_{dt} (%)	ε_h (%)	ε_b (%)	ε_{bt} (%)	ε_{dt} (%)
Case 1A	Ch. 18+945 (Hatch St.) Secant Pile Wall/Bldg. Façade **Design Vertical Alignment**	-0.13%	-0.01%	-0.14%	**-0.15%**	-0.25%	-0.02%	-0.28%	**-0.30%**
Case 1B	Ch. 18+945 (Hatch St.) Secant Pile Wall/Bldg. Façade Raised Vertical Alignment (+3.9m)	-0.36%	-0.02%	-0.37%	**-0.43%**	-0.71%	-0.04%	-0.75%	**-0.85%**
Case 1C	Ch. 18+945 (Hatch St.) Secant Pile Wall/Bldg. Façade Lowered Vertical Alignment (-5.0m)	-0.06%	-0.01%	-0.06%	**-0.07%**	-0.11%	-0.02%	-0.13%	**-0.13%**
Case 2A	Ch. 18+970 (Centre) Internal Building RC Frame **Design Vertical Alignment**	-0.07%	-0.01%	-0.07%	**-0.08%**	-0.13%	-0.02%	-0.15%	**-0.16%**
Case 2B	Ch. 18+970 (Centre) Internal Building RC Frame Raised Vertical Alignment (+5.0m)	-0.17%	-0.01%	-0.18%	**-0.20%**	-0.34%	-0.03%	-0.37%	**-0.41%**
Case 2C	Ch. 18+970 (Centre) Internal Building RC Frame Lowered Vertical Alignment (-5.0m)	-0.04%	-0.01%	-0.04%	**-0.04%**	-0.07%	-0.01%	-0.08%	**-0.08%**
Case 3A	Ch. 18+995 (South Side) Basement Floor Slab **Design Vertical Alignment**	-0.07%	-0.03%	**-0.10%**	-0.07%	-0.14%	-0.07%	**-0.21%**	-0.14%
Case 3B	Ch. 18+995 (South Side) Basement Floor Slab Raised Vertical Alignment (+5.0m)	-0.19%	-0.13%	**-0.32%**	-0.19%	-0.38%	-0.26%	**-0.64%**	-0.38%
Case 3C	Ch. 18+995 (South Side) Basement Floor Slab Lowered Vertical Alignment (-5.0m)	-0.04%	-0.01%	**-0.05%**	-0.04%	-0.07%	-0.03%	**-0.10%**	-0.07%

Table 5-8 – Maximum tensile strain ($\varepsilon_{t\text{-}max}$*)*

Analysis	Profile Details	Maximum Limiting Tensile Strains			
		Lower Bound (V_l = 0.5%)		Upper Bound (V_l = 1.0%)	
		$\varepsilon_{t\text{-}max}$ (%)	Zone	$\varepsilon_{t\text{-}max}$ (%)	Zone
Case 1A	Ch. 18+945 (Hatch St.) Secant Pile Wall/Bldg. Façade **Design Vertical Alignment**	-0.15%	Hogging	-0.30%	Hogging
Case 1B	Ch. 18+945 (Hatch St.) Secant Pile Wall/Bldg. Façade Raised Vertical Alignment (+3.9m)	-0.43%	Hogging	-0.85%	Hogging
Case 1C	Ch. 18+945 (Hatch St.) Secant Pile Wall/Bldg. Façade Lowered Vertical Alignment (-5.0m)	-0.07%	Hogging	-0.13%	Hogging
Case 2A	Ch. 18+970 (Centre) Internal Building RC Frame **Design Vertical Alignment**	-0.08%	Hogging	-0.16%	Hogging
Case 2B	Ch. 18+970 (Centre) Internal Building RC Frame Raised Vertical Alignment (+5.0m)	-0.20%	Hogging	-0.41%	Hogging
Case 2C	Ch. 18+970 (Centre) Internal Building RC Frame Lowered Vertical Alignment (-5.0m)	-0.04%	Hogging	-0.08%	Hogging
Case 3A	Ch. 18+995 (South Side) Basement Floor Slab **Design Vertical Alignment**	-0.10%	Hogging	-0.21%	Hogging
Case 3B	Ch. 18+995 (South Side) Basement Floor Slab Raised Vertical Alignment (+5.0m)	-0.32%	Hogging	-0.64%	Hogging
Case 3C	Ch. 18+995 (South Side) Basement Floor Slab Lowered Vertical Alignment (-5.0m)	-0.05%	Hogging	-0.10%	Hogging

5.6 Building Damage Assessment (BDA)

The results of the building damage assessment calculations are summarised in Table 5-9. The table gives the following values for each analysis case:

- Max limiting tensile strain, ε_{max} (%)
- Maximum ground slope on the settlement trough, m_{max} (%)
- Max settlement over the tunnel centreline, S_v (mm)

The risk category and degree of damage have been determined from the criteria in Table 5-1. The following is a summary of the analyses that were carried out:

- The BDA has been carried out for a lower and upper bound tunnel volume loss (V_l) of 0.5% & 1.0%, respectively. This corresponds to the parameters for the *Refined* Phase 2a assessment in the EIAR.
- At the Arthur Cox building the tunnel will be in rock with at least half a diameter cover (>4.75m) of rock below the building basement. Therefore, the lower bound estimates for a tunnel volume loss, **V_l, of 0.5%** should represent the conditions that could be achieved for modern TBM tunnelling in rock.
- The BDA methodology assumes that the building deforms and articulates to the profile of the greenfield settlement trough at foundation subgrade level. This is conservative as it does not account for re-distribution of stresses and ground movements as a result of the stiffness of the building.
- However, the methodology does not account for concentrated point loads such as those from the integral pad foundations in the basement floor slab, which are supporting the internal concrete building frame, or from the load-bearing piles in the perimeter secant pile wall, which are supporting combined loads from the building structure and external façade . Therefore, we have included calculations for an upper bound volume loss, **V_l, of 1.0%** to represent conditions that could potentially occur where there are concentrated loads over the tunnel and to calibrate the sensitivity of the analysis.
- The impact of concentrated loads from the building foundations in the basement floor slab or from load bearing piles in the perimeter secant pile wall is most acute where the level of the tunnel is high and close to the underside of the foundations. At deeper levels the concentrated loads become more dispersed through the rock so that they become less concentrated.
- The design vertical profile for the tunnel rises by **0.90m** from south to north across the width of the building so that it is shallowest on the south side.
- **Case 1** models the impact of the tunnel on the perimeter secant pile wall and full height building façade on the north side of the building (Ch. 18+945) based on the settlement profile at the pile toe level on Hatch St. (+0.65mOD).
- **Case 2** models the impact of the tunnel on the internal RC structure at the centre of the building (Ch. 18+945) based on the settlement profile at subgrade level for the basement floor slab (+4.8mOD).
- **Case 3** models the impact of the tunnel on the 600mm thick RC basement floor slab at the south end of the building (Ch. 18+945) based on the settlement profile at subgrade level for the basement floor slab (+4.8mOD), where the tunnel is shallowest.

- **Case 1A, Case 2A and Case 3A** represent the analyses that have been carried out at the design vertical profile for the tunnel.
- **Case 1B, Case 2B and Case 3B** represent the analyses that have been carried out for a raised vertical profile of the tunnel within the upper Limit of Deviation proposed in the Railway Order (+5.0m)
- **Case 1C, Case 2C and Case 3C** represent the analyses that have been carried out for a lowered vertical profile of the tunnel at 5.0m below the design level, which is within the upper limit of deviation proposed in the Railway Order (-10.0m)
- For **Case 1** the pile toe level is only 4.9m above the crown of the tunnel at the design profile. At the maximum proposed vertical LoD the TBM will hit the toe of the piles. Therefore, for Case 1B we have only raised the tunnel profile by **3.9m** so that the crown of the tunnel bore is at least **1.0m** below the toe of the piles.

Based on the results of the assessment in Table 5-9:

Results for Design Tunnel Profile (Case 1A, 2A & 3A):

- **At the design tunnel profile**, the lower bound estimates of ground movements for a volume loss of **0.5%** result in a Risk Category of 2 for the basement floor slab (Case 1A) and internal RC structure (Case 2A), which corresponds to Slight Damage. However, this increases to a Risk Category of 2/3 for the perimeter secant pile wall and building façade (Case 3A), which is at the boundary of Slight to Moderate Damage.
- For the upper bound estimates of ground movements corresponding to a volume loss of **1.0%** at the design tunnel profile, the Risk Category raises to 3 for the basement floor slab (Case 1A) and internal RC structure (Case 2A), which corresponds to Moderate Damage, and a Risk Category of 3/4 for the perimeter secant pile wall and building façade (Case 3A), which is at the boundary of Moderate to Severe Damage.
- There is **8.1-9.0m** cover between the subgrade for the internal pad foundations and the top of the TBM tunnel bore. The cover reduces to 4.0-4.9m at the toe level of the secant pile wall, although these are embedded 3.5-4.0m into competent rock below basement level. For these conditions the results for the BDA could represent an upper and lower bound estimate of the damage that could occur, depending on how the foundation loads are managed during construction.

Results for Raised Tunnel Profile (Case 1B, 2B & 3B):

- **For the raised tunnel profile**, there is a significant ***increase*** in concentrated displacements and strains in the building so that the lower bound estimates of ground movements for a volume loss of **0.5%** result in the following Risk Categories:
    - Case 1B (Perimeter Scant Pile Wall/Building Façade):
        - Risk Category = 4/3 (Severe to Moderate Damage)
    - Case 2B (Internal RC Structure):
        - Risk Category = 3/2 (Moderate to Slight Damage)
    - Case 3B (RC Basement Floor Slab):
        - Risk Category = 3 (Moderate Damage)

- At the upper bound estimates of ground movements corresponding to a volume loss of **1.0%** the risk category and degree of damage increases across the building as follows:
    - Case 1B (Perimeter Scant Pile Wall/Building Façade):
        - Risk Category = 4/5 (Severe to Very Severe Damage)
    - Case 2B (Internal RC Structure):
        - Risk Category = 4 (Severe Damage)
    - Case 3B (RC Basement Floor Slab):
        - Risk Category = 4 (Severe Damage)
- At the raised level, the concentrated loads on the internal pad foundations and perimeter secant pile wall will have a more significant impact on ground movements. **Therefore, for Case 1B, 2B and 3B the upper bound ground loss of 1.0% may give a more representative assessment of the risk of building damage.**
- The severe to very severe risk for Case 1B (Risk Category 4/5) at a volume loss of 1.0% still only corresponds to tunnel profile that has been raised by 3.9m so that it is min. 1.0m below the pile toe level. If the tunnel profile is raised to the maximum proposed vertical LoD then the **TBM will hit the toe of the piles. This would cause a higher level of direct damage to the basement structure and building façade which cannot be modelled with the methodology for the Phase 2 assessment.**

Results for Lowered Tunnel Profile (Case 1C, 2C & 3C):

- **For the lowered tunnel profile**, there is a significant ***reduction*** in concentrated displacements and strains in the building so that the lower bound estimates of ground movements for a volume loss of **0.5%** result in the following Risk Categories:
    - Case 1C (Perimeter Scant Pile Wall/Building Façade):
        - Risk Category = 1/2 (Very Slight to Slight)
    - Case 2C (Internal RC Structure):
        - Risk Category = 1 (Very Slight Damage)
    - Case 3C (RC Basement Floor Slab):
        - Risk Category = 1 (Very Slight Damage)
- At the upper bound estimates of ground movements corresponding to a volume loss of **1.0%** the risk category and degree of damage increases across the building as follows:
    - Case 1C (Perimeter Scant Pile Wall/Building Façade):
        - Risk Category = 2 (Slight)
    - Case 2C (Internal RC Structure):
        - Risk Category = 2 (Slight)
    - Case 3C (RC Basement Floor Slab):
        - Risk Category = 2 (Slight)
- At the raised level, the concentrated loads on the internal pad foundations and perimeter secant pile wall will have a less significant impact on ground movements as the loads will become more distributed through the rock with depth. **Therefore, for Case 1C, 2C and 3C the *lower* bound ground loss of 0.5% may give a more representative assessment of the risk of building damage.**

Note that, as discussed previously, the refined Phase 2a building damage assessment is a preliminary semi-empirical estimate of the potential damage that could occur to the building due to tunnelling related ground movements. It does not account for the stiffness of the building, which can reduce and redistribute settlements across the tunnel profile. At the same time, it does not model the concentrated load from the building foundations which can have the opposite effect. The more detailed Phase 3 analysis of the soil-structure response to tunnelling referred to in the EIAR would be required to give a more comprehensive and representative engineering assessment of the response of the building to tunnelling in the underlying rock.

Consideration should also be given to what is an acceptable risk category and degree of damage for the Arthur Cox building, particularly for the façade and for the basement structure and waterproofing system, which would be more sensitive to damage than indicated by the criteria and corresponding risk categories in Table 5-1.

Table 5-9 – Summary of Building Damage Assessment

Analysis	Details	Depth to Tunnel Axis (z_0)/ Cover to Foundation Subgrade (m)	Lower Bound (V_l = 0.5%)					Upper Bound (V_l = 1.0%)				
			Lim. (Max) Tensile Strain ε_{tmax} (%)	Max Ground Slope m_{max} (%)	Max Settlement S_{max} (mm)	Risk Category	Degree of Damage	Lim.(Max) Tensile Strain ε_{tmax} (%)	Max Ground Slope m_{max} (%)	Max Settlement S_{max} (mm)	Risk Category	Degree of Damage
Design Tunnel Profile												
Case 1A	Ch. 18+945 (Hatch St.) Secant Pile Wall/Bldg. Façade **Design Vertical Alignment**	z_0 = 9.6m Cover= 4.9m	-0.15%	0.58%	37	2/3	Slight to Moderate	-0.30%	1.16%	74	3/4	Moderate to Severe
Case 2A	Ch. 18+970 (Centre) Internal Building RC Frame **Design Vertical Alignment**	z_0 = 13.3m Cover= 8.6m	-0.08%	0.30%	27	2	Slight	-0.16%	0.61%	53	3	Moderate
Case 3A	Ch. 18+995 (South Side) Basement Floor Slab **Design Vertical Alignment**	z_0 = 12.9m Cover= 8.1m	-0.10%	0.32%	28	2	Slight	-0.21%	0.65%	55	3	Moderate
Raised Tunnel Profile (Max. Proposed Vertical Deviation = + 5.0m)												
Case 1B	Ch. 18+945 (Hatch St.) Secant Pile Wall/Bldg. Façade Raised Vertical Alignment (+3.87m)	z_0 = 5.7m Cover= 1.0m	-0.43%	1.63%	62	4/3	Severe to Moderate	-0.85%	3.25%	124	4/5	Severe to Very Severe
Case 2B	Ch. 18+970 (Centre) Internal Building RC Frame Raised Vertical Alignment (+5.0m)	z_0 = 8.3m Cover= 3.6m	-0.20%	0.78%	43	3/2	Moderate to Slight	-0.41%	1.55%	85	4	Severe
Case 3B	Ch. 18+995 (South Side) Basement Floor Slab Raised Vertical Alignment (+5.0m)	z_0 = 7.9m Cover= 3.1m	-0.32%	0.87%	45	3	Moderate	-0.64%	1.74%	90	4	Severe
Lowered Tunnel Profile (Max. Proposed Vertical Deviation = - 5.0m)												
Case 1C	Ch. 18+945 (Hatch St.) Secant Pile Wall/Bldg. Façade Lowered Vertical Alignment (-5.0m)	z_0 = 14.6m Cover= 9.9m	-0.07%	0.25%	24	1/2	Very Slight to Slight	-0.13%	0.50%	49	2	Slight
Case 2C	Ch. 18+970 (Centre) Internal Building RC Frame Lowered Vertical Alignment (-5.0m)	z_0 = 18.3m Cover= 13.6m	-0.04%	0.16%	19	1	Very Slight	-0.08%	0.32%	39	2	Slight
Case 3C	Ch. 18+995 (South Side) Basement Floor Slab Lowered Vertical Alignment (-5.0m)	z_0 = 17.9m Cover= 13.1m	-0.05%	0.17%	20	1	Very Slight	-0.10%	0.34%	40	2	Slight

5.7 Building Damage Assessment for Arthur Cox Building in the EIAR

The results of the building damage assessment calculations for the conditions assumed by Jacobs/IDOM in the Building Damage Report (BDR) in Appendix A5.17 of the EIAR are summarised in Table 4-10. The table gives the following values for each analysis case:

- Max limiting tensile strain, ε_{max} (%)
- Maximum ground slope on the settlement trough, m_{max} (%)
- Max settlement over the tunnel centreline, S_v (mm)

The first row of Table 5-10 presents the results of calculations by AGL using the criteria for ground loss, building height, basement depth, structural properties and foundation level that were used by Jacobs/IDOM in their building damage assessment for the Arthur Cox Building in the BDR.

The second row of Table 5-10 presents the results of the calculations by Jacobs/IDOM in their building damage assessment for the Arthur Cox Building, which are presented in Table 5-2 and Table F1 of the BDR.

A copy of the AGL calculations and the relevant criteria for the Jacobs/IDOM assessment from the BDR are included in Appendix D.

The risk category and degree of damage for the assessment in the BDR have been determined from the criteria in Table 5-1. Based on their analysis the **Risk Category** for the Arthur Cox building has been assessed by Jacobs/IDOM as **2**, which corresponds to **Slight Damage**.

Note:

- The Arthur Cox Building has been identified in the BDR as a Case B "special" building that requires special consideration due to its deep basement (>4m) (Building B-238 @ Ch. 18+980 in Appendix B.1 of the BDR).
- The damage assessment for the building is based on the results of the Phase 2a assessment where the lower and upper bound estimates for ground movements in the BDR are based on tunnel volume loss of **0.75%** and **1.50%**, respectively. The BDR does not state which value was used for the assessment for the Arthur Cox Building. However, the results in Table 5-10 indicate that Jacobs/IDOM have only based their assessment on the lower bound volume loss of **0.75%** for tunnelling in rock.
- The assessment has been carried out for a 7-storey building with a total height of 40m including a basement to a depth of 8.1m below ground level. It is implied that the assessment has been carried out to assess the impact of tunnelling settlements at basement subgrade level, although this is not specifically stated.
- The analysis does not consider the impact on the perimeter secant pile wall, which has a foundation level over 4.0m lower than the basement.
- No consideration has been given to the potential for higher settlements due to concentrated loads from the building foundations and load-bearing piles directly over the tunnel.
- The BDR states that the engineering properties that were assumed for the building to assess the structural response to tunnelling settlements [i.e. Young's Modulus

(E)/Shear Modulus (G)] are representative of a masonry structure. These would not be representative of the reinforced concrete frame and basement walls of the Arthur Cox Building, or for the specialist building façade.

- The level of damage that has been considered acceptable for the buildings in the Phase 2a assessment by Jacobs/IDOM is Risk Category 2 (Slight), based on the criteria in Table 5-1. However, this does not account for the sensitivity of the building façade or the basement structure and waterproofing system, which can exhibit unacceptable levels of damage at even lower levels of stress and strain.
- The assessment does not consider the potential impact of a raised tunnel profile within the proposed vertical Limits of Deviation, which has a significant adverse impact on the building.

This is also not identified in the Wider Effects Report (WER) in Appendix 5.19 of the EIAR, which assesses whether the power to deviate the tunnel alignment within the LoD would alter the predicted significant impacts reported in the EIAR.

Furthermore, as discussed in Section 4.3 of this report, if the tunnel is raised by 5.0m, then the crown of the tunnel bore for the TBM cutter head will **will hit the base of the piles in the perimeter secant pile wall**, which has also not been recognised in the BDR or WER reports by Jacobs/IDOM.

Under "Soils and Geology", Table 1.2 of the WER concludes that raising the tunnel alignment will have "*No potential for significant additional impacts*".

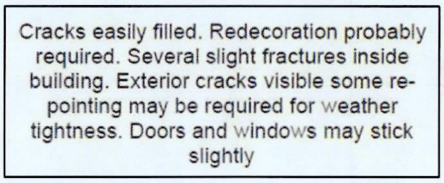
This is a notable omission as raising the tunnel alignment could have significant additional adverse impacts on the Arthur Cox Building which have not been adequately assessed in the EIAR.

Table 5-10 – Summary of Building Damage Assessment in the Jacobs/IDOM BDA Report in Appendix A5.17 of the EIAR

Analysis	Details	Depth to Tunnel Axis (z_o)/ Cover to Foundation Subgrade (m)	Lower Bound (V_l = 0.75%)					Upper Bound (V_l = 1.5%)				
			Lim. (Max) Tensile Strain	Max Ground Slope	Max Settlement	Risk Category	Degree of Damage	Lim.(Max) Tensile Strain	Max Ground Slope	Max Settlement	Risk Category	Degree of Damage
			ε_{tmax} (%)	m_{max} (%)	S_{max} (mm)			ε_{tmax} (%)	m_{max} (%)	S_{max} (mm)		
EIAR Conditions (AGL Calcs)	Ch. 18+980 Internal RC Structure (incl Basement) **Design Vertical Alignment**	zo = 13.4m Cover= 8.7m	-0.12%	0.45%	40	2	Slight	-0.23%	0.90%	79	3	Moderate
EIAR Results (Jacobs/ Idiom BDA)	Ch. 18+980 Internal RC Structure (incl Basement) Design Vertical Alignment	z_o = 13.4m Cover= 8.7m	-0.09%	0.35%	37	2	Slight					

6.0 SUMMARY

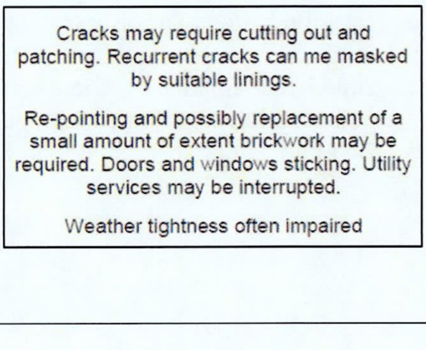
- The Phase 2a building damage assessment that was carried out for the Arthur Cox Building by Jacobs/IDOM takes account of the basement and was carried out using the conservative Phase 2a volume loss parameter for tunnelling in rock (0.75%), which is representative of the actual ground profile at the building.
- Based on their analysis, the potential damage to the building falls into Risk Category 2 (Slight Damage), which corresponds to cracks up to 1-5mm wide and the following damage criteria in Table 5-1:



Cracks easily filled. Redecoration probably required. Several slight fractures inside building. Exterior cracks visible some re-pointing may be required for weather tightness. Doors and windows may stick slightly

- This is considered by Jacobs/IDOM to be an acceptable level of building damage related to tunnelling induced ground movements without requiring any further assessment for the EIAR.
- There are a number of significant limitations to this assessment i.e.:
    - The level of "acceptable" building damage does not account for the sensitivity of the façade or the basement structure and waterproofing system of the Arthur Cox Building, which can exhibit unacceptable levels of damage at even lower levels of stress and strain;
    - The engineering properties that were assumed to assess the structural response of the building are for masonry structures, which would not be representative of the reinforced concrete structure or glass façade of the Arthur Cox Building;
    - The analysis does not take into account the impact of settlements at the lower foundation level of the perimeter secant pile wall, which supports the building internal structure and façade 4.2m below subgrade level for the basement floor slab;
    - No consideration has been given to the potential for higher settlements due to concentrated loads from the building foundations and load-bearing piles directly over the tunnel;
    - The assessment does not consider the potential impact of a raised tunnel profile within the proposed vertical Limits of Deviation, which has a significant adverse impact on the building.
- The significant adverse impact of raising the tunnel alignment is also not identified in the Wider Effects Report (WER) in Appendix 5.19 of the EIAR, which assesses whether the power to deviate the tunnel alignment within the LoD would alter the predicted significant impacts reported in the EIAR.
- If the tunnel is raised by 5.0m, then the TBM cutter head **will hit the base of the piles in the perimeter secant pile wall**, which has also not been recognised in the BDR or WER reports by Jacobs/IDOM.

- Under "Soils and Geology", Table 1.2 of the WER concludes that raising the tunnel alignment will have "*No potential for significant additional impacts*".
- This is a notable omission as raising the tunnel alignment could have significant additional adverse impacts on the Arthur Cox Building which have not been adequately assessed in the EIAR.
- The Building Damage Assessment presented in this report has been carried out using the refined Phase 2a parameters for ground loss of **0.5%** and **1.0%** for tunnelling in rock and soil, respectively. These are considered by Jacobs/IDOM to be compatible with the values experienced using the modern tunnelling equipment and control systems that are expected to be used on the Metrolink project. The value of 0.5% for ground loss related to tunnelling in rock is also consistent with experience on the Dublin Port Tunnel (Gillarduzzi, 2014).
- At the Arthur Cox building the tunnel will be in rock with more than 5m cover of rock under the building at the design profile. Therefore, the lower bound value of 0.5% should generally apply. However, the upper bound ground loss of 1.0% assesses the sensitivity of the analysis and could potentially account for concentrated loads from the building foundations, depending on the level of the tunnel.
- The tunnel rises by 0.9m from north to south. Therefore, we have carried out our analyses at 3 No. representative profiles across the width of the building to assess the impact of the tunnelling on the façade, internal RC frame, and basement floor slab.
- We have accounted for the different foundation levels below the perimeter secant pile wall and basement floor slab.
- We have also assessed the impact of raising and lowering the level of the tunnel by up to 5.0m, which is within the Limits of Deviation proposed in the Railway Order (+5.0m upwards/-10m downwards).
- At the design profile, the potential damage to the building at the lower bound ground loss of **0.5%** has been assessed as **Slight (Risk Category 2)** for the building and basement floor slab, and possibly **Slight to Moderate (Risk Category 2/3)** for the façade, which could still have unacceptable adverse impacts on the structure and basement waterproofing.
- If the ground loss is increased to **1.0%** to account for concentrated building foundation loads directly over the tunnel then the damage level could potentially increase to **Moderate (Risk Category 3)** for the building and basement floor slab, and **Moderate to Severe (Risk Category 3/4)** under the façade.
- Moderate damage corresponds to crack widths up to 5-15mm (or a number of cracks greater than 3mm) and the following damage criteria in Table 5-1, which could have significant unacceptable adverse impacts on the structure and basement waterproofing:

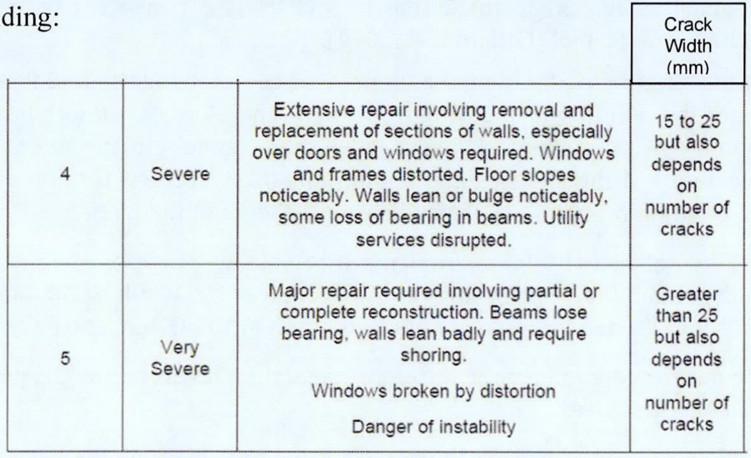


Cracks may require cutting out and patching. Recurrent cracks can me masked by suitable linings.

Re-pointing and possibly replacement of a small amount of extent brickwork may be required. Doors and windows sticking. Utility services may be interrupted.

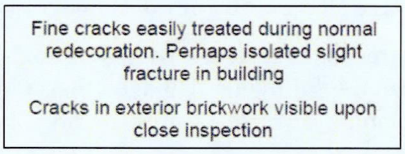
Weather tightness often impaired

- **If the tunnel is raised by up to 5.0m**, there will be less than 3-4m of cover between the tunnel and the basement floor slab and the TBM could hit the base of the secant pile wall, which will significantly increase the potential level of building damage.
- The concentrated loads from the building foundations will also have a greater impact on settlements with the tunnel at this level. Therefore, the upper bound assessment for a ground loss of 1.0% may give a more representative assessment of the risk of building damage, which is **Severe (Risk Category 4)** for the building and basement floor slab, and **Severe to Very Severe (Risk Category 4/5)** for the façade.
- The Severe and Very Severe damage categories correspond to the following criteria in Table 5-1, which would cause significant unacceptable structural distress and damage to the building:



			Crack Width (mm)
4	Severe	Extensive repair involving removal and replacement of sections of walls, especially over doors and windows required. Windows and frames distorted. Floor slopes noticeably. Walls lean or bulge noticeably, some loss of bearing in beams. Utility services disrupted.	15 to 25 but also depends on number of cracks
5	Very Severe	Major repair required involving partial or complete reconstruction. Beams lose bearing, walls lean badly and require shoring. Windows broken by distortion Danger of instability	Greater than 25 but also depends on number of cracks

- **If the tunnel is lowered by 5.0m**, there will be a significant improvement in the potential level of damage to the building.
- The concentrated loads from the building foundations will also have less impact on settlements as the loads become more uniformly distributed into the ground. Therefore, the lower bound assessment for a ground loss of 0.5% may give a more representative assessment of the risk of building damage, which is **Very Slight (Risk Category 1)** for the building and basement floor slab, and **Very Slight to Slight (Risk Category 1/2)** for the façade.
- Risk Category 1 (Very Slight) corresponds to cracks up to 0.1-1mm wide and the following damage criteria in Table 5-1:



Fine cracks easily treated during normal redecoration. Perhaps isolated slight fracture in building

Cracks in exterior brickwork visible upon close inspection

- The refined Phase 2a building damage assessment is a preliminary semi-empirical estimate of the potential damage that could occur to the Arthur Cox building due to tunnelling related ground movements. It does not account for the stiffness of the building, which can reduce and redistribute settlements across the tunnel profile, and it it does not model the impact of concentrated load from the building foundations.

- The more detailed Phase 3 analytical analysis of the soil-structure response to tunnelling referred to in the EIAR would be required to give a more comprehensive and representative engineering assessment of the response of the building.
- Consideration should also be given to what is an acceptable risk category and degree of damage for the Arthur Cox building, particularly for the façade and for the basement structure and waterproofing system, which would be more sensitive to damage than indicated by the criteria and corresponding risk categories in Table 5-1.

7.0 RECOMMENDATIONS

Based on the results of the Refined Phase 2a BDA for the Arthur Cox Building we would recommend that:

- The level of the tunnel should be lowered by at least 5.0m to reduce the impact of tunnelling related ground movements on the Arthur Cox Building;
- The Wider Effects Report should be revised to include a constraint to on the application of the Limits of Deviation for the tunnel under the Arthur Cox Building so that there is no scope for upward vertical deviation of the lowered tunnel alignment due to the potential for significant adverse impacts on the building;
- TII and Jacobs/IDOM should liaise with the structural designers of the building and façade to determine the acceptable threshold of building distortion, damage and ground movements related to tunnelling;
- A more detailed Phase 3 analytic assessment should be carried out to confirm that the building distortion due to tunnelling induced ground movements is within acceptable limits taking account of concentrated foundation loads;
- The EIAR should properly assess the positive impact of lowering the tunnel alignment and should also assess appropriate mitigation measures that are relevant to the Arthur Cox Building. As the building is on rock, lowering the tunnel level will be the most effective mitigation measures to reduce the impact of tunnelling induced ground movements. There will be limited potential for compensation grouting or jacking. Consideration should also be given to specify the type of TBM that will be used, or to specify appropriate limits on building distortion or ground loss due to tunnelling.
- The EIAR should also include appropriate monitoring measures for the building to ensure that settlements and the resulting stresses and strains in the structure are within acceptable limits.
- The building structure and foundations have been designed to support two additional floors at some stage in the future. This should be assessed in the EIAR and taken into account in the design and construction of the tunnel so that there is adequate capacity in place to support the additional loads;

REFERENCES:

Gillarduzzi, Andrea, "*Investigating property damage along Dublin Port Tunnel alignment*", Proc. of the ICE, Forensic Engineering, Vol. 167, Issue FE3, August 2014.

Mair, R.J, & Taylor, R.N., "*Bored tunnelling in the urban environment*", Proc. of the 14th Intl. Conference on Soil Mechanics & Foundation Engineering, Hamburg, 1997.

Mair, R.J, Taylor, R.N., & Burland, J.B., "*Prediction of ground movements and assessment of risk of building damage due to bored tunnelling*", Geotechnical Aspects of Underground Construction in Soft Ground, International Symposium, London, 1996.

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<tr><td colspan="2">Revision No:</td><td colspan="2">Date:</td><td>Notes</td></tr>
<tr><td colspan="2">Rev.0</td><td colspan="2">7/2/2024</td><td>Final Report</td></tr>
<tr><td colspan="2">Rev.1</td><td colspan="2">26/2/2024</td><td>Minor edits</td></tr>
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<tr><td>Made by:</td><td colspan="2">Conor O’Donnell</td><td colspan="2">Conor O'Donnell</td></tr>
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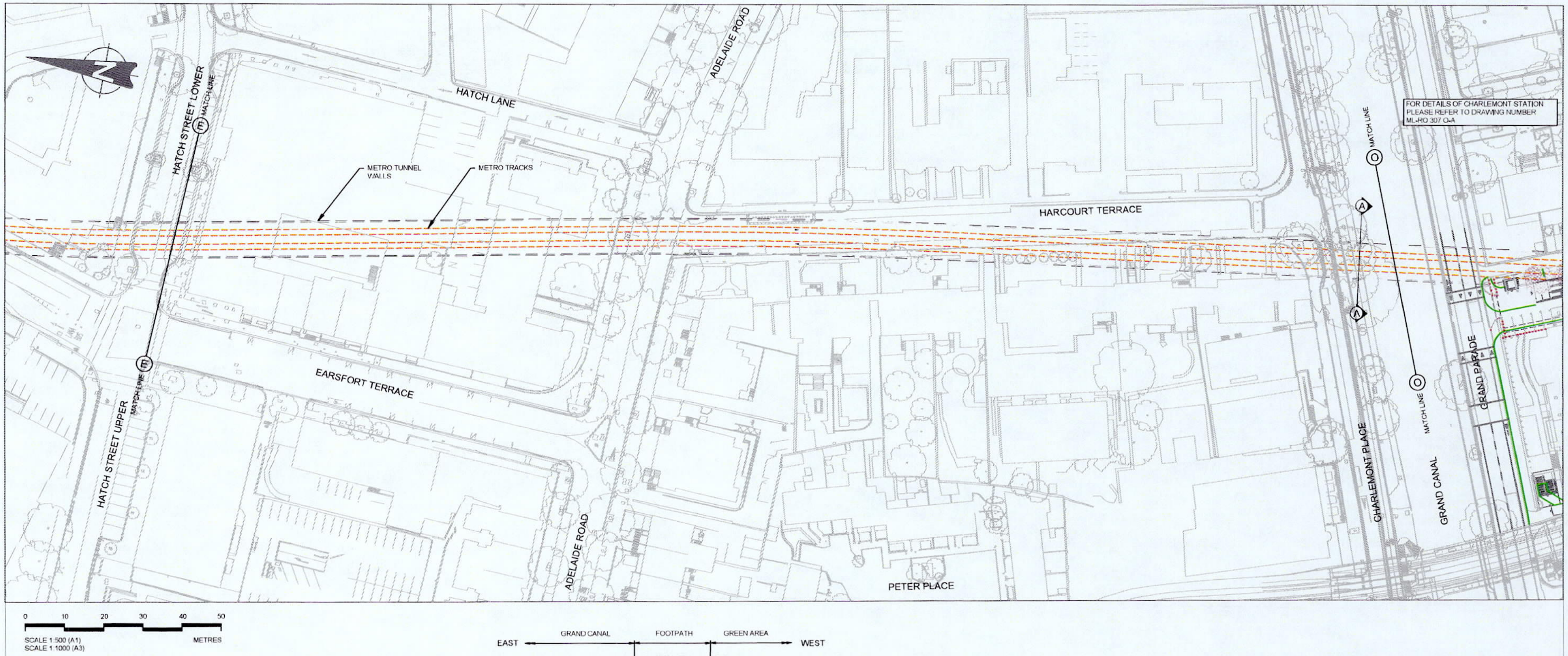
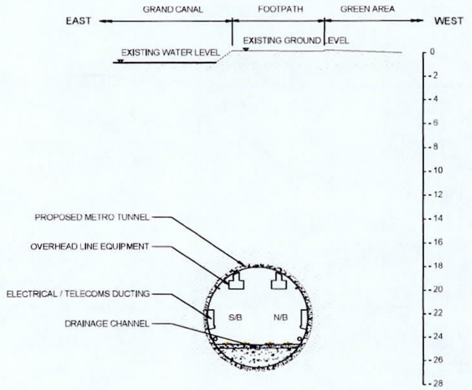
Appendix A
Drawings





SECTION A - A

0 5 10 20
SCALE 1:200 (A1)
SCALE 1:400 (A3)
METRES

DRAWING LEGEND:

┈┈┈	EXISTING KERB
▥	PROPOSED EARTHWORK
┼	OVERHEAD LINES
⇄	TRAFFIC FLOW
═	METRO TUNNEL EXTENTS
═	METRO RAIL TRACKS
○	TREES TO BE REMOVED
○	TREES TO BE RETAINED
••••	EXISTING KERB TO BE REMOVED
───	PROPOSED KERB

NOTES:

1. FOR DETAILS OF STRUCTURES (INCLUDING STATIONS) SEE BOOK OF STRUCTURES DRAWINGS (E.G. DRAWINGS COMMENCING ML ST OR ML BR ETC.)
2. FOR DETAILS OF PROPERTY SEE BOOK OF PROPERTY DRAWINGS (DRAWINGS COMMENCING ML P)
3. FOR DETAILS OF UTILITIES SEE BOOK OF UTILITIES DRAWINGS (DRAWINGS COMMENCING ML UC) AND BOOK OF SURFACE WATER DRAWINGS (DRAWINGS COMMENCING ML UN)

REV.	DATE	Description	DRAWN BY	CHECKED BY	REVIEWED BY	APPROVED BY
P01	12/07/21	For Railway Order	RS	RS	AS	NC
P03	31/10/21	For Railway Order	JR	RS	AS	NC
P04	19/05/22	For Railway Order	BJ	JR	AS	PB
P05	17/08/22	For Railway Order	GB	MM	MM	PB

All elevations are in metres and relate to OSI Geoid Model (OSGM02) Malin Head as defined by existing Project Control.
All Coordinates are in Irish Transverse Mercator Grid (ITM) as defined by OSI active GPS station Tallaght College (TLLG).

Client: TII NTA Údarás Náisiúnta Iompair National Transport Authority

Project: METROLINK

Consultant: JACOBS IDOM

Drawing Title: METROLINK - GENERAL ARRANGEMENT
HATCH STREET LOWER TO GRANDE PARADE

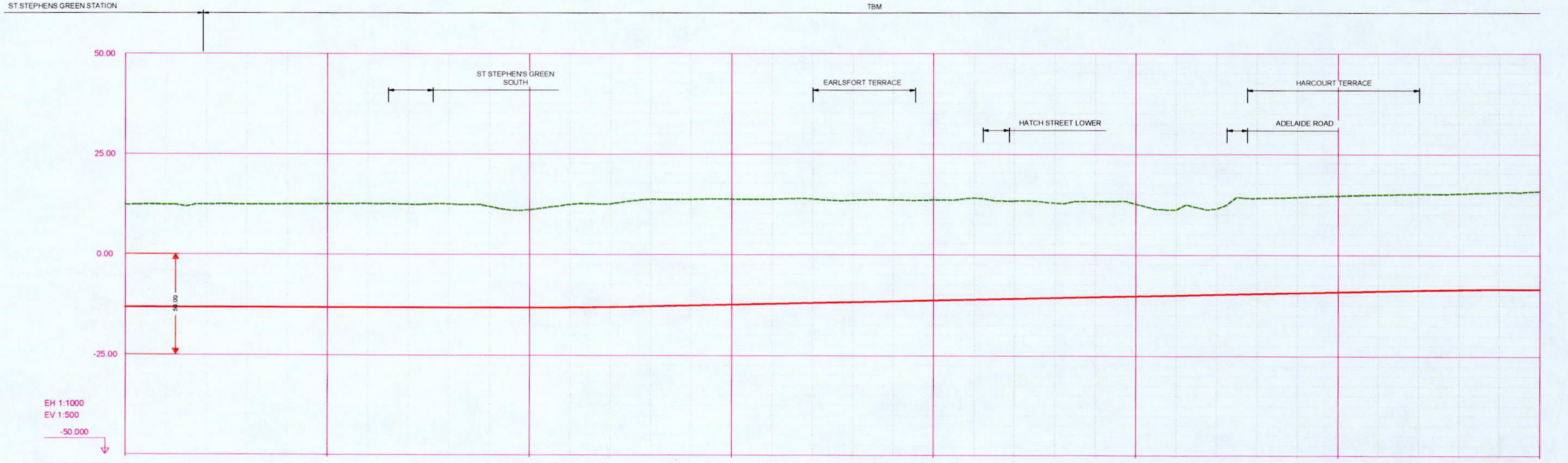
Drawing Status: S0

Drawing Nº: ML1-JAI-ARD-ROUT_XX-DR-Y-03095

Plan Drawing Nº: ML-RO 306 E-O

Scales Original Size A1 AS SHOWN

Sheet 1 of 1



CHAINAGE	18+500					18+600					18+700	
PROPOSED LEVEL	-13.200	-13.200	-13.200	-13.200	-13.200	-13.200	-13.200	-13.200	-13.200	-13.200	-13.200	-13.169
EXISTING GROUND LEVEL	12.347	12.428	12.292	12.437	12.482	12.463	12.334	12.374	11.122	11.307	12.191	12.939

CHAINAGE					18+800					18+900		
PROPOSED LEVEL	-13.058	-12.868	-12.648	-12.428	-12.208	-11.988	-11.768	-11.548	-11.328	-11.108	-10.888	-10.668
EXISTING GROUND LEVEL	13.615	13.633	13.684	13.643	13.488	13.519	13.482	13.482	13.766	13.176	12.731	13.166

CHAINAGE		19+000					19+100					19+200
PROPOSED LEVEL	-10.448	-10.228	-10.008	-9.788	-9.568	-9.348	-9.128	-8.908	-8.688	-8.508	-8.407	-8.384
EXISTING GROUND LEVEL	12.295	11.176	12.984	14.095	14.405	14.680	14.901	15.064	15.191	15.513	15.765	15.870

TO ESTUARY ⬅

TO CHARLEMONT ➡

DRAWING LEGEND

🟥	RAIL LEVEL
🟩	EXISTING GROUND LEVEL

0 10 20 30 40 50 60 70 80 90 100

SCALE 1:1000 (A1)
SCALE 1:2000 (A3)
METRES

REV.	DATE	Description	DRAWN BY	CHECKED BY	REVIEWED BY	APPROVED BY
P01	29/07/21	For Railway Order	JD	JR	RS	NC
P02	21/12/21	For Railway Order	BJ	RS	AS	NC
P03	12/05/22	For Railway Order	BJ	JR	AS	PB

All elevations are in metres and relate to OSI Geoid Model (OSGM02) Malin Head as defined by existing Project Control.
All Coordinates are in Irish Transverse Mercator Grid (ITM) as defined by OSI active GPS station Tallaght College (TLLG).

Client
TII NTA

Project
METROLINK

Consultant
JACOBS IDOM

Drawing Title
METROLINK - ALIGNMENT
LONG SECTION 18

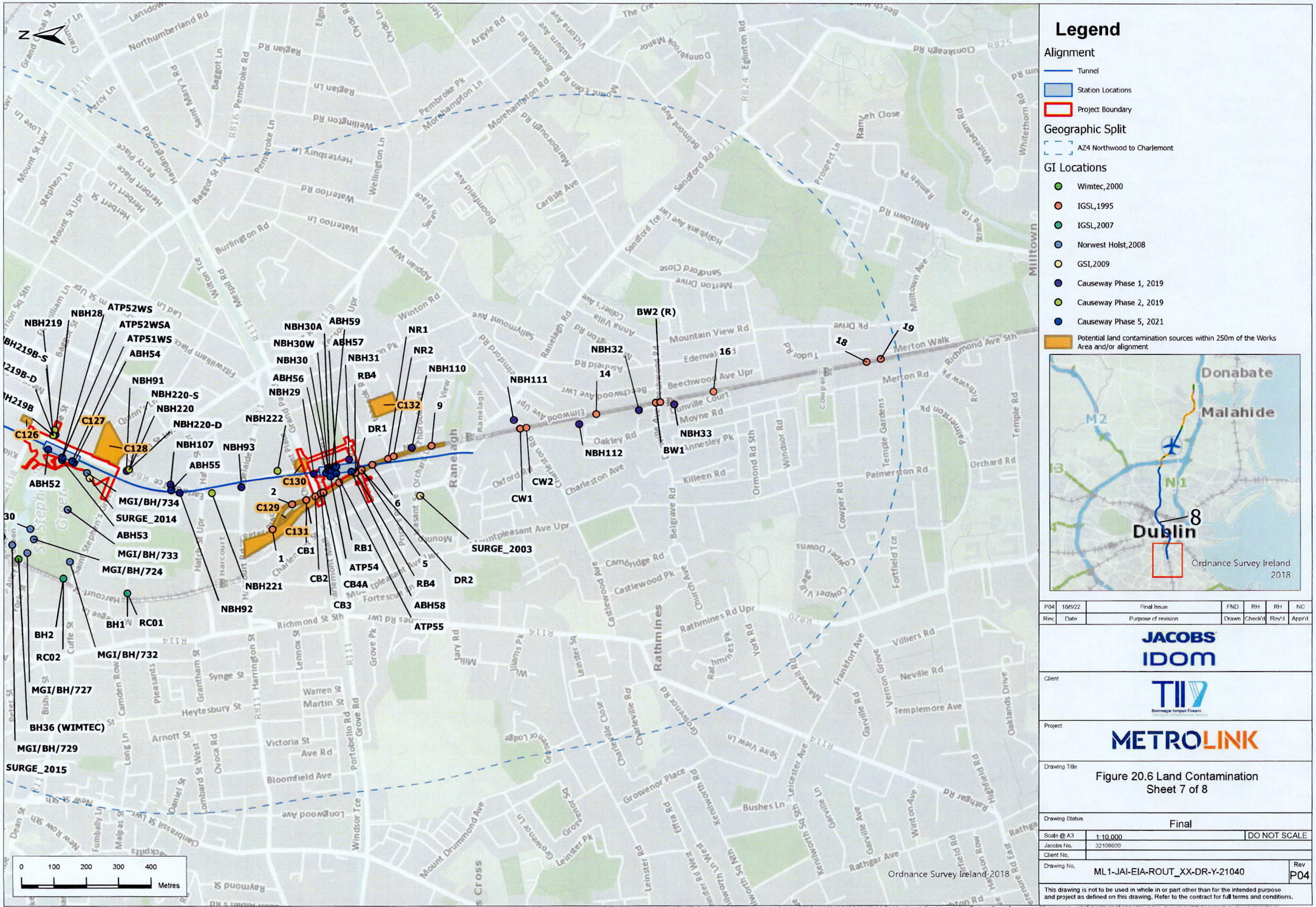
Drawing Status
S0

Drawing N°
ML1-JAI-ARD-ROUT_XX-DR-Y-01018

Plan Drawing N°
ML-LN O-O18

Scales Original Size A1 1:1000

Sheet 18 of 19



P04	18/8/22	Final Issue	FND	RH	RH	NC
Rev.	Date	Purpose of revision	Drawn	Check'd	Rev'd	Appr'd

JACOBS
IDOM

Client
TII
Bonneagar Iompair Éireann
Transport Infrastructure Ireland

Project
METROLINK

Drawing Title
Figure 20.6 Land Contamination
Sheet 7 of 8

Drawing Status
Final

Scale @ A3 1:10,000 DO NOT SCALE
Jacobs No. 32108600
Client No.
Drawing No. ML1-JAI-EIA-ROUT_XX-DR-Y-21040
Rev P04

This drawing is not to be used in whole or in part other than for the intended purpose and project as defined on this drawing. Refer to the contract for full terms and conditions.

NOTES:

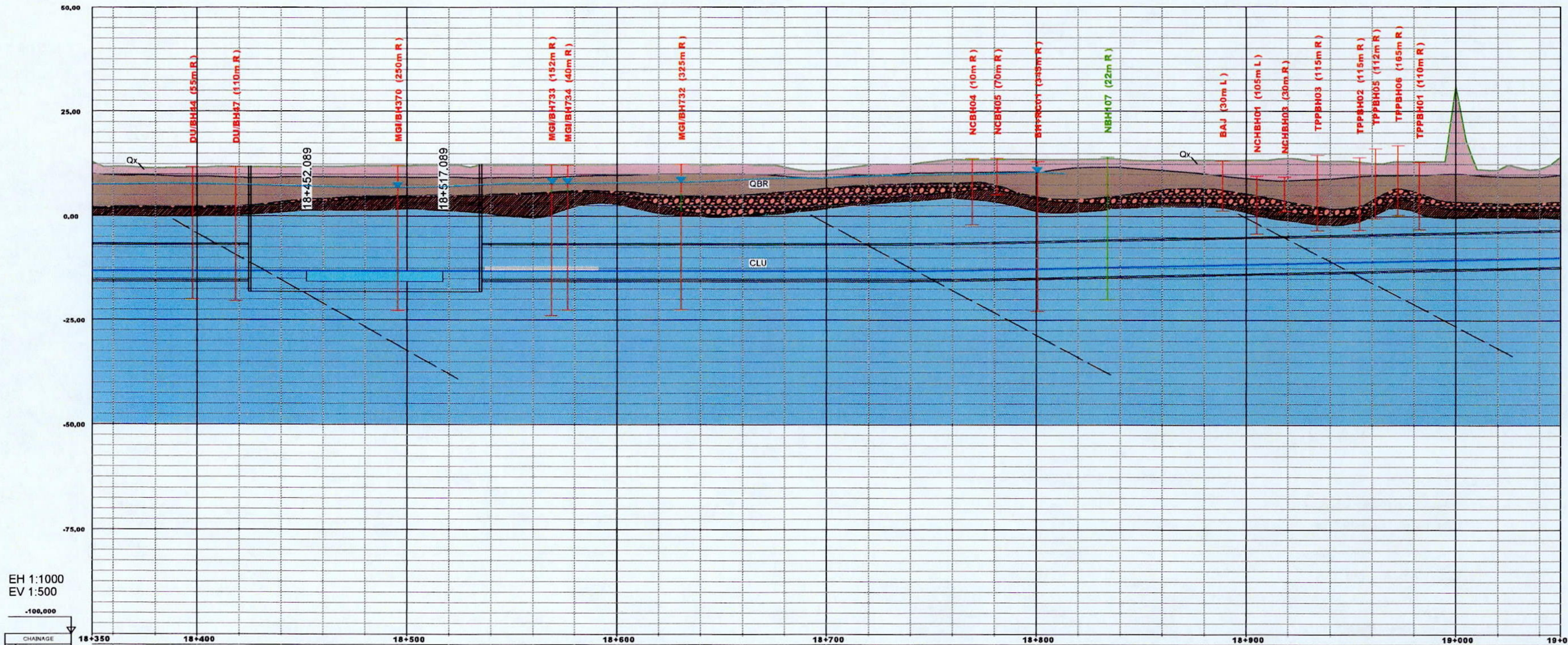
KV= Vertical curve radio (m)
CV= Vertex level (m)
W = Difference between the exit slope minus the entrance slope (‰)
D = Saguitta, difference between CV and TOR level (m)

The distance from TOR to tunnel crown is 6.7 m

SYMBOLOGY:

▨	Cut and cover section
TOR ▽	Rail level (TOR)

STATION
ST. STEPHENS GREEN



	18+350			18+400					18+500				
LEVELS T.O.R. DESIGN	-13,200	-13,200	-13,200	-13,200	-13,200	-13,200	-13,200	-13,200	-13,200	-13,200	-13,200	-13,200	-13,200
LEVELS GROUND	13,020	11,868	11,596	11,740	11,826	11,912	11,934	12,166	12,113	12,226	12,308	12,273	12,382
LEVELS CUT / FILL DEPTHS	-26,220	-25,068	-24,796	-24,940	-25,026	-25,112	-25,134	-25,366	-25,313	-25,426	-25,508	-25,473	-25,582

	18+600					18+700					18+800	
LEVELS T.O.R. DESIGN	-13,200	-13,200	-13,200	-13,200	-13,200	-13,200	-13,200	-13,160	-13,082	-12,905	-12,685	-12,465
LEVELS GROUND	12,446	12,524	12,374	12,480	11,809	10,997	12,329	12,472	13,639	13,591	13,675	13,671
LEVELS CUT / FILL DEPTHS	-25,646	-25,724	-25,574	-25,680	-25,009	-24,197	-25,529	-25,651	-26,722	-26,496	-26,360	-26,136

				18+900					19+000			19+050
LEVELS T.O.R. DESIGN	-12,245	-12,025	-11,805	-11,585	-11,365	-11,145	-10,925	-10,705	-10,485	-10,265	-10,045	-9,935
LEVELS GROUND	13,719	13,445	13,512	13,479	13,945	13,274	12,733	13,203	31,076	11,134	11,396	14,251
LEVELS CUT / FILL DEPTHS	-25,964	-25,470	-25,317	-25,065	-25,310	-24,419	-23,658	-23,908	-41,561	-21,399	-21,441	-24,186

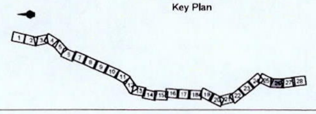
VERTICAL: 0,000‰ L=530,931 · KV=5000,000 L=55,000 · 11,000‰ L=382,800

GEOMETRY CANT (LEFT ——, RIGHT - - -): 90mm

GEOMETRY HORIZONTAL: STRAIGHT L=328,539 · A=154,919 L=60,000 · R=400,000 L=185,971 · A=154,919 L=60,000 · STRAIGHT L=82,995 · A=212,132 L=30,000

18+652,170 · 18+712,170 · 18+898,141 · 18+958,141 · 19+041,136

Key Plan



REV.	DATE	Description	DRAWN BY	CHECKED BY	REVIEWED BY	APPROVED BY
P03	11/12/20	Final Preliminary Design	DT	FP	JB	NC
P02	03/04/20	Preliminary Design	DT	FP	JB	NC
P01	05/12/19	Preliminary Design	DT	FP	JB	NC

All elevations are in metres and relate to OSI Geoid Model (OSGM02) Malin Head as defined by existing Project Control.
All Co-ordinates are in Irish Transverse Mercator Grid (ITM) as defined by OSI active GPS station Tallaght College (TLLG).

Client: TII NTA Údarás Náisiúnta Iompair National Transport Authority

Project: METROLINK

Consultant: JACOBS IDOM

Drawing Title: Ground Investigation
Geological Long Section – Phase 1

Drawing Status: S4

Drawing Nº: ML1-JAI-GEO-ROUT_XX-DR-Y-00013

Scales Original Size A1

Sheet 26 of 28

NOTES:

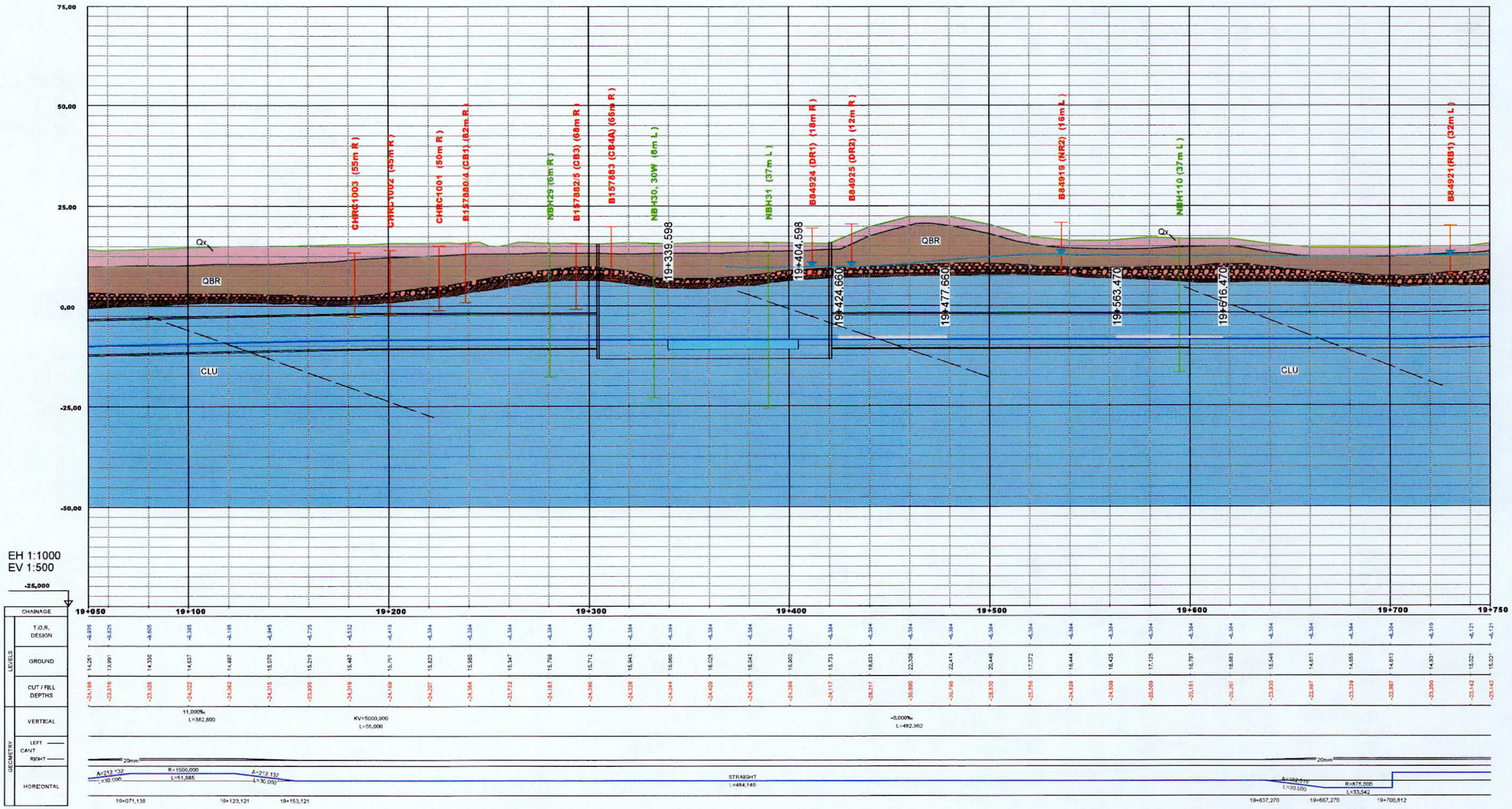
KV= Vertical curve radio (m)
CV= Vertex level (m)
W = Difference between the exit slope minus the entrance slope (‰)
D = Saguitta, difference between CV and TOR level (m)

The distance from TOR to tunnel crown is 6,7 m

SYMBOLOGY:

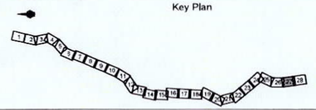
▨	Cut and cover section
TOR	Rail level (TOR)

STATION CHARLEMONT



T.O.R. DESIGN	GROUND	CUT / FILL DEPTHS
-9,935	14,251	-24,186
-9,825	13,991	-23,816
-9,605	14,330	-23,935
-9,385	14,637	-24,022
-9,165	14,897	-24,062
-8,945	15,070	-24,015
-8,725	15,210	-23,935
-8,532	15,487	-24,019
-8,418	15,751	-24,169
-8,384	15,823	-24,207
-8,384	15,980	-24,364
-8,384	15,347	-23,732
-8,384	15,799	-24,183
-8,384	15,712	-24,096
-8,384	15,943	-24,328
-8,384	15,660	-24,044
-8,384	16,025	-24,409
-8,384	16,042	-24,426
-8,384	15,902	-24,386
-8,384	15,733	-24,117
-8,384	19,833	-28,217
-8,384	22,306	-30,690
-8,384	22,414	-30,798
-8,384	20,446	-28,830
-8,384	17,372	-25,756
-8,384	16,444	-24,828
-8,384	16,425	-24,809
-8,384	17,125	-25,509
-8,384	16,797	-25,181
-8,384	16,883	-25,267
-8,384	15,546	-23,930
-8,384	14,613	-22,997
-8,384	14,655	-23,339
-8,384	14,613	-22,997
-8,319	14,931	-23,250
-8,121	15,021	-23,142
-8,121	15,021	-23,142

Key Plan



REV.	DATE	Description	DRAWN BY	CHECKED BY	REVIEWED BY	APPROVED BY
P03	11/12/20	Final Preliminary Design	DT	FP	JB	NC
P02	03/04/20	Preliminary Design	DT	FP	JB	NC
P01	05/12/19	Preliminary Design	DT	FP	JB	NC

All elevations are in metres and relate to OSI Geoid Model (OSGM02) Malin Head as defined by existing Project Control.
All Coordinates are in Irish Transverse Mercator Grid (ITM) as defined by OSI active GPS station Tallaght College (TLLG).

Client
TII
NTA
Údarás Náisiúnta Iompair
National Transport Authority

Project
METROLINK

Consultant
JACOBS
IDOM

Drawing Title
Ground Investigation
Geological Long Section – Phase 1

Drawing Status
S4

Drawing Nº
ML1-JAI-GEO-ROUT_XX-DR-Y-00013

Scales Original Size A1

Sheet 27 of 28

2. General Description of Underground Structures

2.1 TBM Tunnels

The MetroLink tunnel alignment will consist of a single bore bi-directional tunnel constructed by means of a tunnel boring machine (TBM) that will be specified and designed to enable tunnelling generated ground movements to be minimalised. The tunnels have been designed with an internal diameter of 8.5m, determined by the rolling stock kinematic clearance, and railway services requirement (See Figure 2-1).

From a review of the expected geology and hydrogeology along the tunnel alignment, the construction and logistics constraints, and the anticipated TBM operational procedures, it is considered likely that a variable density (VD) TBM or a Mix Shield TBM will be selected. It therefore follows that the main characteristics of the TBM required to meet the tunnel requirements will be as follows.

- Diameter of the cutter head: 9.53m
- Diameter of the frontal shield: 9.50m
- Diameter at the rear of the shield: 9.48m
- Shield length (approx.): 10.00m
- Diametrical gap (outer diameter of excavation): 0.33m
- Minimum radius of curvature: 300m (Note: minimum alignment curve radius is 350m).

The tunnel lining itself has been assessed for all relevant ground loading conditions, manufacturing loads (demoulding, storage, and transportation) and segment installation during ring-build. The main characteristics of the segments are:

- Typology: Universal ring.
- Thickness: 35 cm.
- Concrete class: C40/50
- Reinforcement: Steel bars class C + steel fibres (Model Code FRC 4e)
- Fire protection: Polypropylene fibres

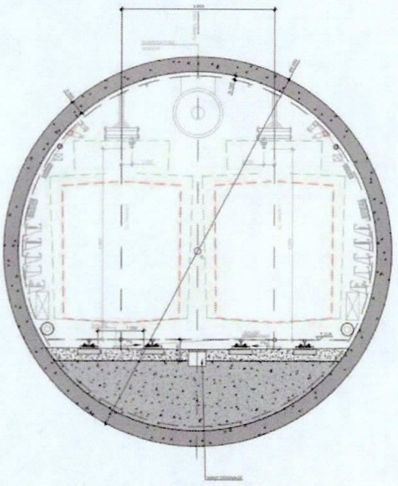
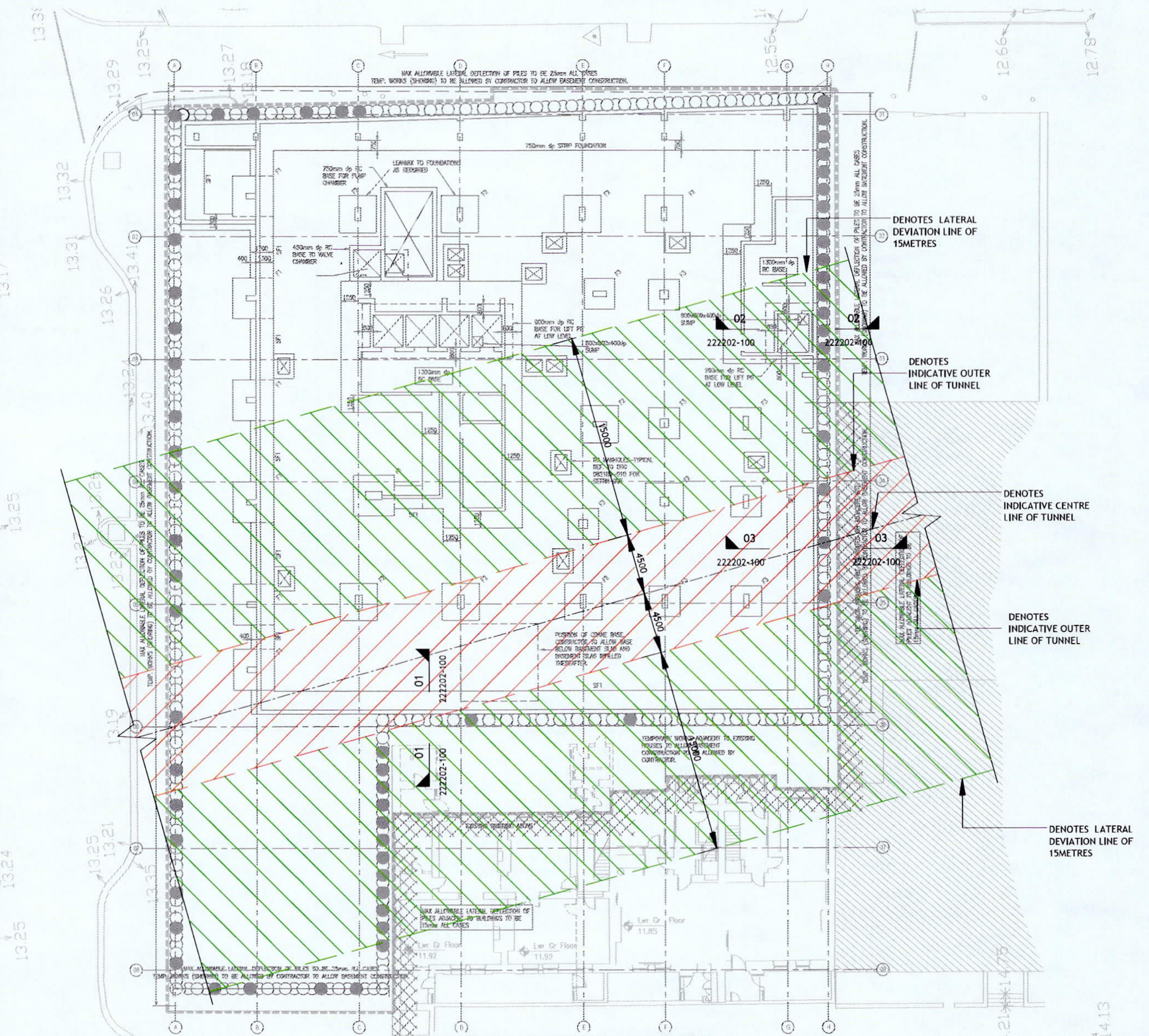


Figure 2-1: TBM Tunnel Geometry

2.2 Non-TBM Underground Structures

Five galleries, comprising two ventilation and three emergency galleries will be required, connected to the main tunnels within the curtilage of Dublin Airport and at Albert College Park Intervention Shaft. These will enable



PLAN INTERFACE OF PROPOSED METROLINK AND EXISTING BASEMENT STRUCTURE

SCALE 1:50

NOTES:

1. DRAWING TO BE READ IN CONJUNCTION WITH ALL RELEVANT ARCHITECTS AND ENGINEERS DRAWINGS AND SPECIFICATIONS.

LEGEND:-

▬	DENOTES 225 THICK RC WALLS U.N.O.
▢ C10	DENOTES RC COLUMN AND REFERENCE TAG
	DENOTES 900ø SECANT PILE WALL
⬡	DENOTES AREA WITH 100mm NON-STRUCTURAL SCREED ON 125 INSULATION
▨	DENOTES 215 THICK SOLID 20N BLOCKWALL U.N.O.
┄	DENOTES STRUCTURAL WALL OR BEAM UNDER U.N.O.
┆	DENOTES PARTITION U.N.O.
⊠	DENOTES STRUCTURAL VOID
325	DENOTES TWO-WAY SPAN RC SLAB & DEPTH
200	DENOTES ONE-WAY SPAN RC SLAB & DEPTH
75 / 150	DENOTES 75mm SCREED ON 150mm HOLLOWCORE SLAB
↔	DENOTES MULTIDECK MD60 V-2 1.2
F11	DENOTES FOUNDATION REFERENCE
+0.000 ⊕	DENOTES STRUCTURAL SLAB LEVEL
TOCB ⊕	DENOTES TOP OF CAPPING BEAM
KOP	DENOTES KNOCK OUT PANEL FOR FUTURE EXPANSION
300	DENOTES STEP IN SLAB LEVEL
●	DENOTES VERTICAL LOAD BEARING PILES. VERTICAL LOAD ON LOAD BEARING PILE = 2200kN (SLS)
○	ALL OTHER MALE PILES TO HAVE MINIMUM AXIAL CAPACITY OF 700kN (SLS)

BUILDING INFORMATION MODELLING (BIM)
NSAI Certified

Rev	Amendment	By	Date	Rev	Amendment	By	Date
P01	ISSUED FOR INFORMATION	BM	21/10/2022				

Client:
EARLDEV PROPERTIES LTD

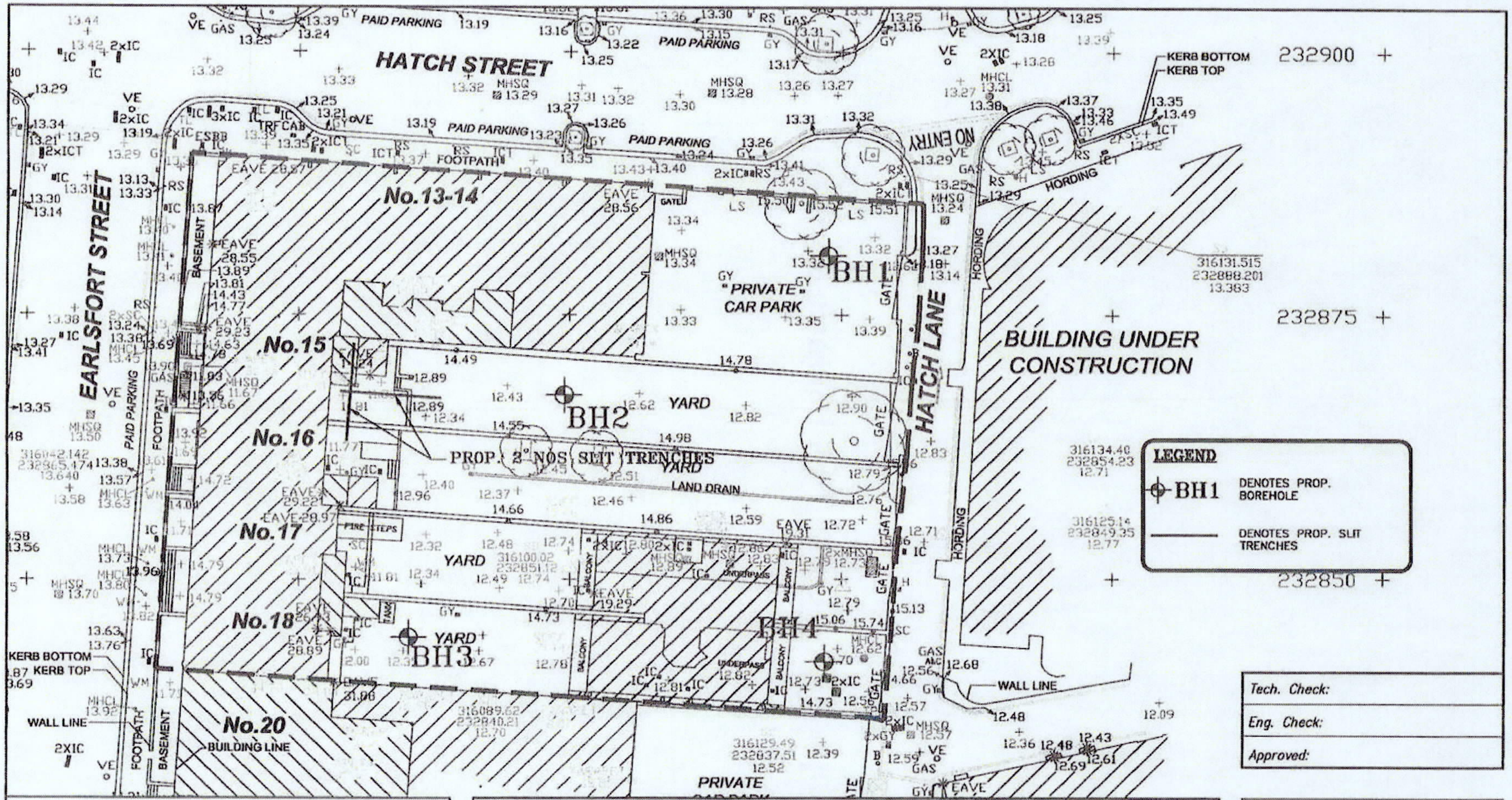
PUNCH consulting engineers
Dublin | Limerick | Cork | Galway | Glasgow
Carnegie House Library Road,
Dun Laoghaire, Co. Dublin, A96 C7W7
t +353 1 271 2200 | w punchconsulting.com

Project: PROJECT METROLINK AT EALRSFORT TERRACE / HATCH STREET
Title: INTERFACE OF PROPOSED METROLINK & EXISTING BASEMENT STUCTURE

Drawn	Date drawn	Technical Check	Engineer Check	Approved
B. Mavudzi	October 2022	B. Mavudzi	R. Coughlan	R. Coughlan

Project No: 222202
Model Ref: 222202-PUNCH-XX-FN-M2-S-100
Drawing Status: S3
Scale @ A1: 1:125
Document No: 222202-PUNCH-XX-FN-DR-S-100
Revision No: P01

Appendix B
SI Data for Arthur Cox Building



Tech. Check:

Eng. Check:

Approved:

Figured dimension only to be taken from this drawing.
All dimensions to be checked on site.
Consultants to be informed immediately of any discrepancies before work proceeds.

Job:	HATCH ST/EARLSFORT TCE CLANCOURT/OPW JOINTVENTURE
Title:	BOREHOLE LAYOUT

Michael Punch & Partners
CONSULTING ENGINEERS

• 97 Henry Street, Limerick. W: www.mpp.ie
T: 061 313 877, F: 061 319 071, E: limerick@mpp.ie
• 2nd Floor, Carnegie House, Library Road,
Dun Laoghaire, Co. Dublin.
T: 01 235 2980, F: 01 235 2985, E: dublin@mpp.ie
• Unit 1B, University Technology Centre,
Curraheen Road, Bishopstown, Cork.
T: 021 438 6100, F: 021 438 6101, E: cork@mpp.ie

Stage:	PRELIMINARY	
Scale:	1:500	
Drawn:	D.GILDEA	
Date:	13/08/07	
Drawing No:		*Rev:*
062304-008		P0

GEOTECHNICAL BORING RECORD

REPORT NUMBER 13263

CONTRACT	Earlsfort Terrace,Dublin 2	**BOREHOLE NO.**	**BH1**
		SHEET	Sheet 1 of 1
CO-ORDINATES(_)		**DATE STARTED**	09/02/2008
GROUND LEVEL (m)		**DATE COMPLETED**	10/02/2008
BOREHOLE DIAMETER (mm)	200	**BORED BY**	J.McDonnell
BOREHOLE DEPTH (m)	8.20	**PROCESSED BY**	F.Clancy
CASING DEPTH (m)	8.20		
CLIENT	Clancourt Management Ltd		
ENGINEER	Michael Punch & Ptnrs		

Depth (m)	Description	Legend	Elevation	Depth (m)	Samples			Field Test Results	Standpipe Details
					Ref. Number	Sample Type	Depth (m)		
0	MADE GROUND (Comprised of tarmac over concrete and stone)								
	MADE GROUND (Comprised of red brick,ash,glass,roots)			0.30					
1					1858	B	1.00	N = 12 (2, 2, 3, 3, 3, 3)	
2					1859	B	2.00	N = 11 (2, 2, 2, 3, 3, 3)	
3					1860	B	3.00	N = 17 (3, 3, 4, 4, 5, 4)	
4	Stiff brown sandy gravelly CLAY			4.00	1861	B	4.10	N = 27 (5, 6, 6, 7, 8, 6)	
5	Soft grey brown very sandy clayey SILT			5.00	1862	B	5.10	N = 4 (1, 1, 1, 1, 1, 1)	
6					1863	B	6.00	N = 7 (1, 2, 2, 1, 2, 2)	
7	Firm black SILT/CLAY			7.00	1864	B	7.10	N = 9 (1, 1, 2, 2, 2, 3)	
	Very stiff black sandy gravelly CLAY with cobbles			7.50					
8					1865	B	8.00	N = 25/75 mm (25, 25)	
	Obstruction End of Borehole at 8.20 m			8.20					
9									

HARD STRATA BORING/CHISELLING

From (m)	To (m)	Time (h)	Comments
0	0.3	1	
8.1	8.2	2	

WATER STRIKE DETAILS

Water Strike	Casing Depth	Sealed At	Rise To	Time (min)	Comments
7.50	7.50	No	5.60	5	Moderate

INSTALLATION DETAILS

Date	Tip Depth	RZ Top	RZ Base	Type
10-02-08	8.00	1.00	8.00	50mm SP

GROUNDWATER DETAILS

Date	Hole Depth	Casing Depth	Depth to Water	Comments
10-02-08	8.20	Nil	5.60	End of Boring

REMARKS Weekend works due to access restrictions

Sample Legend
D - Small Disturbed (tub)
B - Bulk Disturbed
LB - Large Bulk Disturbed
Env - Environmental Sample (Jar + Vial + Tub)
U - Undisturbed 100mm Diameter Sample
P - Undisturbed Piston Sample

GEOTECHNICAL BORING RECORD

REPORT NUMBER 13263

CONTRACT Earlsfort Terrace,Dublin 2

BOREHOLE NO. BH2
SHEET Sheet 1 of 1

CO-ORDINATES(_)

GROUND LEVEL (m)
BOREHOLE DIAMETER (mm) 200
BOREHOLE DEPTH (m) 5.60
CASING DEPTH (m) 5.60

DATE STARTED 21/01/2008
DATE COMPLETED 21/01/2008

CLIENT Clancourt Management Ltd
ENGINEER Michael Punch & Ptnrs

BORED BY J.McDonnell
PROCESSED BY F.Clancy

Depth (m)	Description	Legend	Elevation	Depth (m)	Samples			Field Test Results	Standpipe Details
					Ref. Number	Sample Type	Depth (m)		
0	MADE GROUND (Comprised of tarmac over imported stone fill)								
1	MADE GROUND (Comprised of red bricks and silt/clay)			0.30	1820	B	1.00	N = 8 (2, 2, 2, 2, 2, 2)	
2	Soft black peaty CLAY/SILT			1.50	1821	B	2.00	N = 3/75 mm (3)	
3	Firm to stiff brown sandy gravelly CLAY			2.70	1822	B	3.00	N = 15 (3, 3, 4, 4, 4, 3)	
4	Dense grey/brown sandy silty GRAVEL with lenses of gravelly clay			4.00	1823	B	4.10	N = 50 (6, 9, 11, 15, 14, 10)	
5					1824	B	5.00	N = 50/150 mm (9, 11, 30, 20)	
	Obstruction			5.50	1825	B	5.60		
	End of Borehole at 5.60 m			5.60					
6									
7									
8									
9									

HARD STRATA BORING/CHISELLING

From (m)	To (m)	Time (h)	Comments
0	0.3	2	
4.3	4.6	0.75	
5.5	5.6	2	

WATER STRIKE DETAILS

Water Strike	Casing Depth	Sealed At	Rise To	Time (min)	Comments
4.00	4.00	No	2.70	5	Moderate

INSTALLATION DETAILS

Date	Tip Depth	RZ Top	RZ Base	Type
21-01-08	5.50	1.00	5.50	50mm SP

GROUNDWATER DETAILS

Date	Hole Depth	Casing Depth	Depth to Water	Comments
21-01-08	5.60	Nil	2.50	End of Boring

REMARKS

Sample Legend
D - Small Disturbed (tub)
B - Bulk Disturbed
LB - Large Bulk Disturbed
Env - Environmental Sample (Jar + Vial + Tub)
U - Undisturbed 100mm Diameter Sample
P - Undisturbed Piston Sample

IGSL BH LOG 13263.GPJ IGSL.GDT 6/3/08

GEOTECHNICAL BORING RECORD

REPORT NUMBER 13263

CONTRACT Earlsfort Terrace,Dublin 2

BOREHOLE NO. BH3

SHEET Sheet 1 of 1

CO-ORDINATES(_)

GROUND LEVEL (m)

BOREHOLE DIAMETER (mm) 200

BOREHOLE DEPTH (m) 6.50

CASING DEPTH (m) 6.50

DATE STARTED 16/01/2008

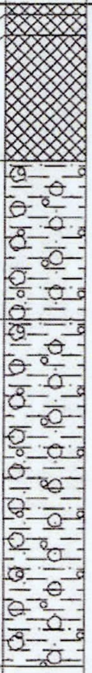
DATE COMPLETED 17/01/2008

CLIENT Clancourt Management Ltd

ENGINEER Michael Punch & Ptnrs

BORED BY J.McDonnell

PROCESSED BY F.Clancy



Depth (m)	Description	Legend	Elevation	Depth (m)	Samples Ref. Number	Sample Type	Depth (m)	Field Test Results	Standpipe Details
0	Tarmac			0.10					
	MADE GROUND (Comprised of imported stone fill)			0.30					
	MADE GROUND (Comprised of brown peaty CLAY with pottery and red brick)				1808	B	1.00	N = 12 (2, 3, 3, 3, 3, 3)	
	Firm to stiff brown sandy gravelly CLAY with occasional cobbles			1.50	1809	B	2.00	N = 15 (3, 3, 3, 4, 4, 4)	
	Very stiff black sandy gravelly CLAY with occasional cobbles			3.00	1810	B	3.10	N = 36 (4, 8, 9, 9, 9, 9)	
					1811	B	4.00	N = 34 (5, 8, 8, 8, 9, 9)	
					1812	B	5.00	N = 37 (5, 8, 9, 9, 10, 9)	
					1813	B	6.00	N = 30/75 mm (6, 10, 30)	
	End of Borehole at 6.50 m			6.30					

HARD STRATA BORING/CHISELLING

From (m)	To (m)	Time (h)	Comments
0	0.3	1	
5.4	5.6	0.5	
6.3	6.5	2	

WATER STRIKE DETAILS

Water Strike	Casing Depth	Sealed At	Rise To	Time (min)	Comments
					No water strike

GROUNDWATER DETAILS

Date	Hole Depth	Casing Depth	Depth to Water	Comments

INSTALLATION DETAILS

Date	Tip Depth	RZ Top	RZ Base	Type

REMARKS

Sample Legend
D - Small Disturbed (tub)
B - Bulk Disturbed
LB - Large Bulk Disturbed
Env - Environmental Sample (Jar + Vial + Tub)
U - Undisturbed 100mm Diameter Sample
P - Undisturbed Piston Sample

GEOTECHNICAL BORING RECORD

REPORT NUMBER 13263

CONTRACT	Earlsfort Terrace,Dublin 2	**BOREHOLE NO.**	BH4
		SHEET	Sheet 1 of 1
CO-ORDINATES(_)		**DATE STARTED**	18/01/2008
GROUND LEVEL (m)		**DATE COMPLETED**	18/01/2008
BOREHOLE DIAMETER (mm)	200	**BORED BY**	J.McDonnell
CLIENT	Clancourt Management Ltd	**PROCESSED BY**	F.Clancy
ENGINEER	Michael Punch & Ptnrs		
BOREHOLE DEPTH (m)	7.10		
CASING DEPTH (m)	7.10		

Depth (m)	Description	Legend	Elevation	Depth (m)	Samples Ref. Number	Sample Type	Depth (m)	Field Test Results	Standpipe Details
0	MADE GROUND (Comprised of imported stone fill)	▨							
	MADE GROUND (Comprised of brown sandy clay with red brick and pottery)	▨		0.50	1814	B	1.00	N = 15 (3, 3, 3, 4, 4, 4)	
	Firm brown sandy CLAY/SILT	∘		1.70	1815	B	2.00	N = 12 (3, 4, 4, 2, 3, 3)	
	Stiff brown sandy gravelly CLAY with occasional cobbles	∘		2.80	1816	B	3.00	N = 22 (4, 4, 4, 6, 6, 6)	
					1817	B	4.00	N = 28 (4, 6, 6, 7, 7, 8)	
	Very stiff black sandy gravelly CLAY with occasional cobbles and boulders	∘		4.50	1818	B	5.00	N = 47 (4, 8, 9, 10, 12, 16)	
					1819	B	6.00	N = 52 (6, 10, 12, 10, 12, 18)	
7	End of Borehole at 7.10 m			7.00				N = 25/75 mm (25, 25)	

HARD STRATA BORING/CHISELLING

From (m)	To (m)	Time (h)	Comments
0	0.5	1.25	
7	7.1	2	

WATER STRIKE DETAILS

Water Strike	Casing Depth	Sealed At	Rise To	Time (min)	Comments
					No water strike

GROUNDWATER DETAILS

Date	Hole Depth	Casing Depth	Depth to Water	Comments

INSTALLATION DETAILS

Date	Tip Depth	RZ Top	RZ Base	Type

REMARKS

Sample Legend
D - Small Disturbed (tub)
B - Bulk Disturbed
LB - Large Bulk Disturbed
Env - Environmental Sample (Jar + Vial + Tub)
U - Undisturbed 100mm Diameter Sample
P - Undisturbed Piston Sample

GEOTECHNICAL CORE LOG RECORD

REPORT NUMBER	13263
CONTRACT	Earlsfort Terrace, Dublin
DRILLHOLE NO	RC1
SHEET	Sheet 1 of 2
CO-ORDINATES(_)	
GROUND LEVEL (m)	
CORE DIAMETER (mm)	84
INCLINATION	-90
FLUSH	Air/Mist
DATE STARTED	10/02/2008
DATE COMPLETED	10/02/2008
CLIENT	
ENGINEER	
DRILLED BY	Creben
LOGGED BY	IGSL

Downhole Depth (m)	Core Run Depth (m)	T.C.R.%	S.C.R.%	R.Q.D.%	Fracture Spacing (mm) 0 250 500	Legend	Non-intact zones (shaded)	Strata description	Depth (m)	Discontinuities	Elevation	Standpipe Details	SPT (N Value)
0								SYMMETRIX OPEN HOLE DRILLING: Observed by driller as returns of clay.					
7								SYMMETRIX OPEN HOLE DRILLING: Observed by driller as returns of gravelly clay.	7.00				
8.80	8.80	100	40	23					8.80				

REMARKS

1 Core box. 1hr Move and set up.

INSTALLATION REMARKS

GROUNDWATER DETAILS

Date	Hole Depth	Casing Depth	Depth to Water	Comments

INSTALLATION DETAILS

Date	Tip Depth	RZ Top	RZ Base	Type

GEOTECHNICAL CORE LOG RECORD

REPORT NUMBER 13263

CONTRACT Earlsfort Terrace, Dublin

DRILLHOLE NO RC1
SHEET Sheet 2 of 2

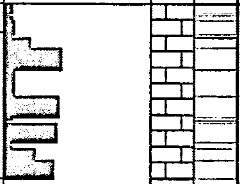
CO-ORDINATES(_)

GROUND LEVEL (m)
CORE DIAMETER (mm) 84
INCLINATION -90
FLUSH Air/Mist

DATE STARTED 10/02/2008
DATE COMPLETED 10/02/2008

CLIENT
ENGINEER

DRILLED BY Creben
LOGGED BY IGSL

Downhole Depth (m)	Core Run Depth (m)	T.C.R.%	S.C.R.%	R.Q.D.%	Fracture Spacing (mm) 0 250 500	Legend	Non-Intact zones (shaded)	Strata description	Depth (m)	Discontinuities	Elevation	Standpipe Details	SPT (N Value)
10	10.30							Strong to locally moderately strong, thin to medium bedded, fine grained, grey to dark grey to black, LIMESTONE, siliceous, argillaceous and calc-shale (probable dispersed pyrite). Fresh to slightly and locally moderately weathered. *(continued)* End of Corehole at 11.8 (m)	11.80	Discontinuities are smooth and planar to undulose. Apertures are tight to open with very locally slightly iron oxide stained surfaces and locally clay smeared and infilled (11.21m-11.23m). Dips are sub horizontal with local vertical fractures (10.96m-11.21m, 11.23m-11.43m) *(continued)*			
11		100	41	41									
	11.80												
12													
13													
14													
15													
16													
17													
18													
19													

REMARKS

1 Core box. 1hr Move and set up.

INSTALLATION REMARKS

GROUNDWATER DETAILS

Date	Hole Depth	Casing Depth	Depth to Water	Comments

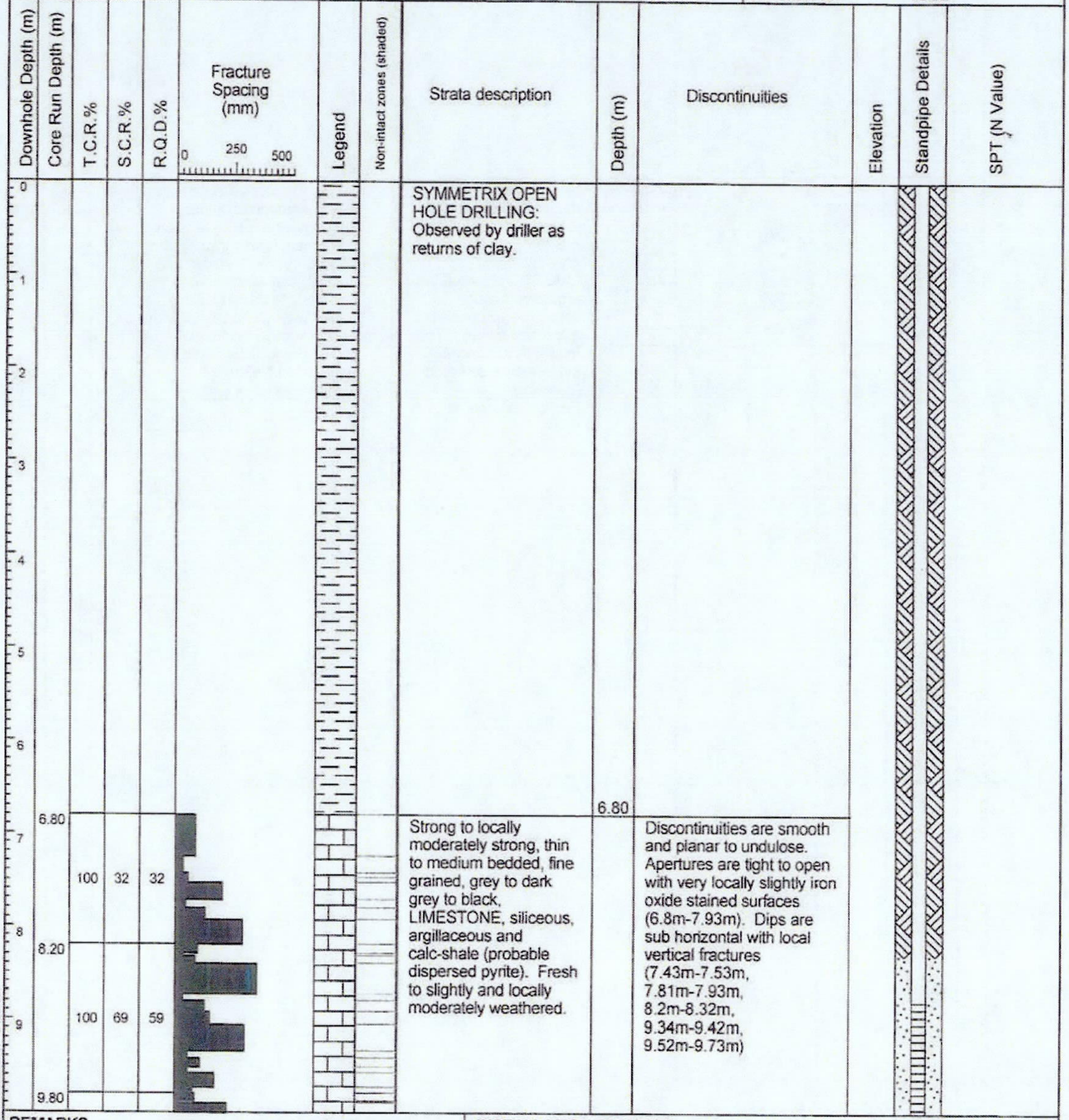
INSTALLATION DETAILS

Date	Tip Depth	RZ Top	RZ Base	Type

GEOTECHNICAL CORE LOG RECORD

REPORT NUMBER 13263

CONTRACT	Earlsfort Terrace, Dublin	**DRILLHOLE NO**	**RC4**
		SHEET	Sheet 1 of 2
CO-ORDINATES(_)		**DATE STARTED**	09/02/2008
GROUND LEVEL (m)		**DATE COMPLETED**	10/02/2008
CORE DIAMETER (mm)	84	**DRILLED BY**	Creben
INCLINATION	-90	**LOGGED BY**	IGSL
FLUSH	Air/Mist		
CLIENT			
ENGINEER			



Core Run Depth (m)	T.C.R.%	S.C.R.%	R.Q.D.%	Strata description	Depth (m)	Discontinuities
				SYMMETRIX OPEN HOLE DRILLING: Observed by driller as returns of clay.	6.80	
6.80	100	32	32	Strong to locally moderately strong, thin to medium bedded, fine grained, grey to dark grey to black, LIMESTONE, siliceous, argillaceous and calc-shale (probable dispersed pyrite). Fresh to slightly and locally moderately weathered.		Discontinuities are smooth and planar to undulose. Apertures are tight to open with very locally slightly iron oxide stained surfaces (6.8m-7.93m). Dips are sub horizontal with local vertical fractures (7.43m-7.53m, 7.81m-7.93m, 8.2m-8.32m, 9.34m-9.42m, 9.52m-9.73m)
8.20	100	69	59			
9.80						

REMARKS

2 Core boxes. 1hr Move and set up. Grout: 0.0m-11.4m.

INSTALLATION REMARKS

GROUNDWATER DETAILS

Date	Hole Depth	Casing Depth	Depth to Water	Comments

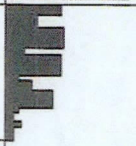
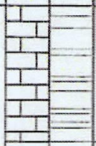
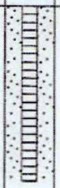
INSTALLATION DETAILS

Date	Tip Depth	RZ Top	RZ Base	Type
10-02-08	11.80	8.30	11.80	50mm SP

GEOTECHNICAL CORE LOG RECORD

REPORT NUMBER 13263

CONTRACT	Earlsfort Terrace, Dublin			**DRILLHOLE NO**	RC4
				SHEET	Sheet 2 of 2
CO-ORDINATES(_)		**GROUND LEVEL (m)**		**DATE STARTED**	09/02/2008
		CORE DIAMETER (mm)	84	**DATE COMPLETED**	10/02/2008
CLIENT		**INCLINATION**	-90	**DRILLED BY**	Creben
ENGINEER		**FLUSH**	Air/Mist	**LOGGED BY**	IGSL

Downhole Depth (m)	Core Run Depth (m)	T.C.R.%	S.C.R.%	R.Q.D.%	Fracture Spacing (mm) 0 250 500	Legend	Non-intact zones (shaded)	Strata description	Depth (m)	Discontinuities	Elevation	Standpipe Details	SPT (N Value)
10–11.40		100	84	64									
	11.40							End of Corehole at 11.4 (m)	11.40				
12													
13													
14													
15													
16													
17													
18													
19													

REMARKS

2 Core boxes. 1hr Move and set up. Grout: 0.0m-11.4m.

INSTALLATION REMARKS

GROUNDWATER DETAILS

Date	Hole Depth	Casing Depth	Depth to Water	Comments

INSTALLATION DETAILS

Date	Tip Depth	RZ Top	RZ Base	Type
10-02-08	11.80	8.30	11.80	50mm SP

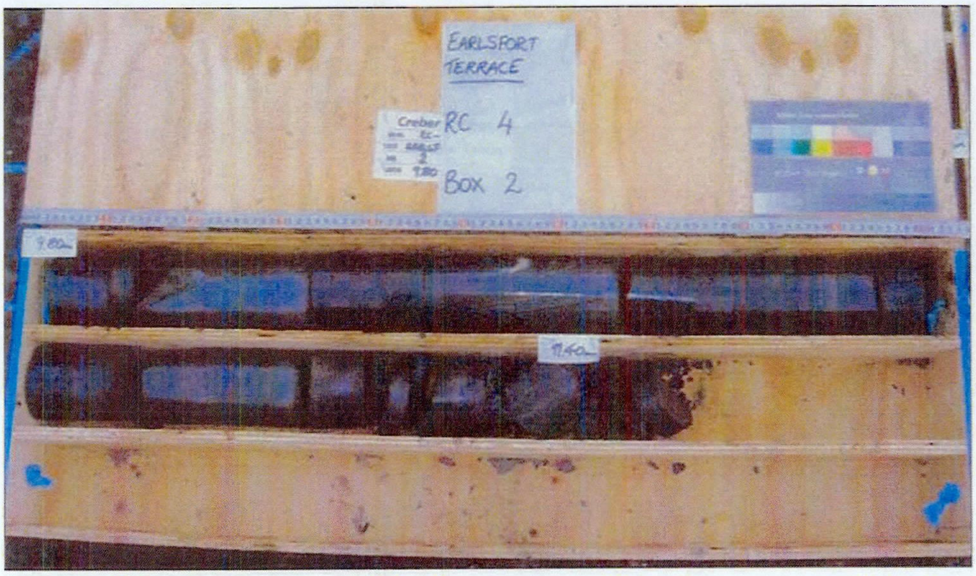
Core Photography – (13263 Earlsfort Terrace)

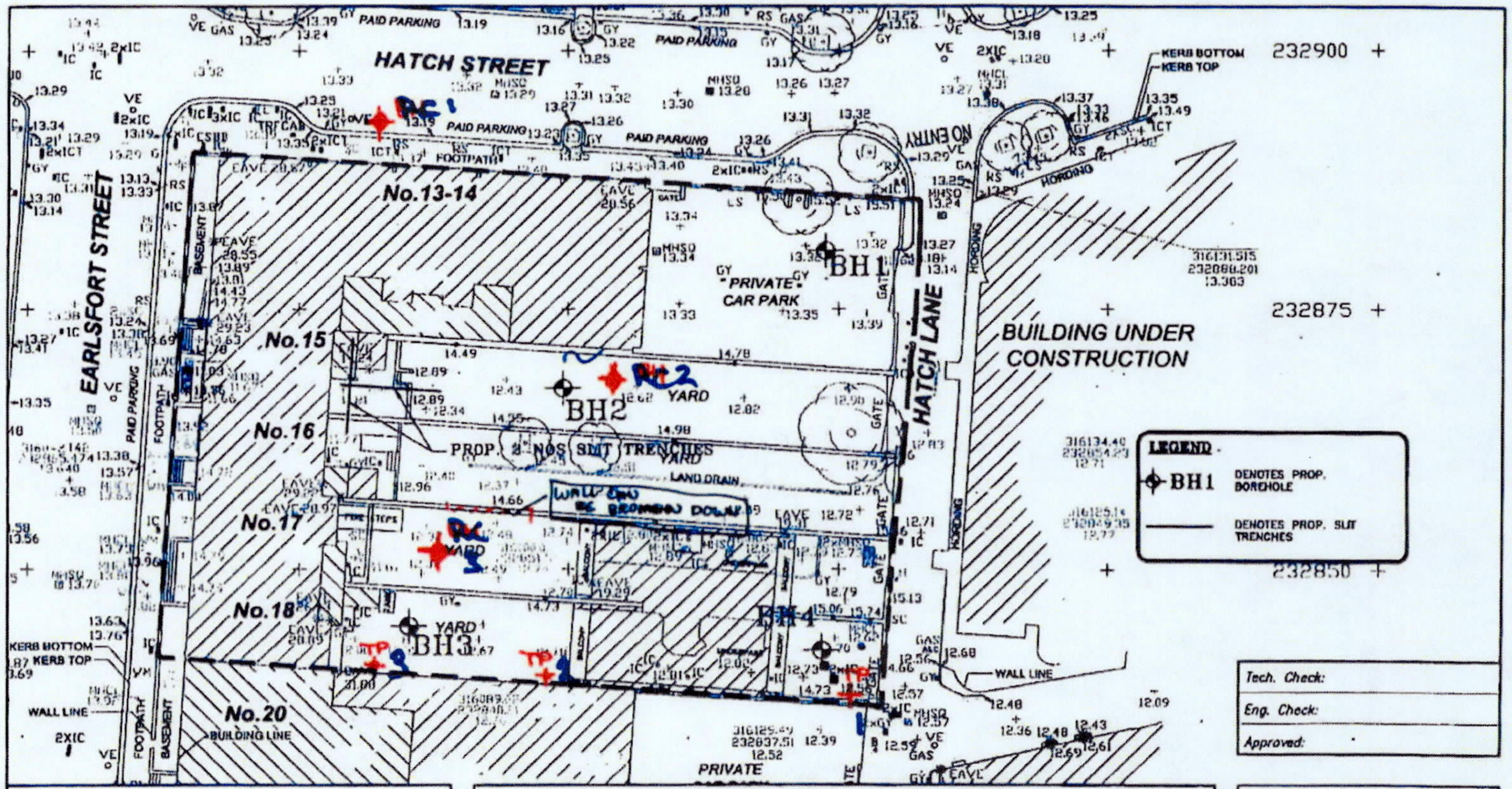
RC 1 Box 1 of 1

RC 4 Box 1 of 2

Core Photography – (13263 Earlsfort Terrace)

RC 4 Box 2 of 2





Tech. Check:

Eng. Check:

Approved:

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Figured dimension only to be taken from this drawing. All dimensions to be checked on site. Consultants to be informed immediately of any discrepancies before work proceeds.

Job:	HATCH ST/EARLSFORT TCE CLANCOURT/OPW JOINTVENTURE
Title:	BOREHOLE LAYOUT

Michael Punch & Partners
CONSULTING ENGINEERS

- 97 Henry Street, Limerick. W: www.mpp.ie
  T: 061 313 877, F: 061 319 071, E: limerick@mpp.ie
- 2nd Floor, Carnegie House, Library Road, Dun Laoghaire, Co. Dublin.
  T: 01 235 2980, F: 01 235 2985, E: dublin@mpp.ie
- Unit 18, University Technology Centre, Curraheen Road, Bishopstown, Cork.
  T: 021 438 6100, F: 021 438 6101, E: cork@mpp.ie

Stage:	PRELIMINARY
Scale:	1:500
Drawn:	D.GILDEA
Date:	13/08/07
Drawing No:	062304-008
Rev:	P0

- 3No. Boreholes Reqd
- 3No. Trial Pits.

- 082189 ETHS
- SI WORKS.

GEOTECHNICAL CORE LOG RECORD

REPORT NUMBER 17833

CONTRACT	ETHS Development, Hatch Lane, Dublin.	**DRILLHOLE NO**	**RC01**
		SHEET	Sheet 1 of 2
CO-ORDINATES		**DATE DRILLED**	23/09/2014
GROUND LEVEL (mOD)		**DATE LOGGED**	23/09/2014
RIG TYPE	Knebel		
FLUSH	Air/Mist		
CLIENT	Clancourt Magagement Ltd.	**INCLINATION (deg)**	-90
ENGINEER	Punch Consulting Engineers	**CORE DIAMETER (mm)**	80
DRILLED BY	Petersen	**LOGGED BY**	D.O'Shea

Downhole Depth (m)	Core Run Depth (m)	T.C.R.%	S.C.R.%	R.Q.D.%	Fracture Spacing Log (mm) 0 250 500	Non-intact Zone	Legend	Description	Depth (m)	Elevation	Standpipe Details	SPT (N Value)
0								SYMMETRIX DRILLING: No recovery, observed by driller as returns of made ground consisting of tarmacadam.	0.20			
								SYMMETRIX DRILLING: No recovery, observed by driller as returns of made ground consisting of clayey cobbly gravel (Clause 804 material).	0.50			
								SYMMETRIX DRILLING: No recovery, observed by driller as returns of made ground consisting of grey clay	1.00			
								SYMMETRIX DRILLING: No recovery, observed by driller as returns of brown clay	4.10			N = 24 (2, 2, 5, 6, 6, 7) N = 29 (2, 3, 6, 7, 7, 9)
								SYMMETRIX DRILLING: No recovery, observed by driller as returns of brown sandy gravelly clay with occasional cobbles	7.90			N = 49/255 mm (6, 9, 13, 11, 16, 9) N = 50/145 mm (7, 14, 19, 31)
								SYMMETRIX DRILLING: No recovery, observed by driller as returns of black weathered rock	9.10			
	9.50							SYMMETRIX DRILLING: No recovery, observed by driller as returns of black rock	9.50			

REMARKS

Hole cased 0.00-9.50m.

WATER STRIKE DETAILS

Water Strike	Casing Depth	Sealed At	Rise To	Time (min)	Comments
7.90					Moderate

GROUNDWATER DETAILS

Date	Hole Depth	Casing Depth	Depth to Water	Comments

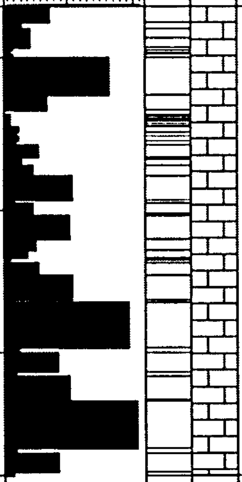
INSTALLATION DETAILS

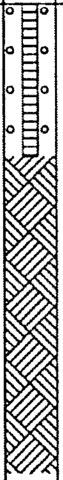
Date	Tip Depth	RZ Top	RZ Base	Type
23-09-14	11.50	8.50	11.50	50mm SP

GEOTECHNICAL CORE LOG RECORD

IGSL

REPORT NUMBER	17833
CONTRACT	ETHS Development, Hatch Lane, Dublin.
DRILLHOLE NO	RC01
SHEET	Sheet 2 of 2
CO-ORDINATES	
GROUND LEVEL (mOD)	
RIG TYPE	Knebel
FLUSH	Air/Mist
DATE DRILLED	23/09/2014
DATE LOGGED	23/09/2014
CLIENT	Clancourt Magagement Ltd.
ENGINEER	Punch Consulting Engineers
INCLINATION (deg)	-90
CORE DIAMETER (mm)	80
DRILLED BY	Petersen
LOGGED BY	D.O'Shea





Downhole Depth (m)	Core Run Depth (m)	T.C.R.%	S.C.R.%	R.Q.D.%	Fracture Spacing Log (mm)	Non-intact Zone	Legend	Description	Depth (m)	Elevation	Standpipe Details	SPT (N Value)
10	10.50	95	81	17				Very strong to moderately strong, thickly to thinly bedded (to thinly laminated where mudstone/shale), grey/dark grey/black, fine-grained, LIMESTONE (predominantely argillaceous limestone grading regularly into calci-siltite limestone, local stylolites, pyrite present), fresh to locally moderately weathered (at mudstone/shale layers at 9.75-9.79m, 11.02-11.06m, 12.03-12.05m, 12.49-12.52m) Discontinuities are medium to.closely spaced, smooth, planar. Apertures are tight to moderately open, locally clay-smeared, locally clay-smeared, locally calcite-filled (1-10mm thick). Dips are sub-horizontal & locally sub-vertical. *(continued)*				
11	12.00	100	100	65								
12 13	13.40	100	95	79								
14	14.60	100	100	85					14.60			
15 16 17 18 19								End of Borehole at 14.60 m				

REMARKS

Hole cased 0.00-9.50m.

WATER STRIKE DETAILS

Water Strike	Casing Depth	Sealed At	Rise To	Time (min)	Comments
7.90					Moderate

INSTALLATION DETAILS

Date	Tip Depth	RZ Top	RZ Base	Type
23-09-14	11.50	8.50	11.50	50mm SP

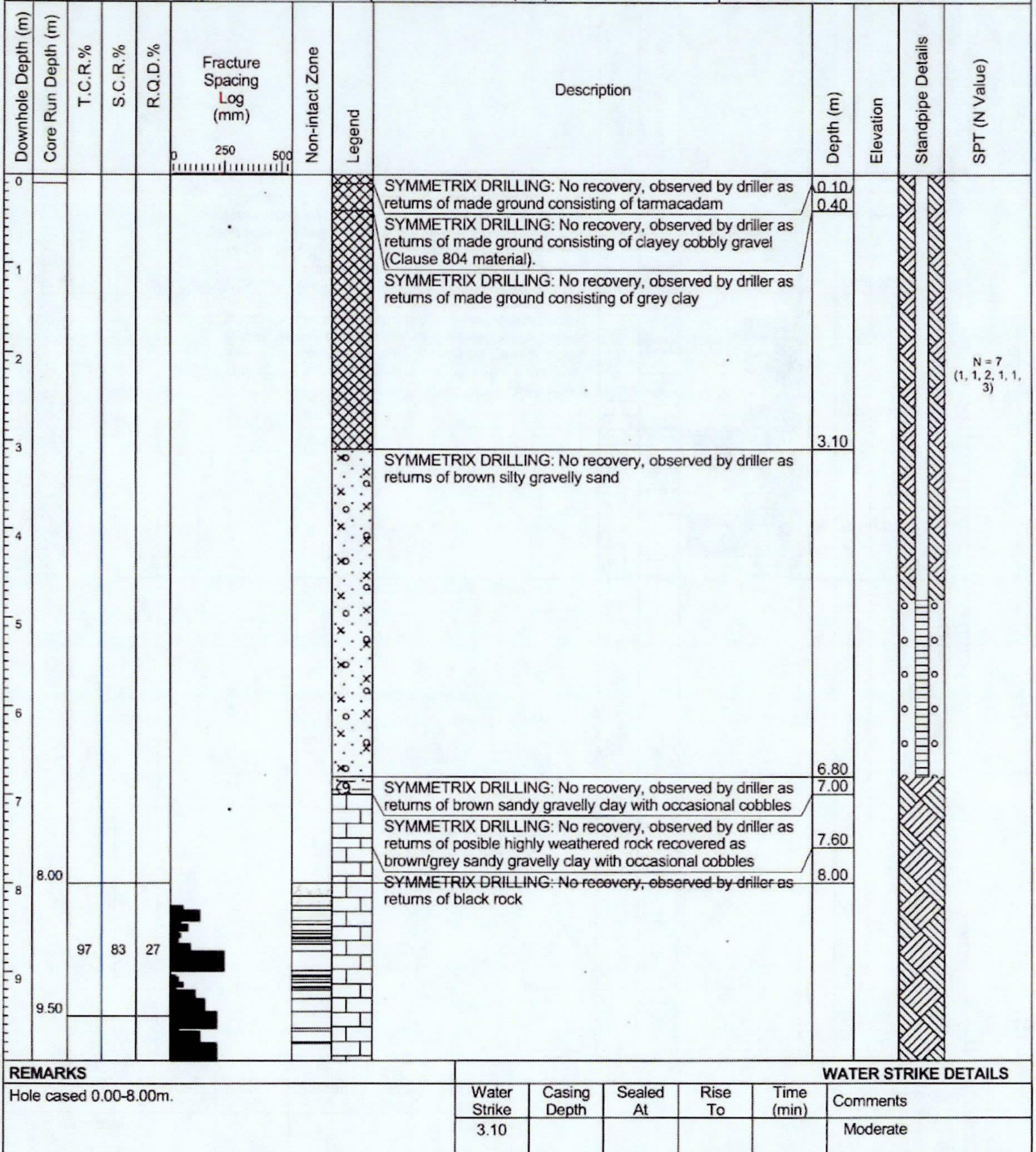
GROUNDWATER DETAILS

Date	Hole Depth	Casing Depth	Depth to Water	Comments
23-09-14	14.60	9.50	5.80	Water level recorded 5 mins after end of drilling.

GEOTECHNICAL CORE LOG RECORD

REPORT NUMBER 17833

CONTRACT	ETHS Development, Hatch Lane, Dublin.	**DRILLHOLE NO**	**RC02**
		SHEET	Sheet 1 of 2
CO-ORDINATES		**DATE DRILLED**	19/09/2014
GROUND LEVEL (mOD)		**DATE LOGGED**	19/09/2014
RIG TYPE	Knebel		
FLUSH	Air/Mist		
CLIENT	Clancourt Magagement Ltd.	**INCLINATION (deg)**	-90
ENGINEER	Punch Consulting Engineers	**CORE DIAMETER (mm)**	80
DRILLED BY	Petersen	**LOGGED BY**	D.O'Shea



Downhole Depth (m)	Core Run Depth (m)	T.C.R.%	S.C.R.%	R.Q.D.%	Fracture Spacing Log (mm)	Non-intact Zone	Legend	Description	Depth (m)	Elevation	Standpipe Details	SPT (N Value)
0								SYMMETRIX DRILLING: No recovery, observed by driller as returns of made ground consisting of tarmacadam	0.10			
								SYMMETRIX DRILLING: No recovery, observed by driller as returns of made ground consisting of clayey cobbly gravel (Clause 804 material).	0.40			
1–2								SYMMETRIX DRILLING: No recovery, observed by driller as returns of made ground consisting of grey clay	3.10			N = 7 (1, 1, 2, 1, 1, 3)
3–6								SYMMETRIX DRILLING: No recovery, observed by driller as returns of brown silty gravelly sand	6.80			
7								SYMMETRIX DRILLING: No recovery, observed by driller as returns of brown sandy gravelly clay with occasional cobbles	7.00			
								SYMMETRIX DRILLING: No recovery, observed by driller as returns of posible highly weathered rock recovered as brown/grey sandy gravelly clay with occasional cobbles	7.60			
8–9	8.00 9.50	97	83	27				SYMMETRIX DRILLING: No recovery, observed by driller as returns of black rock	8.00			

Fracture Spacing Log (mm): 0 250 500

REMARKS

Hole cased 0.00-8.00m.

WATER STRIKE DETAILS

Water Strike	Casing Depth	Sealed At	Rise To	Time (min)	Comments
3.10					Moderate

GROUNDWATER DETAILS

Date	Hole Depth	Casing Depth	Depth to Water	Comments

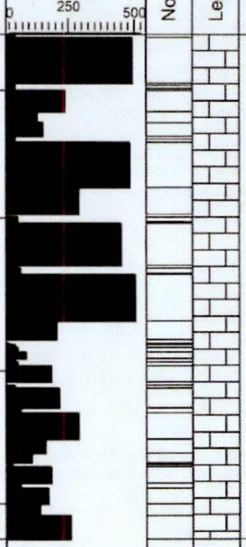
INSTALLATION DETAILS

Date	Tip Depth	RZ Top	RZ Base	Type
19-09-14	6.80	4.80	6.80	50mm SP

GEOTECHNICAL CORE LOG RECORD

REPORT NUMBER	17833
CONTRACT	ETHS Development, Hatch Lane, Dublin.
DRILLHOLE NO	RC02
SHEET	Sheet 2 of 2
CO-ORDINATES	
GROUND LEVEL (mOD)	
RIG TYPE	Knebel
FLUSH	Air/Mist
INCLINATION (deg)	-90
CORE DIAMETER (mm)	80
DATE DRILLED	19/09/2014
DATE LOGGED	19/09/2014
CLIENT	Clancourt Magagement Ltd.
ENGINEER	Punch Consulting Engineers
DRILLED BY	Petersen
LOGGED BY	D.O'Shea

Core Run Depth (m)	T.C.R.%	S.C.R.%	R.Q.D.%
10.55	100	99	88
11.80	100	100	83
13.30	100	100	59
14.60	100	99	78
14.95	100	100	100



Description

Very strong to moderately strong, thickly to thinly bedded (to thinly laminated where mudstone/shale), grey/dark grey/black, fine-grained, LIMESTONE (predominantely argillaceous limestone grading regularly into calci-siltite limestone, local stylolites, pyrite present), fresh to locally moderately weathered (at mudstone/shale layers at 8.15-8.26m, 8.79-9.04m, 9.19-9.21m, 10.48-10.50m, 10.53-10.55m, 11.76-11.79m, 12.99-13.03m, 13.41-13.47m, 14.22-14.24m)

Discontinuities are medium to closely spaced, smooth, planar. Apertures are tight to moderately open, locally clay-smeared, locally clay-smeared. Dips are sub-horizontal & locally sub-vertical. *(continued)*

Depth (m): 14.95

End of Borehole at 14.95 m

REMARKS

Hole cased 0.00-8.00m.

WATER STRIKE DETAILS

Water Strike	Casing Depth	Sealed At	Rise To	Time (min)	Comments
3.10					Moderate

GROUNDWATER DETAILS

Date	Hole Depth	Casing Depth	Depth to Water	Comments
19-09-14	14.95	8.00	3.00	Water level recorded 5 mins after end of drilling.

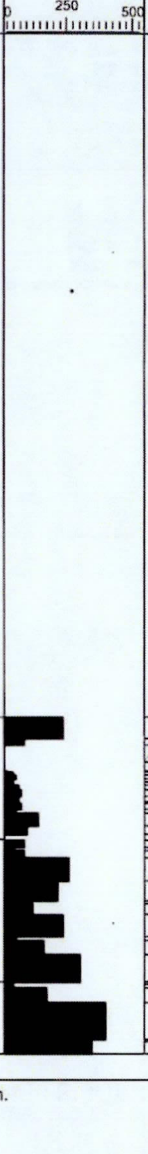
INSTALLATION DETAILS

Date	Tip Depth	RZ Top	RZ Base	Type
19-09-14	6.80	4.80	6.80	50mm SP

GEOTECHNICAL CORE LOG RECORD

REPORT NUMBER 17833

CONTRACT	ETHS Development, Hatch Lane, Dublin.	**DRILLHOLE NO**	**RC03**
		SHEET	Sheet 1 of 2
CO-ORDINATES		**DATE DRILLED**	22/09/2014
GROUND LEVEL (mOD)		**DATE LOGGED**	22/09/2014
RIG TYPE	Knebel		
FLUSH	Air/Mist		
CLIENT	Clancourt Magagement Ltd.	**INCLINATION (deg)**	-90
ENGINEER	Punch Consulting Engineers	**CORE DIAMETER (mm)**	80
DRILLED BY	Petersen	**LOGGED BY**	D.O'Shea



Downhole Depth (m)	Core Run Depth (m)	T.C.R.%	S.C.R.%	R.Q.D.%	Fracture Spacing Log (mm)	Non-intact Zone	Legend	Description	Depth (m)	Elevation	Standpipe Details	SPT (N Value)
0								SYMMETRIX DRILLING: No recovery, observed by driller as returns of made ground consisting of tarmacadam	0.10			
								SYMMETRIX DRILLING: No recovery, observed by driller as returns of made ground consisting of brown clay	1.20			
1								SYMMETRIX DRILLING: No recovery, observed by driller as returns of made ground consisting of grey clay	4.00			
2												N = 23 (1, 6, 6, 6, 6, 5)
3												N = 18 (2, 4, 4, 3, 5, 6)
4								SYMMETRIX DRILLING: No recovery, observed by driller as returns of grey/black sandy gravelly clay with occasional cobbles	6.40			
5												N = 50/195 mm (7, 13, 15, 20, 15)
6								SYMMETRIX DRILLING: No recovery, observed by driller as returns of black rock	6.70			
7	6.70	96	65	36				Very strong to moderately strong, thickly to thinly bedded (to thinly laminated where mudstone/shale), grey/dark grey/black, fine-grained, LIMESTONE (predominantely argillaceous limestone grading regularly into calci-siltite limestone, local stylolites, pyrite present), fresh to locally moderately weathered (at mudstone/shale layers at 6.98-7.14m, 7.53-7.55m, 7.85-7.91m, 9.30-9.32m, 9.86-9.88m, 11.04-11.06m, 12.76-12.79m 13.20-13.22m & 14.02-14.05m) Discontinuities are medium to closely spaced, smooth, planar. Apertures are tight to moderately open, locally clay-smeared, locally clay-smeared, locally calcite/dolomite-filled (1-100m thick). Dips are sub-horizontal & locally sub-vertical.				
8	7.90	100	100	84								
9	9.30											

REMARKS

Hole cased 0.00-6.70m.

WATER STRIKE DETAILS

Water Strike	Casing Depth	Sealed At	Rise To.	Time (min)	Comments
					No water strike recorded

GROUNDWATER DETAILS

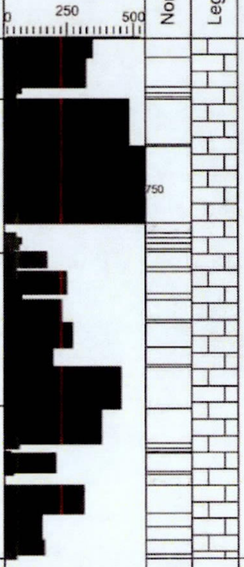
Date	Hole Depth	Casing Depth	Depth to Water	Comments

INSTALLATION DETAILS

Date	Tip Depth	RZ Top	RZ Base	Type
22-09-14	10.00	7.00	10.00	50mm SP
22-09-14	15.10	14.50	15.10	19mm SP

GEOTECHNICAL CORE LOG RECORD

REPORT NUMBER	17833
CONTRACT	ETHS Development, Hatch Lane, Dublin.
DRILLHOLE NO	RC03
SHEET	Sheet 2 of 2
CO-ORDINATES	
GROUND LEVEL (mOD)	
RIG TYPE	Knebel
FLUSH	Air/Mist
INCLINATION (deg)	-90
CORE DIAMETER (mm)	80
DATE DRILLED	22/09/2014
DATE LOGGED	22/09/2014
CLIENT	Clancourt Magagement Ltd.
ENGINEER	Punch Consulting Engineers
DRILLED BY	Petersen
LOGGED BY	D.O'Shea



Downhole Depth (m)	Core Run Depth (m)	T.C.R.%	S.C.R.%	R.Q.D.%	Description	Depth (m)	Elevation	SPT (N Value)
10	10.60	92	92	81	Very strong to moderately strong, thickly to thinly bedded (to thinly laminated where mudstone/shale), grey/dark grey/black, fine-grained, LIMESTONE (predominantely argillaceous limestone grading regularly into calci-siltite limestone, local stylolites, pyrite present), fresh to locally moderately weathered (at mudstone/shale layers at 6.98-7.14m, 7.53-7.55m, 7.85-7.91m, 9.30-9.32m, 9.86-9.88m, 11.04-11.06m, 12.76-12.79m 13.20-13.22m & 14.02-14.05m) Discontinuities are medium to closely spaced, smooth, planar. Apertures are tight to moderately open, locally clay-smeared, locally clay-smeared, locally calcite/dolomite-filled (1-100m thick). Dips are sub-horizontal & locally sub-vertical. *(continued)*			
11								
12	12.10	100	95	77				
13	13.60	100	99	85				
14								
15	15.10	100	99	78		15.10		
					End of Borehole at 15.10 m			
16								
17								
18								
19								

REMARKS

Hole cased 0.00-6.70m.

WATER STRIKE DETAILS

Water Strike	Casing Depth	Sealed At	Rise To	Time (min)	Comments
					No water strike recorded

INSTALLATION DETAILS

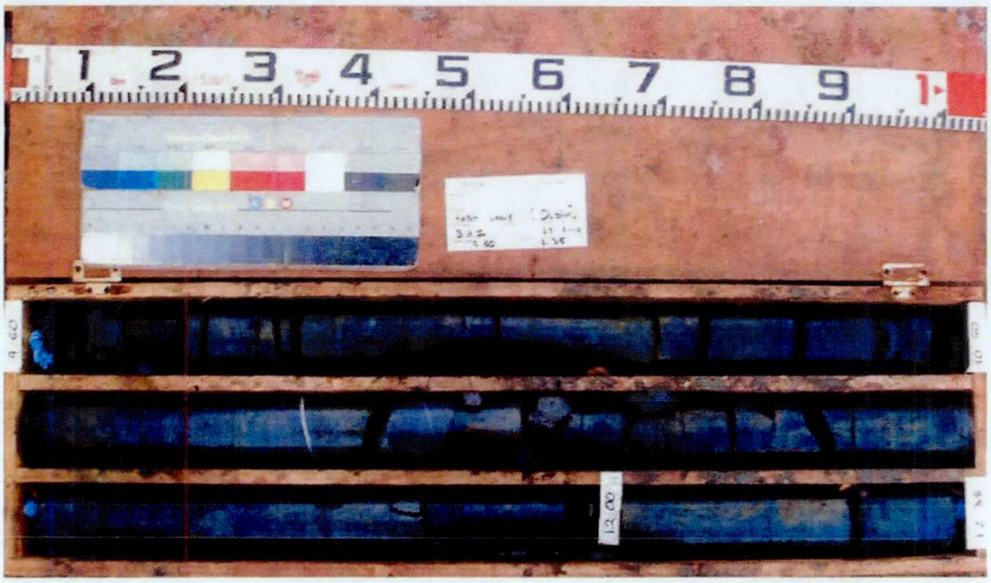
Date	Tip Depth	RZ Top	RZ Base	Type
22-09-14	10.00	7.00	10.00	50mm SP
22-09-14	15.10	14.50	15.10	19mm SP

GROUNDWATER DETAILS

Date	Hole Depth	Casing Depth	Depth to Water	Comments

17833 - ETHS Development, Hatch Street – Core Photography

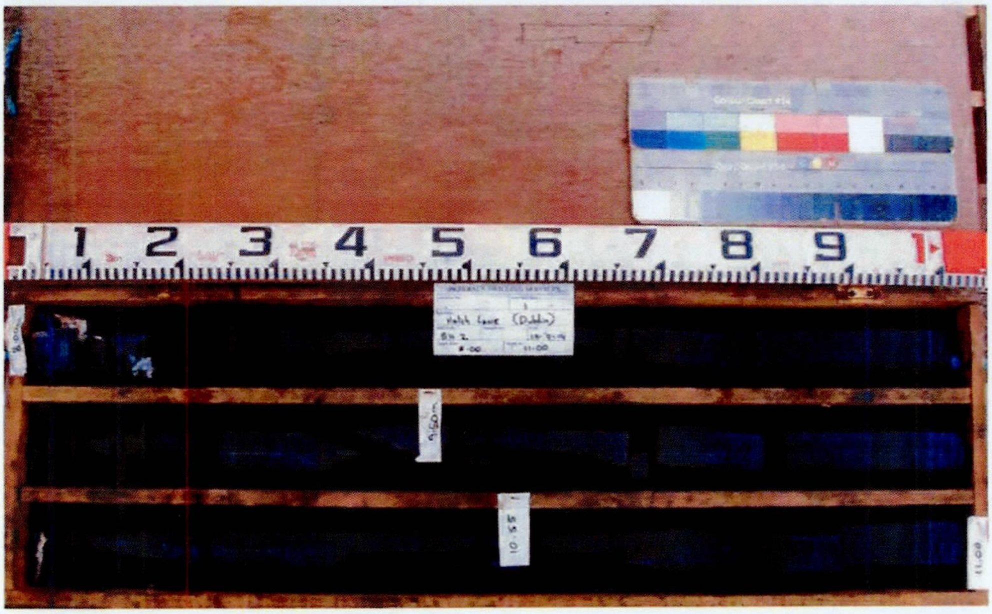
RC01 Box 1 of 2



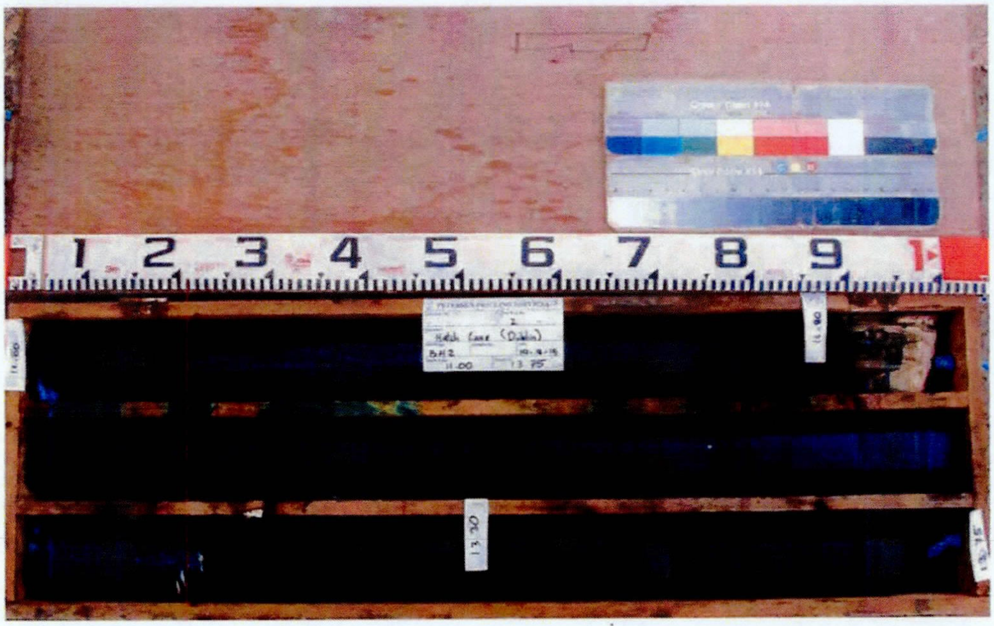
RC01 Box 2 of 2

IGSL Ltd.

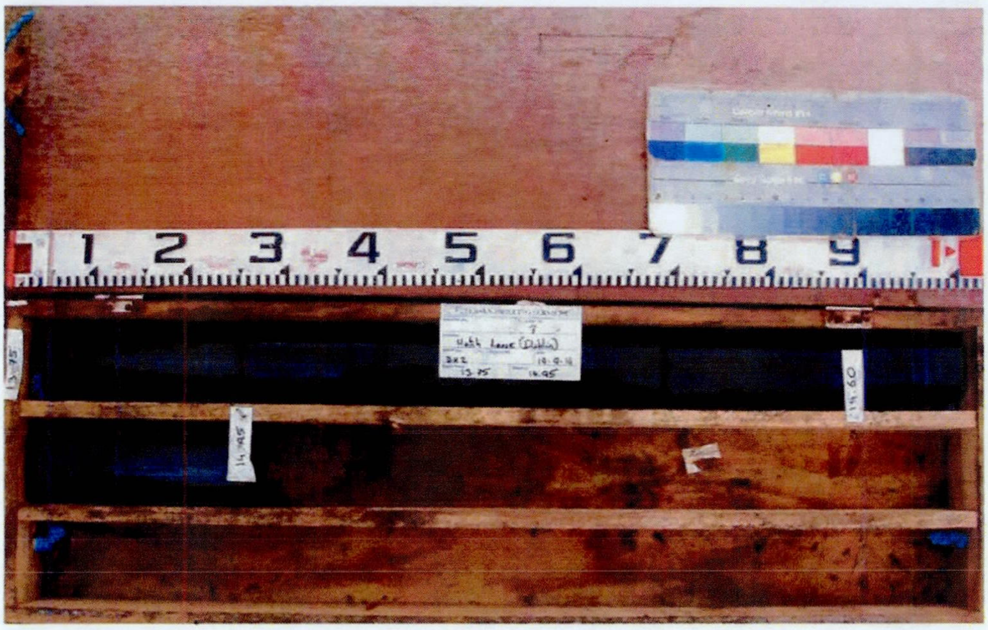
RC02 Box 1 of 3



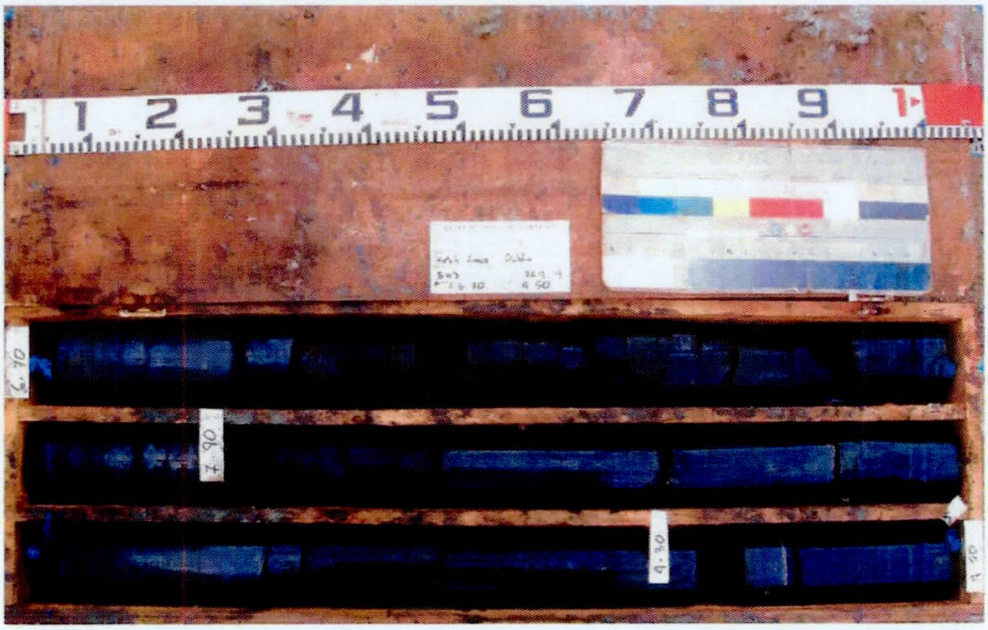
RC02 Box 2 of 3



RC02 Box 3 of 3

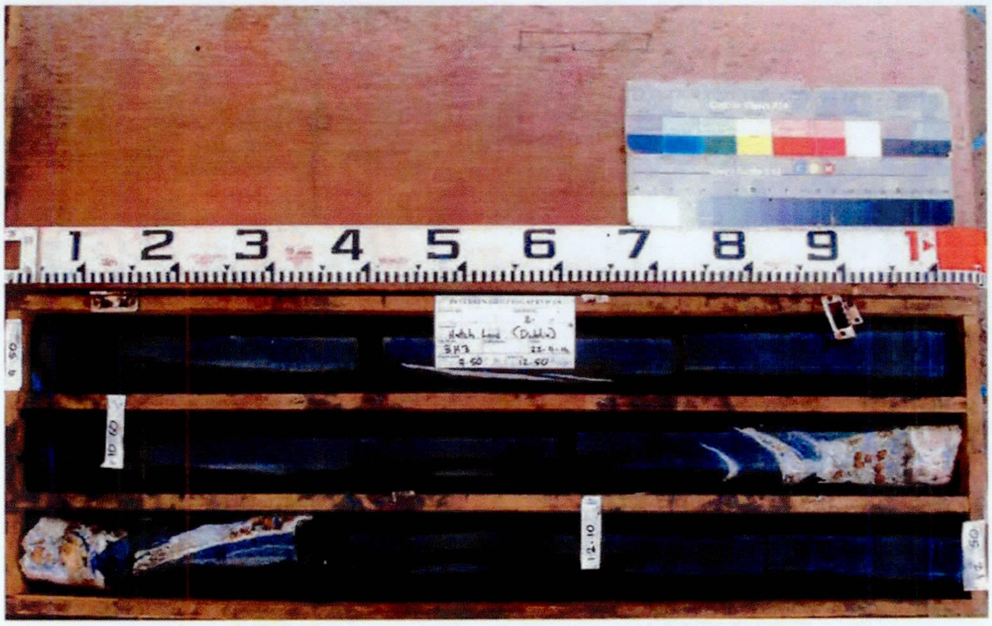


RC03 Box 1 of 3

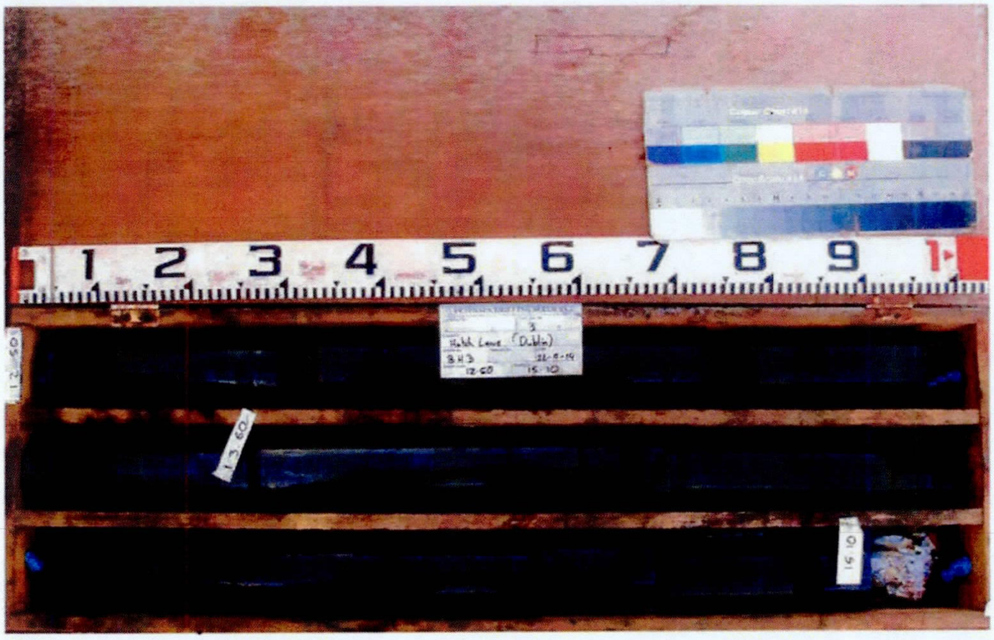


17833 - ETHS Development, Hatch Street – Core Photography

RC03 Box 2 of 3



RC03 Box 3 of 3



POINT LOAD STRENGTH INDEX TEST DATA

Contract: ETHS Development, Hatch Lane, D
Dublin.
Date of test:6/10/14

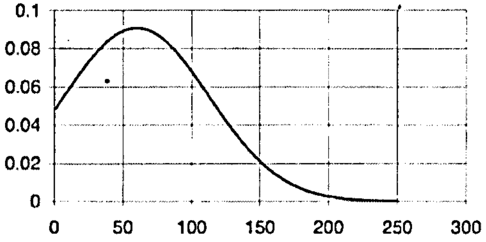
Sample Type: Core
Contract no. 17833

RC No.	Depth m	D (Diameter) mm	P (failure load) kN	F	Is (index strength) Mpa	Is(50) (index strength) Mpa	*UCS MPa	Type	Orientation
RC01	10.1	78	3.0	1.222	0.49	0.60	12	PL	90°
	12.3	78	29.0	1.222	4.77	5.82	116	PL	90°
	13	78	8.0	1.222	1.31	1.61	32	PL	90°
	14.5	78	32.0	1.222	5.26	6.42	128	PL	90°
RC02	8.9	78	4.0	1.222	0.66	0.80	16	PL	90°
	9.90	78	28.0	1.222	4.60	5.62	112	PL	90°
	13.40	78	2.0	1.222	0.33	0.40	8	PL	90°
	14.30	78	6.0	1.222	0.99	1.20	24	PL	90°
RC03	6.80	78	28.0	1.222	4.60	5.62	112	PL	90°
	9.20	78	6.0	1.222	0.99	1.20	24	PL	90°
	12.30	78	2.0	1.222	0.33	0.40	8	PL	90°
	13.50	78	31.0	1.222	5.10	6.22	124	PL	90°

Statistical Summary Data	Is(50)	UCS*
Number of Samples Tested	12	12
Minimum	0.40	8
Average	2.99	60
Maximum	6.42	128
Standard Dev.	2.63	53
Upper 95% Confidence Limit	8.16	163.14
Lower 95% Confidence Limit	-2.17	-43.35

Comments:
*UCS taken as k x Point Load Is(50): k= 20

*UCS Normal Distribution Curve



Abbreviations	
i	irregular
a	axial
b	block
d	diametral

approx. orientation to planes of weakness/bedding

U	unknown
P	perpendicular
//	parallel

Uniaxial Compression Test Report Sheet

I.G.S.L.

Sample Identification

Contract Name: ETHS Development, Hatch Lane, Dublin.
Job Number: 17833
Hole No: RC01
Depth (m): 10.6-10.9m

Sample Description

Colour: Grey
Grain size: Fine-grained
Weathering Grade: Fresh
Rock Type: LIMESTONE

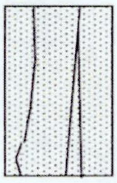
Weathering Grade Criteria

I. Fresh:	Unchanged from original state
II. Slightly weathered:	Slight discolouration, slight weakening
III. Moderately weathered:	Considerable weakening, penetrative discolouration
IV. Highly weathered:	Considerable weakening, penetrative discolouration, breaks in hand

Sample Measurements

Length 196
Diameter (Ø) 78.1 mm

Sketch of Failure Surfaces



Testing

Load Rate 3.3 kN/min
Load at Failure (P) 312 kN

Strength Calculations

$$\text{Uniaxial Compressive Strength} = \frac{312000}{4788.19385}$$

$$= \frac{1000 \times P}{\Pi \times (Ø/2)^2}$$

$$= \boxed{65.13} \text{ (Mpa)}$$

$$\text{Bulk Density} = \boxed{2.66} \text{ (Mg/m}^3\text{)}$$

Notes:

Uniaxial Compression Test Report Sheet

I.G.S.L.

Sample Identification

Contract Name: ETHS Development, Hatch Lane, Dublin.
Job Number: 17833
Hole No: RC01
Depth (m): 10.6-10.9m

Sample Description

Colour: Grey
Grain size: Fine-grained
Weathering Grade: Fresh
Rock Type: LIMESTONE

Weathering Grade Criteria

I. Fresh:	Unchanged from original state
II. Slightly weathered:	Slight discolouration, slight weakening
III. Moderately weathered:	Considerable weakening, penetrative discolouration
IV. Highly weathered:	Considerable weakening, penetrative discolouration, breaks in hand

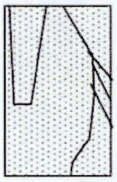
Sample Measurements

Length: 192
Diameter (Ø): 78 mm

Testing

Load Rate: 3.3 kN/min
Load at Failure (P): 283 kN

Sketch of Failure Surfaces



Strength Calculations

Uniaxial Compressive Strength $= \frac{283000}{4775.94}$

$$= \frac{1000 \text{ x } P}{\Pi \text{ x } (Ø/2)\text{\^{}}2}$$

= 59.23 (Mpa)

Bulk Density = 2.67 (Mg/m^3)

Notes:

Uniaxial Compression Test Report Sheet

I.G.S.L.

Sample Identification

Contract Name:	ETHS Development, Hatch Lane, Dublin.
Job Number:	17833
Hole No:	RC02
Depth (m):	11.1-11.4m

Sample Description

Colour:	Grey
Grain size:	Fine-grained
Weathering Grade:	Fresh
Rock Type:	LIMESTONE

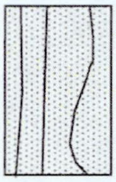
Weathering Grade Criteria

I. Fresh:	Unchanged from original state
II. Slightly weathered:	Slight discolouration, slight weakening
III. Moderately weathered:	Considerable weakening, penetrative discolouration
IV. Highly weathered:	Considerable weakening, penetrative discolouration, breaks in hand

Sample Measurements

Length	194	
Diameter (Ø)	78.2	mm

Sketch of Failure Surfaces



Testing

Load Rate	3.3	kN/min
Load at Failure (P)	433	kN

Strength Calculations

Uniaxial Compressive Strength = $\frac{433000}{4800.4634}$

= $\frac{1000 \times P}{\Pi \times (Ø/2)^2}$

= 90.15 (Mpa)

Bulk Density = 2.68 (Mg/m^3)

Notes:

Uniaxial Compression Test Report Sheet

I.G.S.L.

Sample Identification

Contract Name: ETHS Development, Hatch Lane, Dublin.
Job Number: 17833
Hole No: RC02
Depth (m): 11.9-12.3m

Sample Description

Colour:	Grey
Grain size:	Fine-grained
Weathering Grade:	Fresh
Rock Type:	LIMESTONE

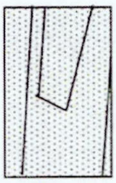
Weathering Grade Criteria

I. Fresh:	Unchanged from original state
II. Slightly weathered:	Slight discolouration, slight weakening
III. Moderately weathered:	Considerable weakening, penetrative discolouration
IV. Highly weathered:	Considerable weakening, penetrative discolouration, breaks in hand

Sample Measurements

Length	198	
Diameter (Ø)	78.1	mm

Sketch of Failure Surfaces



Testing

Load Rate	3.3	kN/min
Load at Failure (P)	189	kN

Strength Calculations

Uniaxial Compressive Strength = $\frac{189000}{4788.19385}$

= $\frac{1000 \times P}{\pi \times (Ø/2)^2}$

= 39.45 (Mpa)

Bulk Density = 2.66 (Mg/m^3)

Notes:

Uniaxial Compression Test Report Sheet

I.G.S.L.

Sample Identification

Contract Name:	ETHS Development, Hatch Lane, Dublin.
Job Number:	17833
Hole No:	RC03
Depth (m):	9.1-9.3m

Sample Description

Colour:	Grey
Grain size:	Fine-grained
Weathering Grade:	Fresh
Rock Type:	LIMESTONE

Weathering Grade Criteria

I. Fresh:	Unchanged from original state
II. Slightly weathered:	Slight discolouration, slight weakening
III. Moderately weathered:	Considerable weakening, penetrative discolouration
IV. Highly weathered:	Considerable weakening, penetrative discolouration, breaks in hand

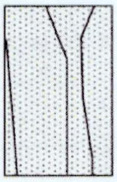
Sample Measurements

Length	194	
Diameter (Ø)	78	mm

Testing

Load Rate	3.3	kN/min
Load at Failure (P)	224	kN

Sketch of Failure Surfaces



Strength Calculations

Uniaxial Compressive Strength = $\frac{224000}{4775.94}$

$= \frac{1000 \times P}{\pi \times (Ø/2)^2}$

= 46.88 (Mpa)

Bulk Density = 2.67 (Mg/m^3)

Notes:

Uniaxial Compression Test Report Sheet

I.G.S.L.

Sample Identification

Contract Name:	ETHS Development, Hatch Lane, Dublin.
Job Number:	17833
Hole No:	RC03
Depth (m):	10.6-11.0m

Sample Description

Colour:	Grey
Grain size:	Fine-grained
Weathering Grade:	Fresh
Rock Type:	LIMESTONE

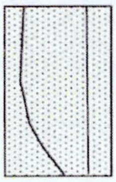
Weathering Grade Criteria

I. Fresh:	Unchanged from original state
II. Slightly weathered:	Slight discolouration, slight weakening
III. Moderately weathered:	Considerable weakening, penetrative discolouration
IV. Highly weathered:	Considerable weakening, penetrative discolouration, breaks in hand

Sample Measurements

Length	195	
Diameter (Ø)	78.1	mm

Sketch of Failure Surfaces



Testing

Load Rate	3.3	kN/min
Load at Failure (P)	201	kN

Strength Calculations

Uniaxial Compressive Strength = $\frac{201000}{4788.19385}$

= $\frac{1000 \times P}{\Pi \times (Ø/2)^2}$

= 41.96 (Mpa)

Bulk Density = 2.67 (Mg/m^3)

Notes:

Appendix D

Building Damage Assessment EIAR Phase 2a Assessment Calculations

Appendix B.1: Buildings Identified from Building Survey

BUILDING CODE	BUILDING DESCRIPTION			BUILDING LOCATION			BUILDING INFORMATION			
	NAME	CONSIDERATION	CATEGORY	Chainage	Dmin (m)	Dmax (m)	Height (m)	Nº Floors	Length (m)	Depth (m)
B-238	Arthur Cox Building	0	0	18+980	0.00	17.81	40.0	7	17.81	-8.10

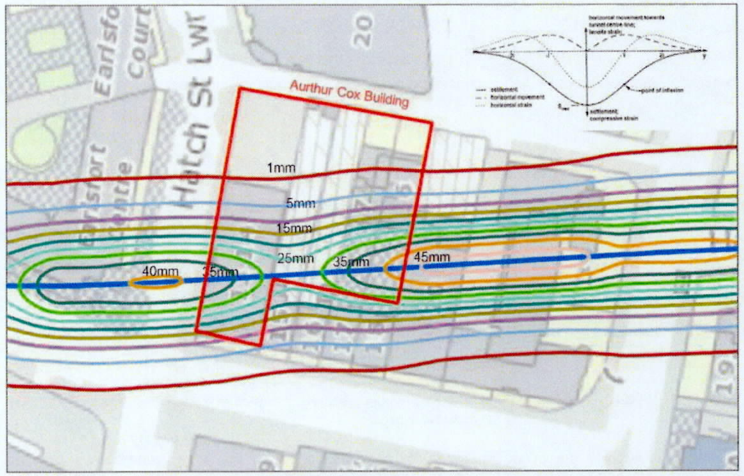
Table 5-1: Details of Ground Conditions, V_L and K Values by Chainage

Start Chainage	End Chainage	Length (m)	Excavated Material	Layer 1	Layer 2	Layer 3	Layer 4	Layer 5	Vs (%)	K
18900	18960	60	CLU	CLU (20%)	Sands and Gravels (20%)	QBR (30%)	Qx (30%)		1.5	0.3
18960	18980	20	**CLU**	**CLU (40%)**	**Sands and Gravels (30%)**	**QBR (10%)**	**Qx (20%)**		**0.75**	**0.4**
18980	19100	120	CLU	CLU (20%)	Sands and Gravels (20%)	QBR (30%)	Qx (30%)		1.5	0.4

- **Phase 1 –** the assessment of the greenfield settlement contours using generic ground parameters and the identification of buildings that are
  - **a)** enclosed by the 10mm contour or with a ground settlement slope > 1:500 and
  - **b)** those buildings enclosed by the 1mm contour subject to 'special' considerations.
- **Phase 2 –** all the buildings identified in Phase 1 are assessed using the greenfield ground movement profile making credible foundation assumptions and are classified into Damage Categories 0 – 5; those buildings placed in Damage Category 3 or above, and those subject to 'special' considerations (see below) are carried through to Phase 3.
- **Phase 3 –** each identified building is considered individually to determine its behaviour using detailed information and assessment methods; this may include a refined ground model, detailed structural surveys, refined construction methodology and use of sophisticated soil-structure interaction analysis such as finite element analysis.

In the context of building damage assessment, 'special' considerations refer to buildings (hereafter referred as 'special' buildings) in proximity of the excavation, with deep basements, or those identified as designated Protected Structures, or sensitive buildings as defined below:

- **Case A:** it is on shallow foundation and is within a distance from a retained cutting, shaft, or box equal to the excavated depth of superficial deposits or 50% of the total excavation depth, whichever is the greater. In this context, superficial deposits are taken to be soils above the rockhead level.
- **Case B:** it has a foundation level deeper than 4m, or (in the case of a bored tunnel) greater than 20% of the depth to tunnel axis.
- **Case C:** it is a Protected Structure
- **Case D:** any 'prominent' or 'sensitive' buildings that might need further assessment to determine whether any protective works required.



4.3 Phase 2 Assessment

4.3.1 General

The Phase 2 assessment is split into two sub-phases, namely Phase 2a and Phase 2b as follows:

a) Phase 2a is undertaken as part of the Preliminary Design. This sub-phase initially adopts the same conservative assumptions used to predict the Phase 1 greenfield ground movements; refined assumptions are sometimes made to assess the sensitivity of the initial assessment results.

b) Phase 2b is a confirmatory/refined analysis undertaken by the detailed designer of the D&B Contractor. This sub-phase usually adopts tighter volume loss parameters and utilises a more refined construction methodology since the D&B contractor will now be progressing the development of the detail design and finalising his construction methodology and planning. .

4.5 Phase 3 Assessment

All buildings that have been classified at the end of the Phase 2b assessment as Damage Category 3 (Moderate) or above (or where there exists any uncertainty after the Phase 2b assessment) will be the subject of a Phase 3 assessment by the D&B Contractor. Furthermore, all 'special' buildings (refer to Section 4.1), which have been the subject of a Phase 2a/2b assessment, but which do not qualify for further assessment (Damage Category 2 or below) will also be the subject of a Phase 3 assessment.

For the Phase 3 assessment, each building will be subject to detailed assessment on an individual basis. Both the strains developing within the building, and the applicability of the classification of risk categories will be reviewed in terms of their relevance for the buildings undergoing Phase 3 assessment. The purpose of the Phase 3 assessment is to ensure that any uncertainty or risk that might lead to damage is minimised.

A detailed survey will be carried out as part of the Phase 3 assessment to provide the necessary additional information to inform this detailed analysis of how the individual elements of the building would be affected by the predicted ground movements. The method and extent of the detailed analysis will be determined on a case-by-case basis and may include a more sophisticated semi-empirical or a detailed soil-structure interaction using finite element modelling methods. As part of this analysis, the detailed design and construction methodology, including the stiffness of the wall and propping system, together with the beneficial effects of the overall structural stiffness of the building will be taken account of. The overall structural stiffness of the building will limit the deformation of the building to the greenfield settlement profile and thus reduce the maximum tensile strains experienced by the building. It is therefore likely that the Phase 3 assessment will yield further improvement to the damage category determined by the Phase 2b assessment.

The ultimate output of the Phase 3 analysis will be to minimise risk and uncertainty and finalise any necessary protection works required to mitigate the impact of construction generated ground movements. This may include further refinement or modification by D&B Contractor of TBM drive parameters and control measures.

5.2 Phase 2a Building Assessment Results

5.2.1 Representative Buildings

<u>Initial Phase 2a Assessment</u>

The initial Phase 2a assessment results for the 'representative' buildings are given in Table 5-2 together with the key relevant building information. The actual location of the building and the worst-case orientation line that passes through the footprint of the buildings (i.e., close to being orthogonal to the settlement contour) have been determined from the OS Map.

The initial Phase 2a assessment shows that the following nine buildings fall within Damage Category 3:

B39, B76, B77, B142, B175, B176, B177, B178 & B179.

<u>Refined Phase 2a Assessment</u>

Considering the nine buildings which fell within Damage Category 3 at the end of the initial Phase 2a assessment, a refined Phase 2a assessment has been carried out with tighter volume loss values considering the advances in tunnelling equipment and control due to the capability of the TBM that will be used, and the Damage Category of all the buildings reassessed. In the refined Phase 2a assessment, the volume loss values have been taken as two-thirds of the corresponding values adopted for the initial Phase 2a as follows:

- Superficial material (clay or granular material): $V_l = 1.0\%$
- Rock strata: $V_l = 0.5\%$

In the case of a mixed strata:

- If the tunnel is wholly in rock and there is at least half-a-tunnel diameter rock cover above the crown, then $V_l = 0.5\%$;
- Else $V_l = 1.0\%$.

These volume loss values are compatible with those experienced using modern tunnelling equipment and control systems from variable density TBMs which it is anticipated will be employed for this project.

For the non-TBM construction, current methodologies with instrumentation and monitoring from the surface providing information to inform the control at the face also improve the losses that can be anticipated and allows the volume loss values to be taken as 50% more than that of the corresponding TBM volume loss values.

These values are moderatly conservate when comparing against the published data in CIRIA PR 30 for stiff fissured clay and glacial deposits.

The refined Phase 2a assessment results show that all the 'representative' buildings fall within Damage Category 2 or below.

Table 5-2: Result of Phase 2a Building Damage Assessment – Representative Buildings

Ref	Chainage	Description	Height (m)	Number of Floors	Length (m)	Depth of basement (m)	Initial Phase 2a Assessment Damage Category	Refined Phase 2a Assessment Damage Category	RPS, NIAH, RMP or other heritage (Y/N/unknown)	Continue to next assessment phase? (Y/N)	Comments
B-238	18980	Arthur Cox Building	40.0	7	17.8	-8.1	2 (Slight)	2 (Slight)	N	Y	Case B (refer to section 4.1)

Table F1: Building Damage Assessment Results for 'Representative' and 'Additional' Buildings - Critical Segments within Each Building (Rev 1)

Specific Building	Parameter	Critical Segment	Start [m]	End [m]	Curvature	Max Slope	Max Settlement [mm]	Max Tensile Strain [%]	Min Radius of Curvature (Hogging) [m]	Min Radius of Curvature (Sagging) [m]	Damage Category
B-238	Max Slope	2	11.666	24.465	Sagging	0.0035255	37.127	0.084266	-	1106.5	2 (Slight)
	Max Settlement	2	11.666	24.465	Sagging	0.0035255	37.127	0.084266	-	1106.5	2 (Slight)
	Max Tensile Strain	1	0	11.666	Hogging	0.003512	22.526	0.091991	2510.6	-	2 (Slight)
	Min Radius of Curvature (Hogging)	3	24.465	39.758	Hogging	0.0035255	22.484	0.086642	2481.8	-	2 (Slight)
	Min Radius of Curvature (Sagging)	2	11.666	24.465	Sagging	0.0035255	37.127	0.084266	-	1106.5	2 (Slight)