Application for Development Consent
Application Reference Number: WWO10001

Tunnel and Bridge Assessments
Central Zone
TWUL Cross Thames Link Tunnel
Doc Ref: 9.15.38
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List of abbreviations

CSO combined sewer overflow
TWUL Thames Water Utilities Limited
MM Mott MacDonald
GRP Ground Response Program
LU London Underground
TT Thames Tunnel
I.D. Internal Diameter
O.D. Outside Diameter
1 Executive Summary

The Thames Tunnel is to be constructed by Thames Water Utilities Limited as part of the London Tideway Tunnels Project. Construction is due to commence in 2014 and is expected to take approximately six years to complete. The Thames Tunnel is to pass beneath the TWUL Cross Thames Link Tunnel with a vertical clearance of approximately 14.3m. The Thames Tunnel is to be excavated through the London Clay at this location; the TWUL Cross Thames Link Tunnel is constructed within the London Clay Formation at this location.

This report documents the assessment of the ground movements associated with excavation of the Thames Tunnel and their impact on the section of the TWUL Cross Thames Link Tunnel beneath the River Thames at Battersea. The document aims to assure both the London Tideway Tunnels Project and TWUL that the proposed works do not present an unacceptable risk to the TWUL Cross Thames Link Tunnel in the vicinity of the proposed Thames Tunnel works. The objective of this report is to demonstrate that the works can be carried out with an acceptable risk (As Low As Reasonably Practicable) to the existing asset.

A maximum settlement of approximately 21mm is anticipated at invert level of the TWUL Cross Thames Link Tunnel for the moderately conservative volume loss of 1.0%. The key results of this assessment are summarised below:

Table 1.1 Results of Tunnel Assessment – External Lining

<table>
<thead>
<tr>
<th>Input Parameters</th>
<th>Results of Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tunnel Distortion</td>
</tr>
<tr>
<td></td>
<td>Transverse&lt;sup&gt;1&lt;/sup&gt;</td>
</tr>
<tr>
<td>VL (%)</td>
<td>K</td>
</tr>
<tr>
<td>1.0</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Notes

1. The ground movement predictions at crown, invert and axis level determined in the empirical analysis have been used to determine the transverse distortion of the TWUL Cross Thames Link Tunnel.

2. Deformation has been assessed in the longitudinal direction through the radius of curvature imposed on the TWUL Cross Thames Link Tunnel; curvature has been determined in both hogging and sagging zones of the settlement trough.

3. The loads on the tunnel lining are defined as follows: N is the hoop load per m run of tunnel; M the bending moment per m run of tunnel; ∆M is the change in bending moment per m run of tunnel due to the tunnelling-induced ground movements.

4. The numbers in square brackets are the maximum/minimum acceptable values as appropriate.

5. The radii of curvature presented in this table take the beneficial effects of skew into account.

For the moderately conservative input parameters, the results of the assessment indicated non-compliance with the assessment criteria in relation to longitudinal deformation (i.e. radius of curvature) and structurally through the Pressure Confinement Ratio. It should be noted that the criteria for the Pressure Confinement Ratio under the surge internal pressure condition is not satisfied in the existing...
condition. The corresponding Pressure Confinement Ratios post-Thames Tunnel construction are less than that required in both operating and surge pressure conditions (at 1.26 and 0.8 respectively). The results for the Pressure Confinement Ratio suggest that further detailed assessment is unlikely to demonstrate an acceptable situation and therefore mitigation measures are likely to be needed.

Potential mitigation measure options include:

1. The installation of an internal secondary lining to the tunnel. This internal lining could be a cast in situ/precast concrete lining or perhaps a GRP lining. Whilst the latter lining type is attractive in terms of impact on tunnel hydraulics/flow capacity the structural feasibility of such a lining type would have to be investigated further. The impact of the former option on tunnel hydraulics/flow capacity would also have to be investigated.

2. The adoption of an observational approach. The section of the TWUL Cross Thames Link Tunnel affected would be taken out of service over the period the Thames Tunnel is to be constructed. Firstly, the pre-construction condition survey would be carried out and tunnel-specific instrumentation would be installed, with background monitoring undertaken. The Thames Tunnel would then be constructed beneath the TWUL Cross Thames Link Tunnel; monitoring of the Cross Thames Link Tunnel would continue throughout. Once construction is complete the post-construction condition survey would be carried out. If this survey revealed the need for remedial measures to the TWUL Cross Thames Link Tunnel these would be carried out before the tunnel is put back in service. It is likely that in-tunnel monitoring would cease once the existing asset is put back in service.

The selection of the appropriate mitigation measures will be dependent upon more than just ground movement effects; there are likely to be logistical/operating issues as well as environmental matters to be considered.

Given the above, suitable construction control limits shall be developed once the mitigation measures have been confirmed as will the instrumentation and monitoring requirements at this interface.

The assessment is based on the information currently available and the construction methods and techniques likely to be adopted. It is understood that it is not possible to carry out an Inspection for Assessment of this tunnel asset at present. Furthermore, there are no known historic inspections of the Cross Thames Link Tunnel and the currently available ‘as-built’ record drawings appear inconsistent when compared with the tunnel lining details provided by TWUL. The definition of the tunnel lining used in this tunnel assessment has been based on the information provided by TWUL. It has been assumed that the Cross Thames Link Tunnel has an expanded unbolted wedge block-type segmental external lining; there is no internal secondary tunnel lining.

Notwithstanding the above it is recommended that an Inspection for Assessment of the Cross Thames Link Tunnel should be carried out prior to the construction of the Thames Tunnel and this assessment subsequently reviewed and revised as necessary.

It is recommended that pre- and post-construction condition surveys of the section of the TWUL Cross Thames Link Tunnel are carried out as part of the asset protection process.
2 Introduction

The London Tideway Tunnels Project, which is being promoted by TWUL, comprises the construction of two major tunnels – the Lee and Thames tunnels – and associated, shafts/connecting tunnels that will help make the River Thames cleaner and healthier. These tunnels will substantially reduce the amount of untreated sewage being discharged into the River Thames. The proposed Thames Tunnel comprises an approximately 23 kilometre long tunnel beneath the River Thames; it will intercept the flows from the 34 most polluting CSOs before it enters the river. The tunnel is to start in the west of London and end at the Abbey Mills Treatment Works in the East of London and be located at depths of up to 75m below the existing ground surface. The internal diameter of the tunnel varies, being 7.2m at its eastern end and 6.5m at its western end. Construction is due to commence in 2014 and is expected to take approximately six years to complete.

At Battersea in Central London, the proposed Thames Tunnel is to pass beneath the TWUL Cross Thames Link Tunnel with an invert-crown clearance of approximately 14.3m. (See Figure 2.1a for the relative skew of the proposed Thames Tunnel in relation to the existing TWUL Cross Thames Link Tunnel and Figure 2.1b for the levels of the two tunnels and the in-situ geology). This report documents the assessment of the impact of the ground movements associated with the excavation of the Thames Tunnel on the TWUL Cross Thames Link Tunnel at this location. The assessment is based on the information currently available and the construction methods and techniques likely to be adopted.
Figure 2.1a: Plan of interface between TU038 TWUL Cross Thames Link Tunnel at Battersea and Proposed Thames Tunnel.
Figure 2.1b: Section along TU038 TWUL Cross Thames Link Tunnel at Battersea.
3 Geology

At the interface between the TWUL Cross Thames Link Tunnel and the Thames Tunnel at Battersea the existing river bed level is at approximately 96 mTD. Based on the information provided in Figure 2.1 the anticipated geological profile at this location comprises approximately one metre of Superficial Deposits overlying the London Clay Formation and, at depth, the Lambeth Group, Thanet Sand and Chalk.
4 Asset Descriptions

4.1 The TWUL Cross Thames Link Tunnel

The length of the TWUL Cross Thames Link Tunnel under consideration in this assessment is understood to have been constructed in the early 1990s. The specific section of interest is located at Battersea in Central London. At this location, the axis level of the Cross Thames Link Tunnel is approximately 14.2m below riverbed level and the tunnel is on a generally straight alignment in plan (See Drawing titled ‘Western PS to Heathwall PS, Cross Thames Link’, in Appendix A).

Based on the details provided by TWUL (email Greenwood/Milner of 19 October 2011 refers), it has been assumed that the Cross Thames Link Tunnel has, at this location, an expanded unbolted wedge block-type segmental lining. However, it should be noted that this is not consistent with the information shown on the currently available ‘as-built’ record drawing (the drawing titled ‘Western PS to Heathwall PS, Cross Thames Link’ in Appendix A refers), which suggests a 2.54m Internal Diameter Bolted Smoothbore lining in the area of interest. TWUL have also indicated that there is not an internal secondary tunnel lining at this location email Greenwood/Milner of 11 October 2011 refers).

The assessment presented herein has been based on an Internal Diameter of 2.54m as indicated on the aforementioned ‘as-built’ record drawing.

4.2 The Proposed Thames Tunnel

The proposed Thames Tunnel will have an internal diameter of 7.2m; the primary lining will comprise a reinforced concrete tapered segmental lining ring approximately 350mm thick with 7 segments plus key with an outer diameter of 8.5m to allow for an internal secondary lining. For ground movement prediction, an excavated tunnel diameter of 8.8m has been assumed to allow for overcut of the TBM.

In Alignment Revision AJ the Thames Tunnel is to pass below the TWUL Cross Thames Link Tunnel, at an angle of approximately 46 degrees (see Figure 2.1).

It is understood that the TWUL Cross Thames Link Tunnel was constructed wholly within the London Clay, in the bottom half of the stratum, employing conventional open-face tunnelling techniques. The Thames Tunnel is to be constructed at the base of the London Clay at the interface between the London Clay and the Lambeth Group. It is currently envisaged that the tunnel will be excavated employing an Earth Pressure Balance Tunnel Boring Machine.
5 Assessment Criteria

The criteria employed in the assessment of the impact on this tunnel asset of the anticipated tunnelling-induced ground movements due to the construction of the Thames Tunnel were in relation to the transverse distortion, longitudinal deformation and structural capacity of the tunnel, and are summarised below. The criteria were established following discussions with TWUL.

Table 5.1 Tunnel Assessment Criteria

<table>
<thead>
<tr>
<th>Input Parameters</th>
<th>Assessment Criteria</th>
<th>Comments</th>
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</thead>
<tbody>
<tr>
<td>Moderately Conservative Volume Loss (%)</td>
<td>Tunnel Distortion</td>
<td>Lining Load</td>
</tr>
<tr>
<td>Transverse Change in Tunnel Diameter (mm)</td>
<td>Longitudinal Radius of Curvature (km)</td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td>0.5</td>
<td>4.2 (0.15% O.D.)</td>
</tr>
</tbody>
</table>

For the purposes of this assessment the moderately conservative volume loss is defined as a volume loss that is considered to be readily achievable by standard, good construction practice in uniform ground conditions.

5.1.1 Radius of Curvature

The value selected for the radius of curvature was based on experience from the Channel Tunnel Rail Link Project, where the running tunnels of the Channel Tunnel Rail Link passed beneath the tunnels of London Underground’s Central Line between Stratford and Leyton (Moss & Bowers, 2005); a radius of curvature for assessment of 15km was specified at this interface.

5.1.2 Ovalisation

In the absence of geometrical information concerning the pre-existing deformed state of TWUL’s Cross Thames Link Tunnel at Battersea an onerous criterion based on Mott MacDonald’s experience in tunnel assessment was adopted in the initial evaluation of the impact of the anticipated transverse distortions resulting from the construction of the Thames Tunnel (i.e. the transverse distortion on any diameter of the tunnel is not to exceed 0.15% of the outside diameter of the tunnel).

5.1.3 Structural Capacity in Bending/Tension

The concrete tunnel lining was assessed using Limit State principles. The material characteristic strengths of concrete and the partial factors on material strength for assessment are given in Table 5.2. The structural capacity of the lining using the strength parameters presented in Table 5.2 should be reviewed to account for deterioration or defects in accordance with Section 7.5 of LU G-055 following the Inspection for Assessment.
5 Assessment Criteria

Table 5.2: Concrete: Characteristic Material Strength and Partial Factors (LU Standard 1-055)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
</tr>
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<tbody>
<tr>
<td>Characteristic compressive strength (N/mm$^2$)</td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
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<td>cylinder</td>
<td>20</td>
<td>30</td>
<td>40</td>
<td>50</td>
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<tr>
<td>Characteristic compressive strength (N/mm$^2$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>cube</td>
<td>25</td>
<td>37</td>
<td>50</td>
<td>60</td>
<td>72</td>
</tr>
<tr>
<td>Young’s Modulus (N/mm$^2$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Short term/long term</td>
<td>24000/12000</td>
<td>26000/13000</td>
<td>28000/14000</td>
<td>30000/15000</td>
<td>32000/16000</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
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Material Partial Factors

<table>
<thead>
<tr>
<th>Source: Tables 10 and 13 of London Underground Standard 1-055</th>
</tr>
</thead>
<tbody>
<tr>
<td>ULS</td>
</tr>
<tr>
<td>SLS</td>
</tr>
</tbody>
</table>

The overriding criterion was for a positive hoop load to be maintained in the tunnel lining following the excavation of the Thames Tunnel.

The ULS partial factors on loads adopted in the assessment were based on those given in Table 7 of London Underground Standard 1-055:

(i) Super-imposed Dead Load (i.e. the soil) $\gamma_{fl} = 1.2$;
(ii) Live Load $\gamma_{fl} = 1.4$.

In the case of the internal water pressure a value of 1.1 was used for $\gamma_{fl}$ in the case of a surge condition reflecting the transient nature of the load in such a situation. For the operating internal water pressure a vale for $\gamma_{fl}$ of 1.4 was assumed.

5.1.4 Pressure Confinement Ratio

The Cross Thames Link Tunnel is a pressurised water tunnel. In the first instance a simplified check was undertaken to assess compliance through consideration of the ratio of the vertical confining pressure to the internal water pressure, referred to as the Pressure Confinement Ratio. Two cases were considered: the operating and surge pressure conditions. The acceptable Pressure Confinement Ratios (PCR) specified by TWUL for these cases are as follows:

- At Normal Operating Pressure within the Cross Thames Link Tunnel:
  $\text{PCR} = 1.5$ or more;
- When the Cross Thames Link Tunnel is subject to a Surge Pressure:
  $\text{PCR} = 1.33$ or more.

Low water level was assumed for the river level and was obtained from the Port of London Authority Tide Tables for 2011.
6 Assessment Methodology

6.1 Ground Movement Prediction

Empirical sub-surface greenfield ground movement predictions were made employing the ribbon sink approach of New & Bowers (1994). The settlement trough perpendicular to the new tunnel was estimated using an inverted normal probability curve; the corresponding forward trough was estimated using a cumulative probability curve. The greenfield settlement trough predictions were determined using the empirically-based in-house MM software, GRP (Version 5.05) – the Ground Response Program.

In the assessment the existing structure was assumed to move with the ground and assumed not to modify this movement.

6.2 Assessment of Impact on Tunnel Lining

The effect of the proposed Thames Tunnel works on the existing tunnel lining was assessed in both transverse and longitudinal planes.

6.2.1 Transverse Distortion

The greenfield ground movement predictions at crown, invert and axis level were used to determine the transverse distortion (ovalisation) of the tunnel section due to the excavation of the Thames Tunnel below. The transverse settlement trough was used to calculate the differential vertical movement at the crown and invert of the tunnel while the forward settlement trough was used to calculate the differential horizontal movement at diametrically opposite points on the tunnel axis. The greater of these values was assumed in order to determine the maximum differential distortion. This approach assumes that the maximum vertical distortion does not occur at the same location as the maximum horizontal distortion.

6.2.2 Longitudinal Deformation

In the first instance deformation was assessed in the longitudinal direction through the radius of curvature imposed on the tunnel by the ground movement induced by construction of the Thames Tunnel. The radius of curvature was calculated for both hogging and sagging zones on the transverse settlement trough. The deformation is critical where the tunnel deforms (bends) within the hogging zone as this causes the crown of the tunnel lining to experience tensile strains. This can lead to overstressing of the lining. Where the tunnel deforms within a sagging zone the zone of tension is at the invert of the tunnel and the tunnel is generally in a zone of longitudinal compression therefore overstressing of the lining does not present such a safety critical case. Stresses in the linings are checked within both the hogging and sagging zones. Only the hogging zone checks are used to identify a safety critical case. Shear deformation of the tunnel was conservatively ignored for the initial assessment; shear deformation will reduce the extreme fibre stresses thus increasing the radius of curvature.

6.2.3 Structural

In the structural assessment of the tunnel lining it was assumed that the external primary tunnel lining is designed to withstand the ground and external water pressures imposed. The ability to withstand the internal water pressure was
assessed through the use of the Pressure Confinement Ratio. In the absence of a value for the operating internal water pressure, a pressure that would result in a PCR of 1.5 has been initially determined and defined as the allowable operating internal water pressure.

The tunnel lining was assessed using permissible stress methods, taking into account as far as possible any damage to the linings during original construction or operation (including distortion, cracking, loss of section, modifications and other works), by applying a condition factor based on the guidance given in Section 7.5 of the LU Engineering Manual of Good Practice G-055. The effect of the proposed Thames Tunnel works on the existing tunnel lining was assessed in both transverse and longitudinal planes.

A three-stage process was adopted when assessing the acceptability of the change in lining stresses due to the excavation of the Thames Tunnel:

1. The permissible lining capacity of the asset was determined;
2. The existing stresses within the tunnel lining were estimated; and
3. The change in stress within the tunnel lining as a result of the transverse distortion induced by the Thames Tunnel works was assessed.

The existing stresses within the tunnel lining, and the minimum and maximum hoop stress, were calculated adopting an elastic continuum method after Duddeck and Erdmann (1985); the bending moment was calculated using Morgan’s equation (1961). The initial set of parameters given in Section 3.4 of London Underground Engineering Standard 1-055 (see Table 6.1) were used in these calculations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Initial Value</th>
<th>Reference</th>
</tr>
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<tbody>
<tr>
<td>Earth Pressure Coefficient, K</td>
<td>0.7</td>
<td>Clause 3.4.12 of LU 1-055</td>
</tr>
<tr>
<td>Percentage of Overburden</td>
<td>100%</td>
<td>Clause 3.1.11.4 of LU 1-055</td>
</tr>
<tr>
<td>Surface Surcharge</td>
<td>75kPa</td>
<td>Clause 3.4.7.3 of LU 1-055</td>
</tr>
<tr>
<td>Existing Ovalisation</td>
<td>1.0% for segmental concrete lining</td>
<td>Clause 3.4.7.3 of LU 1-055</td>
</tr>
<tr>
<td>Lining Stiffness for bending moment calculation</td>
<td>$I_r = l(4/n)^2$</td>
<td>Clause 3.4.7 of LU 1-055</td>
</tr>
</tbody>
</table>

For the assessment of the transverse distortions resulting from the tunnelling-induced ground movements, it has been assumed that the additional ovalisation results in an increase in the bending moment in the lining. The existing lining stress and the predicted lining stress following construction of the Thames Tunnel have been compared with the permissible lining capacity envelope and the results presented using a moment/thrust interaction chart. Any points falling outside the resistance envelope have been deemed to have a lower factor of safety than is generally acceptable and to have failed the assessment.

The capacity of the tunnel lining(s) to accommodate the anticipated surge and operating pressures was assessed through Limit State principles.
7 Tunnel Inspection for Assessment

There are no known historic inspections of this tunnel asset. Moreover, it is understood that there is a substantial amount of silt in the bottom of Manhole 1 that restricts any tunnel inspection; removal of the silt will be a significant undertaking. In addition, there are other issues such as the distance between exits and the extra equipment that would have to be hired to facilitate the inspection. There may also be a problem with penstocks A and B at the Western Pumping Station. As a result the assumption being made is that it is not currently feasible to carry out an Inspection for Assessment for this asset.

Notwithstanding the above it is recommended that an Inspection for Assessment of the Cross Thames Link Tunnel is carried out prior to the construction of the Thames Tunnel and this tunnel impact assessment subsequently reviewed and revised as necessary.
8 Tunnel Impact Assessment

The results of the tunnel impact assessment are presented in the following sub-sections. Details of the greenfield ground movements and distortions, including supporting calculations, are presented in Appendix B; the corresponding details for the tunnel lining are presented in Appendix C.

8.1 Greenfield Ground Movement Predictions

The anticipated tunnelling-induced greenfield ground movements due to the construction of the Thames Tunnel for the moderately conservative assessment case (i.e. 1% volume loss) are presented in Figures B1 and B2 in Appendix B; a maximum ground movement of approximately 21mm is expected at tunnel invert level.

8.2 Impact Assessment on Tunnel Lining

The results of the tunnel lining impact assessment for the anticipated excavation-induced ground movements are summarised in the following sub-sections.

8.2.1 Transverse Deformation

In the transverse direction the horizontal and vertical tunnel distortions resulting from the tunnelling-induced ground movements were calculated in accordance with Section 6.1; the greater of these values, the maximum differential distortion, is presented in Table 8.1. This value is less than the allowable value of 4.2mm for a tunnel of 2820mm external diameter. The variation in vertical distortion along the length of the existing tunnel is presented in Figure B3 whilst the variation in horizontal distortion is presented in Figure B6.

8.2.2 Longitudinal Deformation

In the longitudinal direction the tunnel distortion resulting from the tunnelling-induced ground movements was assessed in terms of radius of curvature. As shown in Table 8.1 and Figure B4 the anticipated radius of curvature within the sagging zone for the moderately conservative volume loss is less than the minimum acceptable radius of curvature specified by TWUL for this asset of 15km.

8.2.3 Structural

The change in the bending moment of the external tunnel lining due to the distortion of the tunnel ring caused by the anticipated excavation-induced ground movement is presented in Table 8.1 together with the pre-existing hoop load and bending moment; the loading due to as-built imperfections was included in this assessment. The hoop load and bending moment are within the capacity envelope of the tunnel lining (Figure 8.1).

The loading due to the internal water pressure was assessed through the Pressure Confinement Ratio. As shown in Appendix C.1.2 the Pressure Confinement Ratio was less than that required under the surge pressure condition in both the current and proposed (i.e. post Thames Tunnel construction) scenarios. In the absence of a value for the operating pressure a back analysis to determine the internal water pressure that would result in a Pressure Confinement Ratio of 1.5 was undertaken; this indicated an operating pressure of about 2.1Bar.

Full details of the calculations undertaken in the assessment are detailed in Appendix C.
### Table 8.1 Results of Tunnel Impact Assessment – External Lining

<table>
<thead>
<tr>
<th>Input Parameters</th>
<th>Results of Assessment</th>
</tr>
</thead>
<tbody>
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<td>Tunnel Distortion</td>
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<tr>
<td></td>
<td>Transverse&lt;sup&gt;1&lt;/sup&gt;</td>
</tr>
<tr>
<td>VL (%) K</td>
<td>Distortion (mm)&lt;sup&gt;4&lt;/sup&gt;</td>
</tr>
<tr>
<td>1.0 0.5</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
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</tr>
</tbody>
</table>

**Notes**

1. The ground movement predictions at crown, invert and axis level determined in the empirical analysis have been used to determine the transverse distortion of the Cross Thames Link Tunnel.

2. Deformation has been assessed in the longitudinal direction through the radius of curvature imposed on the Cross Thames Link Tunnel; curvature has been determined in both hogging and sagging zones of the settlement trough.

3. The loads on the tunnel lining are defined as follows: N is the hoop load per m run of tunnel; M the bending moment per m run of tunnel; ∆M is the change in bending moment per m run of tunnel due to the tunnelling-induced ground movements.

4. The numbers in square brackets are the maximum/minimum acceptable values as appropriate.

5. The radii of curvature presented in this table take the beneficial effects of skew into account.

### 8.3 Summary

The tunnel impact assessment indicates that the anticipated transverse distortions are within the acceptable limit as are the loads on the tunnel lining. However, the longitudinal deformation expressed through the tunnel curvature exceeds that initially recommended by TWUL for the Cross Thames Link Tunnel in the sagging zone of the transverse settlement trough for the moderately conservative input parameters. The loading due to the internal water pressure was assessed through the Pressure Confinement Ratio in the impact assessment. The PCR is less than that required under surge pressure conditions in both the pre-existing and proposed scenarios; the PCR is also less than that required in the operating condition post-Thames Tunnel construction.

Full details of the calculations undertaken in this impact assessment are presented in Appendices B and C.

Correspondence with the existing asset owner is included in Appendix D for information.
Figure 8.1: N:M Interaction Plot – External Primary Tunnel Lining – Impact Assessment

<table>
<thead>
<tr>
<th>LOADCASES</th>
<th>CASE</th>
<th>$N_{ca}$</th>
<th>$M_{ca}$</th>
<th>CASE</th>
<th>$N_{ca}$</th>
<th>$M_{ca}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(ULS)</td>
<td>Existing</td>
<td>534</td>
<td>7.2</td>
<td>Existing</td>
<td>379</td>
<td>7.2</td>
</tr>
<tr>
<td></td>
<td>After TT</td>
<td>534</td>
<td>9.9</td>
<td>After TT</td>
<td>379</td>
<td>9.9</td>
</tr>
</tbody>
</table>
9 Construction Control Limits

The results of the impact assessment indicate the need for mitigation at this interface given the magnitude of the anticipated tunnelling-induced movements/distortions when the moderately conservative input parameters are assumed. Construction control limits are to be developed once these mitigation measures have been confirmed.
10 Instrumentation and Monitoring

The instrumentation and monitoring requirements at this interface are to be developed once the mitigation measures have been confirmed.
11 Conclusions and Recommendations

For the moderately conservative input parameters, the results of the assessment indicate non-compliance with the assessment criteria in relation to longitudinal deformation (i.e. radius of curvature) and structurally through the Pressure Confinement Ratio. It should be noted that the criteria for the Pressure Confinement Ratio under the surge internal pressure condition is not satisfied in the existing condition. The corresponding Pressure Confinement Ratios post-Thames Tunnel construction are less than that required in both operating and surge pressure conditions (at 1.26 and 0.8 respectively). The results for the Pressure Confinement Ratio suggest that further detailed assessment is unlikely to demonstrate an acceptable situation and therefore mitigation measures are likely to be needed.

Potential mitigation measure options include:

1. The installation of an internal secondary lining to the tunnel. This internal lining could be a cast in situ/precast concrete lining or perhaps a GRP lining. Whilst the latter lining type is attractive in terms of impact on tunnel hydraulics/flow capacity the structural feasibility of such a lining type would have to be investigated further. The impact of the former option on tunnel hydraulics/flow capacity would also have to be investigated.

2. The adoption of an observational approach. The section of the TWUL Cross Thames Link Tunnel affected would be taken out of service over the period the Thames Tunnel is to be constructed. Firstly, the pre-construction condition survey would be carried out and tunnel-specific instrumentation would be installed, with background monitoring undertaken. The Thames Tunnel would then be constructed beneath the TWUL Cross Thames Link Tunnel; monitoring of the Cross Thames Link Tunnel would continue throughout. Once construction is complete the post-construction condition survey would be carried out. If this survey revealed the need for remedial measures to the TWUL Cross Thames Link Tunnel these would be carried out before the tunnel is put back in service. It is likely that in-tunnel monitoring would cease once the existing asset is put back in service.

The selection of the appropriate mitigation measures will be dependent upon more than just ground movement effects; there are likely to be logistical/operating issues as well as environmental matters to be considered.

Given the above suitable construction control limits shall be developed once the mitigation measures have been confirmed. Similarly, the instrumentation and monitoring requirements at this interface shall be developed once the mitigation measures have been confirmed.

The assessment is based on the information currently available and the construction methods and techniques likely to be adopted. It is understood that it is not possible to carry out an Inspection for Assessment of this tunnel asset at present. Furthermore, there are no known historic inspections of the Cross Thames Link Tunnel and the currently available ‘as-built’ record drawings appear inconsistent when compared with the tunnel lining details provided by TWUL. The definition of the tunnel lining used in this tunnel assessment has based on the information provided by TWUL. It has been assumed that the TWUL Cross Thames Link Tunnel has an expanded unbolted wedge block-type segmental lining; there is no internal secondary tunnel lining.
Notwithstanding the above it is recommended that an Inspection for Assessment of the Cross Thames Link Tunnel should be carried out prior to the construction of the Thames Tunnel and this assessment subsequently reviewed and revised as necessary.

It is recommended that pre- and post-construction condition surveys of the section of the TWUL Cross Thames Link Tunnel affected are carried out as part of the asset protection process.
References


5. Port of London Authority Tide Tables for 2011.

**London Underground Standard:**

1-055 – Civil Engineering – Deep Tube Tunnels and Shafts, Version A1, October 2007

**London Underground Manual of Good Practice:**

Appendices

Appendix A – Existing Asset Drawings
Appendix B – Greenfield Settlements/Distortions
Appendix C – Tunnel Lining Assessment
Appendix D – Correspondence with Asset Owner
Appendix B - Greenfield Settlement/Distortions
B.1 Watertightness
Calculation of TU038 Cross Thames Link Tunnel Watertightness

In determining the allowable crack width for assessment purposes some basic calculations were undertaken to determine the quantity of water that will enter/leave the tunnel. In these calculations the worst case scenario of an infinitely long, unlined tunnel in a homogeneous, isotropic porous medium was modelled. The pressure head on the tunnel walls was assumed to be atmospheric and the water table maintained at a constant elevation, i.e. riverbed level. The corresponding steady-state flow net is as shown below.

Tunnel as Steady State Drain (after Freeze & Cherry, 1979)

For the TU038 at Battersea:

$H_0 := 15.668 \text{ m}$

$r := 1.4 \text{ m}$ \quad outer radius of tunnel

$k_v = 10^{-9} \frac{\text{m}}{\text{s}}$ \quad for London Clay

For the case of a tunnel of radius $r$ acting as a steady state drain in a homogeneous isotropic media of hydrostatic conductivity $K$, the ratio of ground water inflow $Q_0$ per unit length of tunnel is given:

$$Q_0 = \frac{2 \cdot \pi \cdot K \cdot H_0}{2.3 - \log\left(\frac{2r}{H_0}\right)}$$

$$Q_0 = 3.178 \times 10^7 \frac{\text{m}^3}{\text{s}}$$

Daily inflow for 100m length of tunnel

Length := 100m

Day := 60:60:245 = 8.64 \times 10^6 \text{s}

Vol100m\_daily := Q_0 \times 100 \text{m Day} = 274.58 \text{L}

Allowable daily water leakage in L/m2 for reference lengths of 100m from STUVA (Studiengesellschaft für Unterrirdische Verkehrsanlagen e.V.)

Allowable\_daily\_leakage := 0.5 \frac{\text{L}}{\text{m}^2}\text{m}^2

Vol100m\_daily\_allowable := Length \cdot \pi(2r) \cdot \text{Allowable\_daily\_leakage} = 442.965 \frac{\text{L}}{\text{m}}
B.2 Figures

Figure B1: TU038 Cross Thames Link Tunnel - Greenfield Displacements at Tunnel Invert Level

Figure B2: TU038 Cross Thames Link Tunnel - Greenfield Settlement at Tunnel Crown and Invert Level

Figure B3: TU038 Cross Thames Link Tunnel – Vertical Tunnel Distortion

Figure B4: TU038 Cross Thames Link Tunnel – Longitudinal Radius of Curvature

Figure B5: TU038 Cross Thames Link Tunnel - Greenfield Displacements at Tunnel Axis Level for Forward Trough

Figure B6: TU038 Cross Thames Link Tunnel - Greenfield Distortion at Tunnel Axis Level for Forward Trough
Figure B1: TU038 Cross Thames Link Tunnel - Greenfield Displacements at Tunnel Invert Level

Figure B2: TU038 Cross Thames Link Tunnel - Greenfield Settlement at Tunnel Crown and Invert Level
Appendices

Figure B3: TU038 Cross Thames Link Tunnel – Vertical Tunnel Distortion

Figure B4: TU038 Cross Thames Link Tunnel – Longitudinal Radius of Curvature
Figure B5: TU038 Cross Thames Link Tunnel - Greenfield Displacements at Tunnel Axis Level for Forward Trough

Figure B6: TU038 Cross Thames Link Tunnel - Greenfield Distortion at Tunnel Axis Level for Forward Trough
Appendix C – Tunnel Lining Assessment
Appendices

C.1 Ground and Groundwater Loads on Primary Lining Tunnel
Detailed Assessment Calculations for TU038 Cross Thames Link Tunnel

A: Wedgeblock finished OD
B: Wedgeblock finished ID
C: Bolted smoothbore segment OD
D: Bolted smoothbore finished ID (primary only)
E: Bolted smoothbore finished ID (secondary lining)

T1: Wedgeblock segment thickness
T2: Smoothbore segment thickness
T3: Secondary in situ lining thickness
T4: Grout space (tailskin + brushes)

<table>
<thead>
<tr>
<th></th>
<th>Small system</th>
<th>Large system</th>
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<tbody>
<tr>
<td>A</td>
<td>2950</td>
<td>3310</td>
</tr>
<tr>
<td>B</td>
<td>2590</td>
<td>2910</td>
</tr>
<tr>
<td>C</td>
<td>2820</td>
<td>3180</td>
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<tr>
<td>D</td>
<td>2460*</td>
<td>2780*</td>
</tr>
<tr>
<td>E</td>
<td>2240</td>
<td>2520</td>
</tr>
<tr>
<td>T1</td>
<td>180</td>
<td>200</td>
</tr>
<tr>
<td>T2</td>
<td>180</td>
<td>200</td>
</tr>
<tr>
<td>T3</td>
<td>110</td>
<td>110</td>
</tr>
<tr>
<td>T4</td>
<td>60</td>
<td>60</td>
</tr>
</tbody>
</table>

* Critical dimension for passage of trains/equipment

Phase 2 tunnels (a) TWRM (wedgeblock system-seven segments + key and bolted wedgeblock); (b) 1991 tunnelling system (smooth-bore/bolted system - seven segments + key); from Farrow, J.P. and Claye, P.M. (1994). Civil engineering and tunnel design. Proceedings of the Institution of Civil Engineers Thames Water Ring Main Supplement to Civil Engineering Volume 102, Special Issue 2, 1994, pp 30,
1. Assessment Inputs

1.1 Tunnel Properties and Geometry

- OD := 2.82 m
- t := 140 mm
- n := 7
- $E_{\text{long}} := 10 \text{ GPa}$
- $E_{\text{short}} := 32 \text{ GPa}$
- $v_1 := 0.2$

Tunnel external diameter
Lining thickness
Number of segments
Long Term Elastic Modulus of Lining (Grade 60 concrete)
Short Term Elastic Modulus of Lining (Grade 60 concrete)
Poisson’s Ratio of Lining

1.2 Soil Properties and Geometry

- GL := 95.943 m
- AL := 80.275 m
- Z := GL - AL = 15.668 m
- LTL := 98.643 m
- $E_c := 50 \text{ MPa}$
- $K_0 := 0.7$
- $\gamma_g := 20 \text{ kN/m}^3$
- $\gamma_w := 9.81 \text{ kN/m}^3$
- $S := (\text{LTL} - \text{GL}) \cdot \gamma_w = 26.487 \cdot \text{kPa}$
- $v_g := 0.1$

Ground Level (Riverbed level)
Cross Thames Link Tunnel axis level
Depth to Cross Thames Link Tunnel axis level
Low tide level
Elastic Modulus of Ground
Earth Pressure Coefficient
Bulk Unit Weight of Ground
( Hydrostatic groundwater table assumed)
Bulk Unit Weight of Water
Surcharge due to river at low tide
Poisson’s ratio of ground
1.3 Partial Factors
Partial factors are taken from Table 7 of London Underground Standard 1-055

\[ \gamma_{\text{soil}} := 1.2 \]  
Partial factor on super-imposed dead load (soil)

\[ \gamma_{\text{live}} := 1.4 \]  
Partial factor on live load

\[ \gamma_{\text{transient}} := 1.1 \]  
Partial factor on transient load

2. Lining Geometry Calculations
2.1 Calculated Parameters

\[ I := \frac{1 \cdot m \cdot t^3}{12} \]  
Moment of Inertia of Tunnel Lining Segment

\[ I = 2.287 \times 10^{-4} \, m^4 \]

\[ I_r := \frac{4}{n^2} \left( \frac{4}{n} \right)^2 \]  
Reduced Moment of Inertia of Tunnel Lining Segment (after Muir Wood, 1975)

\[ I_r = 7.467 \times 10^{-5} \, m^4 \]

\[ I_{nx} := \frac{I_r}{1 \cdot m} \]  
Reduced Moment of Inertia per metre run

\[ I_{nx} = 7.467 \times 10^{-5} \, m^4/m \]

\[ \sigma_{V, \text{unfactored}} := \gamma_g Z + S = 339.847 \, kPa \]

\[ \sigma_{V, \text{factored}} := \gamma_g Z \cdot \gamma_{\text{soil}} \cdot \gamma_{\text{live}} = 413.114 \, kPa \]

\[ A := 1 \cdot m \cdot t = 0.14 \, m^2 \]

\[ R := \frac{(OD - t)}{2} = 1.34 \, m \]  
Mean Radius

\[ R_{\text{internal}} := \frac{(OD - 2t)}{2} = 1.27 \, m \]  
Radius

\[ A_{nx} := \frac{A}{1 \cdot m} = 0.14 \, m^2/m \]

\[ E := \frac{E_{I, \text{long}}}{1 - \nu_l^2} = 16.667 \, GPa \]  
Modified Young’s Modulus for lining after Muir Wood (1975)
## 3 Assessment of Ground Loads on Primary Lining

### 3.1 Existing Bending Moment and Hoop Forces due to Ground Load

The hoop load and bending moment within the tunnel lining are assessed employing an elastic continuum analysis after Duddeck & Erdmann (1985), conservatively assuming full bond between the lining and the ground.

\[
M_{\text{factored}} := \sigma_v \cdot (1 - K_0) \cdot R \cdot \frac{1}{4 + \frac{3 - 2 \cdot \nu_g}{3 \cdot (1 + \nu_g) \cdot (3 - 4 \cdot \nu_g)}} \cdot \frac{E_c \cdot R^3}{E_I_{\text{rx}}}
\]

\[
M_{\text{factored}} = 6.26 \text{ kNm/m}
\]

\[
N_{1 \text{- factored}} := \sigma_v \cdot (1 + K_0) \cdot R \cdot \frac{1}{2 + \frac{2}{1 + \nu_g} \cdot \frac{E_c \cdot R}{E_{I_{\text{long}} \cdot A_{\text{rx}}}}}
\]

\[
N_{1 \text{- factored}} = 458.08 \text{ kN/m}
\]

\[
N_{2 \text{- factored}} := \sigma_v \cdot (1 - K_0) \cdot R \cdot \left[ \frac{1 + \frac{12}{(1 + \nu_g) \cdot E_{I_{\text{long}} \cdot A_{\text{rx}}}}}{} \right] \cdot \frac{E_c \cdot R^3}{E_{I_{\text{long}} \cdot A_{\text{rx}}}}
\]

\[
N_{2 \text{- factored}} = 77.74 \text{ kN/m}
\]

\[
N_{\text{max \_ factored}} := N_{1 \text{- factored}} + N_{2 \text{- factored}} = 535.82 \text{ kN/m}
\]

\[
N_{\text{min \_ factored}} := N_{1 \text{- factored}} - N_{2 \text{- factored}} = 380.33 \text{ kN/m}
\]

ULS partial factors are applied to M, Nmax, and Nmin during the lining assessment in accordance with London Underground Standard 1-055.

### 3.2 Bending Moment due to As-Built Imperfections

Assumed upper bound of construction tolerance, i.e. 1% ovalisation of primary lining

\[
u_{\text{max}} = \frac{1.0}{100} \cdot \text{OD} = 28.2 \text{ mm}
\]

Radial distortion due to existing ovalisation/squat

\[
\text{Mod \_ Factor} = \frac{M_{\text{factored}}}{0.25 \cdot \sigma_v \cdot (1 - K_0) \cdot R_{\text{internal}}} = 0.125
\]
3.3 Bending Moment Induced due to Thames Tunnel Construction

The construction of the Thames Tunnel beneath the Tunnel Asset TU038 will distort the existing tunnel and induce bending

\[ \delta_d = 2.2 \text{ mm} \]

Diametrical distortion - difference between greenfield movements at crown and invert

\[ \delta_r = \frac{\delta_d}{2} = 1.1 \text{ mm} \]

Radial distortion

\[ \Delta M = \left( \frac{3E_1 r_x}{R_{\text{internal}}} \right) \frac{\Delta r}{2} f_{\text{soil}} = 3.055 \frac{\text{kN.m}}{\text{m}} \]

Bending Moment induced due to vertical distortion (after Morgan, 1961)

3.4 Outputs for ULS Assessment of Primary Lining due to Ground Loads

Assumed existing bending moment in tunnel lining prior to Thames Tunnel construction

\[ M_{\text{existing}} = M_{\text{factored}} + M_{\text{as built}} = 8.153 \frac{\text{kNm}}{\text{m}} \]

Assumed final bending moment in tunnel lining following Thames Tunnel construction

\[ M_{\text{final}} = M_{\text{factored}} + \Delta M + M_{\text{as built}} = 11.208 \frac{\text{kNm}}{\text{m}} \]

\[ N_{\text{max factored}} = 535.829 \frac{\text{kN}}{\text{m}} \]

Maximum hoop force

\[ N_{\text{min factored}} = 380.332 \frac{\text{kN}}{\text{m}} \]

Minimum hoop force
C.2 Internal Water Pressure
TU038: Pressure / Confinement Ratio

1. Existing Conditions

The Cross Thames Link Tunnel carries an internal water pressure. TWUL have advised MM that a check of the ratio of the confining vertical stress of the ground to the internal water pressure can be used as a simple check of the Cross Thames Link Tunnel’s safe capacity. A target confining vertical stress ratio of greater than 1.5 and 1.33 is required for operating and surge pressures respectively, where these values are not achieved more detailed calculation is likely to be required.

GL := 95.943 m  
CL := 81.745 m  
Z := GL - CL = 14.198 m  
LTL := 1.37 m  
LTL := 98.643 m  
\( \gamma_g := 20 \frac{kN}{m^3} \)  
\( \gamma_w := 9.81 \frac{kN}{m^3} \)  
S := (LTL - GL) \( \gamma_w = 26.487 \) kPa  
\( \sigma_V := Z \cdot \gamma_g + S = 310.447 \) kPa  

The target operating Pressure Confinement stress Ratio (PCR) is 1.5. In the absence of a value for the operating internal water pressure, a pressure that would result in a PCR of 1.5 is determined and defined as the max allowable operating pressure.

Given the calculated confining vertical stress, the maximum allowable operating pressure is:

\[ P_{operating} = \frac{\sigma_V}{1.5} = 2.07 \text{ bar} \]

Max allowable internal water pressure under operating conditions.
The internal water pressure under surge conditions is based on the top level of the Heathwall Shaft, 104.5m A.D.

\[ P_{\text{surge}} = 3.3 \text{ bar} \]

\[ \frac{\sigma_v}{P_{\text{surge}}} = 0.941 \]  

\text{Surge pressure confinement stress ratio (target >1.33) }

\text{Fail}

\textbf{Conclusion:} The confining vertical stress of the ground is insufficient to safely bear the internal water pressure under surge pressure conditions.

\textbf{2 - After Thames Tunnel Construction}

The excavation of the Thames Tunnel will result in a change in vertical stress at the level of the TWUL Cross Thames Link Tunnel. The magnitude of this change in vertical stress directly below the Thames Tunnel has been estimated using the Kirsch Equations for the stresses in the material surrounding a circular hole in a stressed elastic body.

\begin{align*}
\text{OD}_{\text{asset}} &= 2.82 \text{ m} \\
\text{OD}_{TT} &= 8.8 \text{ m} \\
\text{AL}_{TT} &= 60.208 \text{ m} \\
k &= 0.7 \\
\gamma g &= 20 \frac{\text{kN}}{\text{m}^3} \\
Z_{TT} &= \text{GL} - \text{AL}_{TT} = 35.735 \text{ m}
\end{align*}

\text{Tunnel external diameter of asset} \\
\text{Thames Tunnel Excavated diameter} \\
\text{Thames Tunnel Axis level (mATD)} \\
\text{Earth Pressure Coefficient} \\
\text{Bulk Unit Weight of Ground} \\
\text{Depth from riverbed level to Thames Tunnel Axis Level}
separation := 14.347·m  

The vertical separation between the TWUL Ring Main and the Thames Tunnel

\[ p_z := \gamma g Z_{TT} + S = 741.187 \text{ kPa} \]

Vertical stress in the "infinite plate"

**Initial Conditions**

\[ \sigma_1 := p_z = 741.187 \text{ kPa} \]

\[ \sigma_2 := p_z k = 518.831 \text{ kPa} \]

**After Thames Tunnel Excavated**

\[ a := \frac{OD_{TT}}{2} = 4.4 \text{ m} \]

Excavated radius of Thames Tunnel

Stress components at point \((r, \theta)\) below tunnel centerline

\[ \theta := \pi \quad r := \text{separation} + \frac{OD_{TT}}{2} + \frac{OD_{asset}}{2} = 20.157 \text{ m} \]

The stress components are given by the Kirsch Equations

**Radial**

\[ \sigma_r := \frac{1}{2} p_z \left[ (1 + k) \left( 1 - \frac{a^2}{r^2} \right) + (1 - k) \left( 1 - 4 \frac{a^2}{r^2} + 3 \frac{a^4}{r^4} \right) \cos(\theta) \right] = 690.735 \text{ kPa} \]

**Tangential**

\[ \sigma_\theta := \frac{1}{2} p_z \left[ (1 + k) \left( 1 + \frac{a^2}{r^2} \right) - (1 - k) \left( 1 + 3 \frac{a^4}{r^4} \right) \cos(\theta) \right] = 548.093 \text{ kPa} \]

**Shear**

\[ \tau_{r\theta} := \frac{1}{2} p_z \left[ -(1 - k) \left( 1 + 2 \frac{a^2}{r^2} - 3 \frac{a^4}{r^4} \right) \sin(\theta) \right] = 0 \text{ kPa} \]

Principal stresses in plane of paper at point \((r, \theta)\)

**maximum**

\[ \sigma_1 \text{ after} := \frac{1}{2} \left( \sigma_r + \sigma_\theta \right) + \left[ \frac{1}{4} (\sigma_r - \sigma_\theta)^2 + \tau_{r\theta}^2 \right]^{\frac{1}{2}} = 690.735 \text{ kPa} \]

**minimum**

\[ \sigma_2 \text{ after} := \frac{1}{2} \left( \sigma_r + \sigma_\theta \right) - \left[ \frac{1}{4} (\sigma_r - \sigma_\theta)^2 + \tau_{r\theta}^2 \right]^{\frac{1}{2}} = 548.093 \text{ kPa} \]
Change in stress at the ring main level due to construction of the Thames Tunnel are as follows:
\[ \Delta \sigma_1 := \sigma_{1\text{ after}} - \sigma_1 = -50.452 \text{kPa} \quad \text{Change in vertical stress} \]
\[ \Delta \sigma_2 := \sigma_{2\text{ after}} - \sigma_2 = 29.262 \text{kPa} \quad \text{Change in horizontal stress in plane of page} \]

**Pressure / Confinement Ratio - After Thames Tunnel Construction**

\[ \sigma_v := (GL - CL) \gamma_g + S + \Delta \sigma_1 = 259.995 \text{kPa} \quad \text{Confining vertical stress} \]

\[ \frac{\sigma_v}{P_{\text{operating}}} = 1.256 \quad \text{Operating pressure confinement stress ratio (target >1.5) based on an operating pressure of 2.07\text{bar}} \]

\[ \frac{\sigma_v}{P_{\text{surge}}} = 0.788 \quad \text{Surge pressure confinement stress ratio (target >1.33)} \]

**Maximum Safe Internal Water Pressures**

**Maximum safe operating pressure (FoS = 1.5)**
\[ P_{\text{safe\_operating}} := \frac{\sigma_v}{1.5} = 1.733 \text{\text{bar}} \]

**Maximum safe surge pressure (FoS = 1.33)**
\[ P_{\text{safe\_surge}} := \frac{\sigma_v}{1.33} = 1.955 \text{\text{bar}} \]
Appendix D – Correspondence with Owner
# MEETING MINUTES

**Subject:** Thames Tunnel interface with Phase B Thames Water Tunnels  
**Purpose:** Discuss Phase B interfaces and assessment process  
**Date and time:** 2nd August 2011 – 11.00am  
**Location:** The Point, Paddington  
**Attendees:** Rob Milner (RM) and Sue Hitchcock (SH) - Thames Tunnel (TT)  
Graham Taylor (GRT) – Mott MacDonald (MM)  
Jon Green (JG) and Barry New (BN) – Thames Water (TW)  
**Apologies:**  
**Minute taker:** Rob Milner  
**Doc ref:** 100-OM-TPI-TWULD-100602

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<th>By who</th>
<th>By when</th>
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<tbody>
<tr>
<td>1. Introductions</td>
<td>All members introduced themselves and their roles and responsibilities. <strong>RM</strong> is the TT TPI Tunnels Engineer, <strong>SH</strong> is the TT TPI Manager and <strong>GRT</strong> is the project manager for MM carrying out assessments for TW assets. <strong>JG</strong> is the Asset Condition Manager and <strong>BN</strong> provides technical advice for TW.</td>
<td>Note</td>
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<tr>
<td>2. Project Overview</td>
<td><strong>RM</strong> gave a brief update on the design changes following public consultation and explained the alignment now crossed the Ring Main at a slightly different location (Barnes to Ashford Common) to previously discussed (Barnes to Barrow Hill). He explained that the second phase (B) of tunnel assessments had started.</td>
<td>Note</td>
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| 3. Initial Assessments | **RM** explained that MM had been commissioned to carry out Phase B of the tunnel assessments which consisted of the following TW assets:  
- TU038 - Cross Thames Link Tunnel  
- TU052 - Thames to Lea Valley Raw Water Tunnel  
- TU384 - Ring Main (Barnes to Ashford Common)  
**GRT** presented initial Greenfield movement predictions for these assets and they were discussed in turn by the group. | Note | |
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<th>By who</th>
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<tr>
<td>3a</td>
<td>Cross Thames Link Tunnel</td>
<td></td>
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<tr>
<td></td>
<td>JG stated that Kevin Mackenzie or Mike Gunn should be contacted to obtain information and organise an inspection of this tunnel.</td>
<td>GRT</td>
<td>10/08/11</td>
</tr>
<tr>
<td></td>
<td>Pressure within the tunnel is understood to relate directly to the depth but confirmation of this should be obtained from Mike Gunn or John Greenwood. RM agreed to speak to John Greenwood and the TT survey team regarding this asset.</td>
<td>RM</td>
<td>10/08/11</td>
</tr>
<tr>
<td></td>
<td>GRT explained this tunnel is situated within the London Clay and the TT tunnel will cross beneath it with approximately a 9m clearance.</td>
<td>Note</td>
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<td></td>
<td>GRT presented Greenfield settlement drawings and initial results. These predicted a maximum settlement of 26mm and a minimum radius of curvature of 6.5km. It was agreed that MM needed to carry out more detailed assessments for this interface, using a similar method to the Battersea to Barrow Ring Main assessment.</td>
<td>GRT</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>BN explained that the main concern for this and other pressurised tunnels would be negative hoop stress within the lining. GRT stated the tunnel had been assessed for this and the internal pressure would also be included within calculations.</td>
<td>GRT</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Overburden pressure was discussed and GRT explained that MM intended to use a value of 65% in the assessment.</td>
<td>Note</td>
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<tr>
<td>3b</td>
<td>Ring Main (Barnes to Ashford Common)</td>
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<td>Pressure within the Ring Main was discussed and understood to be a maximum of 3.5bar. JG understood pressures for each section were explained in the TW Black and Veatch report provide and agreed to check and confirm these. Post Meeting Note: JG provided further clarification on Ring Main pressures and the B&amp;V report.</td>
<td>JG</td>
<td>05/08/11</td>
</tr>
<tr>
<td></td>
<td>GRT explained that the ring main was bolted expanded lining and situated within the London Clay strata. GRT presented a drawing showing that the TT will cross 3-4m above the TW tunnel.</td>
<td>Note</td>
<td></td>
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<tr>
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<td>GRT presented the initial assessment for this tunnel which predicted a maximum heave of approximately 5mm and minimum radius of curvature of 11km.</td>
<td>Note</td>
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<tr>
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<td>GRT stated the assessment had used the work of Loganathan and Poulos to predict movements. BN expressed his opinion that these predictions were likely to be conservative and this needs to be discussed in the report and justified using case study data.</td>
<td>GRT</td>
<td>-</td>
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<td></td>
<td>During the next outage for an inspection of this tunnel the group agreed that it would be prudent to also carry out a line and level survey. A cloud point survey should also be considered.</td>
<td>Note</td>
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<tr>
<td>3c</td>
<td>Thames to Lea Valley Raw Water Tunnel</td>
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<tr>
<td></td>
<td>GRT explained that the tunnel was situated within the London Clay strata and the TT tunnel will cross 3-4m above the TW tunnel.</td>
<td>Note</td>
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<td>Item:</td>
<td>Action item/Notes for the record</td>
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<tr>
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<td>GRT presented the initial assessment for this tunnel which predicted a maximum heave of approximately 3mm and minimum radius of curvature of 11km.</td>
<td>Note</td>
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<td></td>
<td>BN explained that the pressure within this tunnel is related to the ground level at Hampton and as the Barnes area is the lowest point in the tunnel the pressure will be approximately equal to the maximum in this area. The pressure is explained in an ICE paper on the tunnel. JG will check if there is a surge model for the tunnel and provide this.</td>
<td>JG</td>
<td>19/08/11</td>
</tr>
<tr>
<td>4</td>
<td>Inspections</td>
<td>JG</td>
<td>19/08/11</td>
</tr>
<tr>
<td></td>
<td>Inspections of the TW assets were discussed and it was agreed that an inspector from TW would accompany any inspections. JG said he would confirm planned inspection dates/outages for the three assets.</td>
<td>JG</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Approval Process</td>
<td>BN/JG</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Post Meeting Note: Following the meeting approvals were discussed between JG, BN, SH and RM and it was agreed that BN would provide a technical review and acceptance and notify JG so that he could provide a letter of approval / no-objection on behalf of TW.</td>
<td>BN/JG</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>AOB</td>
<td>RM</td>
<td>05/08/11</td>
</tr>
<tr>
<td></td>
<td>BN and JG expressed concern regarding the effects of heave from the TBM on TW assets and pressurised water pockets within the clay on the construction of the TT. RM agreed to discuss this with the relevant members of the TT team.</td>
<td>RM</td>
<td>05/08/11</td>
</tr>
<tr>
<td></td>
<td>Post Meeting Note: These issues are being considered as part of the TT design and construction method and appropriate assessments will be produced.</td>
<td>RM</td>
<td>05/08/11</td>
</tr>
</tbody>
</table>

**Next meeting (Date, time, location):** TBC – dependant on assessment process

**Next minute taker:** TBC
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