# Thames Tunnel

## Tunnel Asset TU025 National Grid Wimbledon to Kensal Green Cable Tunnel

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List of abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>CSO</td>
<td>Combined Sewer Overflow</td>
</tr>
<tr>
<td>TWUL</td>
<td>Thames Water Utilities Limited</td>
</tr>
<tr>
<td>MM</td>
<td>Mott MacDonald</td>
</tr>
<tr>
<td>NG</td>
<td>National Grid</td>
</tr>
<tr>
<td>GRP</td>
<td>Ground Response Program</td>
</tr>
<tr>
<td>LU</td>
<td>London Underground</td>
</tr>
<tr>
<td>TT</td>
<td>Thames Tunnel</td>
</tr>
<tr>
<td>I.D.</td>
<td>Internal Diameter</td>
</tr>
<tr>
<td>O.D.</td>
<td>Outside Diameter</td>
</tr>
<tr>
<td>LDPE</td>
<td>Low-Density Polyethylene</td>
</tr>
</tbody>
</table>
1 Executive Summary

The 7.2m Internal Diameter Thames Tunnel is to be constructed by Thames Water Utilities Limited. Construction is due to commence in 2016 and is expected to take approximately six years to complete. The Thames Tunnel is to pass underneath the National Grid (NG) Wimbledon to Kensal Green Cable Tunnel at Wandsworth. The Thames Tunnel is to be excavated through the London Clay at this location; the NG Wimbledon to Kensal Green Cable Tunnel is also to be constructed within the London Clay Formation.

This report documents the assessment of the ground movements associated with the excavation of the Thames Tunnel and their impact on the NG Wimbledon to Kensal Green Cable Tunnel for a tunnel clearance of 6m. The objective of this report is to demonstrate to the Thames Tunnel Project team and NG that the works can be carried out with an acceptable risk (As Low As Reasonably Practicable) to the existing asset.

A maximum settlement of 31mm is anticipated at invert level of the NG Wimbledon to Kensal Green Cable Tunnel for the moderately conservative volume loss of 1.0%. The key results of this assessment are summarised in Table 1.1:

### Table 1.1 Results of Tunnel Assessment

<table>
<thead>
<tr>
<th>Input Parameters</th>
<th>Results of Assessment</th>
<th>Lining loads&lt;sup&gt;3&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tunnel Distortion</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Transverse&lt;sup&gt;1&lt;/sup&gt;</td>
<td>Longitudinal&lt;sup&gt;2&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>Before TT</td>
<td>After TT</td>
</tr>
<tr>
<td>VL (%) K Surface Surcharge (kPa) Distortion (mm) [5.32mm]&lt;sup&gt;4&lt;/sup&gt;</td>
<td>Radius of Curvature (km)&lt;sup&gt;5&lt;/sup&gt; [15km in both hogging and sagging zones]&lt;sup&gt;4&lt;/sup&gt;</td>
<td>N (kN/m run) K&lt;sup&gt;6&lt;/sup&gt;</td>
</tr>
<tr>
<td>1.0 (MC) 0.5</td>
<td>0 75</td>
<td>5.4</td>
</tr>
<tr>
<td>0.85 0.5</td>
<td>0 75</td>
<td>4.6</td>
</tr>
</tbody>
</table>

Notes:

(MC) - Moderately Conservative.

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 NG Wimbledon to Kensal Green Cable Tunnel.

2. Deformation has been assessed in the longitudinal direction through the radius of curvature imposed on the NG Wimbledon to Kensal Green Cable 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.

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.

The results of the assessment indicate that without the inclusion of mitigation measures the assessment criteria are not satisfied for the moderately conservative input parameters (i.e. a Volume Loss of 1.0% and a trough width parameter of 0.5)
presented in Table 1.1 for the tunnel clearance of 6m under consideration. Mitigation measures, the inclusion of 6mm thick LDPE packers in the circle joints throughout the anticipated transverse settlement trough, a distance of approximately 60m, and the imposition of an appropriate volume loss (0.85%) as a construction control limit at this interface within the Thames Tunnel construction contract, are required to ensure that acceptable radii of curvature result.

In addition, NG have confirmed that it would be inappropriate to locate a joint bay at any point in the cable tunnel that may be subject to movement or deformation. As a result a 100m ‘exclusion zone’ spanning the interface has been included as an additional design criterion for the cable tunnel. This requirement may result in an additional joint bay per cable circuit.

Proposals for instrumentation and monitoring the response of the NG Wimbledon to Kensal Green Cable Tunnel during the construction of the Thames Tunnel have also been included. Conventional instrumentation and monitoring, for example the use of Robotic Total Stations and prisms, and basic line and level surveying methods, could be adopted to monitor tunnel movements and deformations.

The assessment is based on the information currently available and the construction methods and techniques likely to be adopted. In the absence of information concerning construction tolerance and post-construction deformations of the NG Wimbledon to Kensal Green Cable Tunnel an onerous criterion based on Mott MacDonald’s experience in tunnel assessment (i.e. the transverse distortion on any diameter of the tunnel is not to exceed 0.15% of the Outside Diameter of the tunnel) has been adopted in this assessment for evaluating the impact of the anticipated transverse distortions resulting from the construction of the Thames Tunnel. The post-construction state of the NG Wimbledon to Kensal Green Cable Tunnel will be verified prior to the construction of the Thames Tunnel and this assessment revised if necessary. In addition, it has been assumed that the NG Wimbledon to Kensal Green Cable Tunnel will have been in the ground at least 12 months prior to the passage of the Thames Tunnel below.

The effect of tunnelling-induced deformation on internal Mechanical and Electrical installations has not been considered in this work. It has been agreed with NG that such installations in the vicinity can accommodate the movements predicted in this assessment.
2 Introduction

The Thames Tunnel Project, which is being promoted by TWUL, comprises the construction of the Thames Tunnel 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 Thames Tunnel comprises an approximately 23 kilometre long, 7.2m internal diameter tunnel beneath the River Thames; it will intercept the flows from the 34 most polluting CSOs before they enter the river. The tunnel is to start in the west of London and end at the Abbey Mills Treatment Works and be located at depths of up to 75m below the existing ground surface. Construction is due to commence in 2016 and is expected to take approximately six years to complete.

The Thames Tunnel is to pass beneath the proposed NG Wimbledon to Kensal Green Cable Tunnel at Wandsworth (see Figure 2.1). This report documents the assessment of the ground movements associated with the excavation of the Thames Tunnel and their impact on the NG Wimbledon to Kensal Green Cable Tunnel at this location for a tunnel clearance of 6m.

The assessment is based on the information currently available and the construction methods and techniques likely to be adopted. In the absence of information concerning construction tolerance and post-construction deformations of the NG Wimbledon to Kensal Green Cable Tunnel an onerous criterion based on Mott MacDonald’s experience in tunnel assessment (i.e. the transverse distortion on any diameter of the tunnel is not to exceed 0.15% of the Outside Diameter of the tunnel) has been adopted in this assessment for evaluating the impact of the anticipated transverse distortions resulting from the construction of the Thames Tunnel. The post-construction state of the NG Wimbledon to Kensal Green Cable Tunnel will be verified prior to the construction of the Thames Tunnel and this assessment revised if necessary.
3 Geology

In the area under consideration the existing ground level is approximately 106 mATD. Based on the ground investigations undertaken for the Thames Tunnel and NG Wimbledon to Kensal Green Cable Tunnel projects, the anticipated geological profile comprises 4-10m of Superficial Deposits including Made Ground, Alluvium and River Terrace Deposits, overlying the London Clay Formation and, at depth, the Lambeth Group.
4 Asset Descriptions

4.1 National Grid Wimbledon to Kensal Green Cable Tunnel

National Grid (NG) are proposing to construct a 3.55m Outside Diameter (O.D.) tunnel to house high voltage electrical transmission cables between sub-stations at Wimbledon in South West London and Kensal Green in North West London (See Figure 4.1).

Within the vicinity of the Thames Tunnel crossing, the proposed works comprise:

- A 3.0 m internal diameter, TBM-driven cable tunnel;
- A 10m internal diameter, 42.2m deep shaft at Earl’s Court;
- A 15m internal diameter, 30.0m deep shaft at Wandsworth;

A construction contract for these works has been awarded; construction has commenced.

At the interface with the Thames Tunnel the invert of the TBM-driven cable tunnel is to be located approximately 27m below existing ground level entirely within the London Clay Formation of the Thames Group.

The lining of the 3.55m O.D. NG Wimbledon to Kensal Green Cable Tunnel is to be of the unbolted expanded-type with smooth bore rings, constructed employing open-face techniques; the segmental concrete lining is to be 190mm thick fibre reinforced and comprises 6 segments plus key (see Figure 4.2).

4.2 The Proposed Thames Tunnel

It is currently proposed that the 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 a secondary lining. An excavated tunnel diameter of 8.8m has been assumed in ground movement prediction to allow for overcut of the TBM.

In Alignment Revision AH the Thames Tunnel is to pass below the NG Wimbledon to Kensal Green Cable Tunnel at an oblique angle of approximately 60 degrees (see Figure 2.1).

At Wandsworth, both the Thames Tunnel and NG Wimbledon to Kensal Green Cable Tunnel are to be excavated wholly within the London Clay Formation. At its interface with the NG Wimbledon to Kensal Green Cable Tunnel the invert level of the Thames Tunnel is 63.202mTD and the corresponding vertical clearance between the tunnels is 6m.
5 Assessment Methodology

5.1 Ground Movement Prediction

Empirical sub-surface greenfield ground movement predictions have been 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 greenfield settlement trough predictions have been made employing the empirically-based in-house MM software, GRP (Version 5.05) – the Ground Response Program.

5.2 Impact on Tunnel Lining

5.2.1 Transverse Deformation

The greenfield ground movement predictions at crown, invert and axis level have been used to determine the transverse distortion of the tunnel section due to the excavation of the Thames Tunnel below. In this assessment the existing structure has been assumed to move with the ground. The greater of these values has been used to determine the maximum differential distortion. This approach assumes that the maximum differential movements between the crown and invert are equal and opposite of the differential movements at axis level.

5.2.2 Longitudinal Deformation

In the longitudinal direction, deformation has been assessed through the radius of curvature imposed on the tunnel by the ground movement induced due to the construction of the Thames Tunnel. The critical mode of longitudinal deformation is where the tunnel deforms (bends) within a hogging zone, i.e. where the crown of the tunnel lining is in tension. This can lead to overstressing of the lining in the tunnel crown potentially resulting in cracked sections falling-in. Where the tunnel deforms within a sagging zone the zone of tension is at the invert of the tunnel therefore overstressing of the lining does not present such a safety critical case. Stresses in the linings were checked within both the hogging and sagging zones. Only the hogging zone checks were used to identify a safety critical case. Shear deformation of the tunnel has been conservatively ignored for the initial assessment; shear deformation will reduce the extreme fibre stresses thus increasing the radius of curvature.

5.2.3 Structural

The concrete segmental tunnel lining has been assessed using permissible stress methods. The effect of the proposed Thames Tunnel works on the existing tunnel has been assessed in both transverse and longitudinal planes.

A three-stage process has been adopted when assessing the change in lining stresses due to the deformation of the existing tunnel asset as a result of the excavation of the Thames Tunnel:

1. The permissible lining capacity of the asset was determined;
2. The existing stresses within the tunnel lining estimated; and
3. The change in stress within the tunnel lining as a result of the transverse distortion due to the Thames Tunnel works assessed.
The existing stresses within the tunnel lining, and the minimum and maximum hoop stress, have been calculated adopting an elastic continuum method after Duddeck and Erdmann (1985); bending moment has been calculated using Morgan’s equation (1961).

The existing stresses have been calculated in accordance with the initial set of parameters given in Section 3.4 of London Underground Engineering Standard 1-055 (see Table 5.1 below).

**Table 5.1 Initial Set of Parameters for Existing Stress Determination**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Initial Value</th>
<th>Reference</th>
</tr>
</thead>
<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 expanded concrete lining</td>
<td>Clause 3.4.7 of LU 1-055</td>
</tr>
<tr>
<td>Lining Stiffness for bending moment calculation</td>
<td>$I_r = I(4/n)^2$</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 hoop stresses in the tunnel have been assumed to remain largely unchanged. For the purposes of structural assessment this additional ovalisation due to the Thames Tunnel works is considered to occur in any plane of the tunnel and is therefore applied to the lining over and above the existing ovalisation. The increase in bending moment has been calculated using Morgan’s equation (1961). 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. Any such lining will be subject to further detailed investigation as part of the assessment, e.g. review the appropriateness of adopting the default assessment values and justify the use of a modified value if appropriate.
6 Assessment Criteria

The criteria to be employed in the assessment of the impact on the National Grid (NG) Wimbledon to Kensal Green Cable Tunnel of the anticipated tunnelling-induced ground movements due to the construction of the Thames Tunnel are summarised below in Table 6.1.

Table 6.1 Tunnel Assessment Criteria

<table>
<thead>
<tr>
<th>Input Parameters</th>
<th>Assessment Criteria</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume Loss (%)</td>
<td>Tunnel Distortion</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Transverse</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Change in Tunnel Diameter (mm)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Longitudinal</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Radius of Curvature (km)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lining Load (kN)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hoop Load (kN)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.0 (MC)</td>
<td>0.5</td>
<td>5.32 (0.15% O.D.)</td>
</tr>
</tbody>
</table>

Note
(MC) – Moderately Conservative.

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 the absence of information concerning construction tolerance and post-construction deformations of the NG Wimbledon to Kensal Green Cable Tunnel an onerous criterion based on Mott MacDonald’s experience in tunnel assessment (i.e. the transverse distortion on any diameter of the tunnel is not to exceed 0.15% of the Outside Diameter of the tunnel) has been adopted in this assessment for evaluating the impact of the anticipated transverse distortions resulting from the construction of the Thames Tunnel. In setting this acceptance criterion allowance has been made for some pre-existing distortion of the cable tunnel. It has been assumed that the NG Wimbledon to Kensal Green Cable Tunnel will have been in the ground at least 12 months prior to the passage of the Thames Tunnel.

The concrete tunnel lining has been assessed using Limit State principles. The material characteristic strengths of concrete and the partial factors on material strength for assessment are given in Table 6.2; the parameters used in the assessment are highlighted.
### Table 6.2: 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>
<th>72</th>
</tr>
</thead>
<tbody>
<tr>
<td>Characteristic compressive strength (N/mm²): cylinder</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Characteristic compressive strength (N/mm²): cube</td>
<td>25</td>
<td>37</td>
<td>50</td>
<td>60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Young’s Modulus (N/mm²)</td>
<td>24000/12000</td>
<td>26000/13000</td>
<td>28000/14000</td>
<td>30000/15000</td>
<td>32000/16000</td>
<td></td>
</tr>
<tr>
<td>Short term/long term</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></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>
<td>0.2</td>
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</table>

#### Material Partial Factors

<table>
<thead>
<tr>
<th>Source: Tables 10 and 13 of London Underground Standard 1-055</th>
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<td></td>
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</tbody>
</table>
7 Tunnel Impact Assessment

The assessment of the impact on the National Grid (NG) Wimbledon to Kensal Green Cable Tunnel of the anticipated tunnelling-induced ground movements due to the excavation of the Thames Tunnel are presented in the following sub-sections.

7.1 Greenfield Ground Movement Predictions

The anticipated tunnelling-induced greenfield ground movements due to the construction of the Thames Tunnel are presented in Figures 7.1 and A1 (Appendix A) for the moderately conservative assessment case (i.e. a volume loss of 1%).

7.2 Impact on Tunnel Lining

The results of the tunnel lining impact assessment for the anticipated tunnelling-induced ground movements are summarised in Table 7.1 and the following sub-sections.

7.2.1 Transverse Deformation

In the transverse direction the tunnel distortion (see Figure A2) resulting from the tunnelling-induced ground movements has been calculated between tunnel crown and invert using the values of ground movement presented in Figure A1. The maximum differential distortion of 5.4mm is marginally greater than the maximum allowable value of 5.32mm.

7.2.2 Longitudinal Deformation

In the longitudinal direction tunnel distortion resulting from the predicted tunnelling-induced ground movements has been assessed in terms of the radius of curvature. The radii of curvature for the moderately conservative volume loss of 1% are less than the minimum acceptable in both hogging and sagging zones; the minimum acceptable radius of curvature for this asset in the absence of mitigation measures is 15km.

Only the hogging zone checks were used to identify a safety critical case.

7.2.3 Structural

The impact of the anticipated tunnelling-induced greenfield ground movements on the hoop load and bending moment in the tunnel lining of the NG Wimbledon to Kensal Green Cable Tunnel are detailed in Table 7.1; a positive hoop load is essentially maintained in the lining.

These lining loads have been compared to the typical tunnel lining design anticipated for the cable tunnel. As shown in Appendix B these tunnel lining loads plot within the envelope of the respective interaction diagram.

Full details of the structural assessment of the impact of the excavation of the Thames Tunnel on the NG Wimbledon to Kensal Green Cable Tunnel are presented in Appendix B.
### 7. Tunnel Impact Assessment

#### Table 7.1 Results of Tunnel Assessment

<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 (%) K</td>
<td>Surface Surcharge (KPa)</td>
</tr>
<tr>
<td>1.0 0.5</td>
<td>0</td>
</tr>
<tr>
<td>75</td>
<td>Approx 6 (Hogging)</td>
</tr>
<tr>
<td>0.85 0.5</td>
<td>0</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 NG Wimbledon to Kensal Green Cable Tunnel.

2. Deformation has been assessed in the longitudinal direction through the radius of curvature imposed on the NG Wimbledon to Kensal Green Cable 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.

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.

#### 7.3 Summary and Mitigation Measure Proposals

The results of the assessment indicate that in the absence of mitigation measures the assessment criteria are not satisfied for the moderately conservative input parameters and the tunnel clearance of 6m. Consequently, mitigation measures are considered necessary at this interface.

For a tunnel clearance of 6m the volume loss that would have to be achieved to ensure an acceptable radius of curvature result from the construction of the Thames Tunnel is 0.85%. Resilient packers, for example LDPE, in the circle joints will also be required to enhance the flexibility of the NG Wimbledon to Kensal Green Cable Tunnel such that the anticipated movements can be tolerated.

Potential Mitigation Measure Proposals are summarised in Table 7.2 with supporting calculations presented in Appendices A, B and C; the governing criterion is the longitudinal tunnel deformation, i.e. the imposed radius of curvature.

For radii of curvature between about 3km and 15km it is considered that the inclusion of resilient packers, for example 6mm thick LDPE (Low Density Poly-Ethylene) glued to the circle joints of the tunnel segments throughout the anticipated transverse settlement trough, a distance of approximately 60m, will enhance the flexibility of the NG Wimbledon to Kensal Green Cable Tunnel such that the anticipated movements can be tolerated by the tunnel. Calculations demonstrating the feasibility of this mitigation measure are included in Appendix C.
For radii of curvature less than about 3km (based on moderately conservative input parameters) further mitigation measures could include the imposition of an appropriate volume loss (i.e. less than the moderately conservative value of 1%) within the Thames Tunnel construction contract at this interface to ensure that acceptable radii of curvature result (i.e. approximately 3km or more).

**Table 7.2 Mitigation Measure Proposals**

<table>
<thead>
<tr>
<th>Longitudinal Tunnel Curvature Wished-in-Place: Radius of Curvature</th>
<th>Volume Loss (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>0.85</td>
</tr>
<tr>
<td>Approx 2.7km (Sagging): Approx 6km (Hogging)</td>
<td></td>
</tr>
<tr>
<td>Approx 3.2km (Sagging): Approx 7km (Hogging)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Transverse Tunnel Deformation – Vertical Distortion</th>
<th>Volume Loss (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>0.85</td>
</tr>
<tr>
<td>5.4mm</td>
<td>4.6mm</td>
</tr>
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**Mitigation Measure Proposals**

<table>
<thead>
<tr>
<th>Volume loss (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
</tr>
<tr>
<td>4</td>
</tr>
</tbody>
</table>

**Legend: Mitigation Measure Proposals**

<table>
<thead>
<tr>
<th>Class</th>
<th>Colour Code</th>
<th>Radii of Curvature (km)**</th>
<th>Transverse Tunnel Deformation (mm)</th>
<th>Mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Green</td>
<td>&gt;15</td>
<td>&lt;5.25</td>
<td>No mitigation required.</td>
</tr>
<tr>
<td>2</td>
<td>Yellow</td>
<td>3 to 15</td>
<td>-</td>
<td>Limited mitigation required – for example the inclusion of LDPE packers in the circle joints.</td>
</tr>
<tr>
<td>3</td>
<td>Orange</td>
<td>&lt; 3</td>
<td>-</td>
<td>Considerable intrusive mitigation required, for example locally thickened tunnel lining.</td>
</tr>
<tr>
<td>4</td>
<td>Red</td>
<td>&lt; 1</td>
<td>&gt;5.25</td>
<td>Substantial intrusive mitigation required. The implementation of such mitigation measures is not recommended.</td>
</tr>
</tbody>
</table>

**Notes**

1 - For a radius of curvature of about 3km the inclusion of 6mm thick LDPE packers in the circle joints are recommended.

2 - An appropriate volume loss (i.e. less than the moderately conservative value of 1%) would have to be imposed within the Thames Tunnel construction contract at this interface to ensure that acceptable radii of curvature result (i.e. not less than 3km).

NG have confirmed that it would be inappropriate to locate a joint bay at any point in the cable tunnel that may be subject to movement or deformation. As a result a 100m ‘exclusion zone’ spanning the Thames Tunnel crossing has been included as an additional design criterion for the cable tunnel. This requirement may result in an additional joint bay per cable circuit.

In conclusion, the radii of curvature induced by the excavation of the Thames Tunnel assuming a moderately conservative volume loss of 1.0% and tunnel separation of 6m are not acceptable in the absence of mitigation measures. Mitigation measures, the inclusion of LDPE packers in the circle joints and the imposition of an appropriate volume loss (0.85%) as a construction control limit within the Thames Tunnel construction contract at this interface, are required to ensure that acceptable radii of curvature result.
8 Instrumentation and Monitoring

Instrumentation and monitoring will form a fundamental part of the asset protection process for the National Grid (NG) Wimbledon to Kensal Green Cable Tunnel as will the undertaking of pre- and post-construction condition surveys. The instrumentation and monitoring will confirm that the NG Wimbledon to Kensal Green Cable Tunnel is behaving as anticipated.

Following clarification on access arrangements to the NG Wimbledon to Kensal Green Cable Tunnel, conventional instrumentation and monitoring, for example the use of Robotic Total Stations and prisms, and basic line and level surveying methods, could be adopted to monitor tunnel movements and deformations. Sophisticated real-time monitoring systems using fibre optics, for example the BOTDR system, are unlikely to be necessary.
9 Construction Control Limits

The results of the impact assessment indicate that the imposition of a volume loss less than the moderately conservative value of 1% but greater than the corresponding best estimate volume loss of 0.5%, will result in acceptable radii of curvature being induced at this interface for a 6m tunnel clearance. The value of the volume loss that would have to be imposed as a construction control limit is 0.85% (see Appendix A for further details).
10 Conclusions and Recommendations

A maximum settlement of 31mm is anticipated at invert level of the National Grid (NG) Wimbledon to Kensal Green Cable Tunnel as a result of the construction of the Thames Tunnel. The corresponding results of the tunnel assessment indicate that in the absence of mitigation measures the assessment criteria are not satisfied for the moderately conservative input parameters (i.e. a moderately conservative volume loss of 1.0%) for the tunnel clearance under consideration, 6m, at this interface between the Thames Tunnel and the NG Wimbledon to Kensal Green Cable Tunnel.

Mitigation measures, the inclusion of 6mm thick LDPE packers in the circle joints throughout the anticipated transverse settlement trough, a distance of approximately 60m, and the imposition of an appropriate volume loss (0.85%) as a construction control limit within the Thames Tunnel construction contract at this interface, are required to ensure that the assessment criteria are complied with.

Conventional instrumentation and monitoring, for example the use of Robotic Total Stations and prisms, and basic line and level surveying methods, could be adopted to monitor the subsequent tunnel movements and deformations. In addition, it is recommended that pre- and post-construction condition surveys of the NG Wimbledon to Kensal Green Cable Tunnel are carried out. Based on the findings of the post-construction condition survey it may be necessary to caulk the circle joints of the NG Wimbledon to Kensal Green Cable Tunnel at this interface.

The post-construction state of the NG Wimbledon to Kensal Green Cable Tunnel will be verified prior to the construction of the Thames Tunnel and this assessment, including instrumentation and monitoring proposals and construction control limit, reviewed and revised if necessary.

The effect of deformation on internal Mechanical and Electrical installations has not been considered in this work. It has been agreed with NG that such installations in the vicinity can accommodate the movements predicted in this assessment.

The assessment of this interface is based on the information currently available and the construction methods and techniques likely to be adopted. In the absence of information concerning construction tolerance and post-construction deformations of the NG Wimbledon to Kensal Green Cable Tunnel an onerous criterion based on Mott MacDonald’s experience in tunnel assessment (i.e. the transverse distortion on any diameter of the tunnel is not to exceed 0.15% of the Outside Diameter of the tunnel) has been adopted in this assessment for evaluating the impact of the anticipated transverse distortions resulting from the construction of the Thames Tunnel. In setting this acceptance criterion allowance has been made for some pre-existing distortion of the cable tunnel. It has been assumed that the NG Wimbledon to Kensal Green Cable Tunnel will have been in the ground at least 12 months prior to the passage of the Thames Tunnel.
References


**London Underground Standards:**

Figures

Figure 2.1a: Thames Tunnel and NG Wimbledon to Kensal Green Cable Tunnel Crossing - Plan
Figure 2.1b: Thames Tunnel and NG Wimbledon to Kensal Green Cable Tunnel Crossing - Profile

AXIS LEVEL 78.952mATD

NG WIMBLEDON TO KENSAL GREEN CABLE TUNNEL

AXIS LEVEL 66.802mATD

THAMES TUNNEL

SUPERFICIAL DEPOSITS AND MADE GROUND
RIVER THAMES
LONDON CLAY FORMATION
LAMBETH GROUP
THANET SAND FORMATION
CHALK GROUP
Figure 4.1: Proposed NG Wimbledon to Kensal Green Cable Tunnel alignment

- Earls Court Shaft
- Kensal Green Shaft
- Wandsworth Shaft
- Wimbledon Shaft
Figure 4.2: NG Wimbledon to Kensal Green Cable Tunnel - Tunnel Lining Details (Extracted from Drg No. 78-HAL-00030-21282-XXX-CIV REV E)

ELEVATION OF TRAILING EDGE

ELEVATION OF LEADING EDGE
Figures

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Printed 27/03/2012
Appendices

Appendix A – Ground Movement Analysis
Appendix B – Structural Assessment
Appendix C – Mitigation Measures
Appendices

Appendix A – Ground Movement Analysis

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<td>Longitudinal Settlement of National Grid Wimbledon to Kensal Green Cable Tunnel – VL=1%</td>
<td>26</td>
</tr>
<tr>
<td>A2</td>
<td>Longitudinal Vertical Distortion of National Grid Wimbledon to Kensal Green Cable Tunnel – VL=1%</td>
<td>26</td>
</tr>
<tr>
<td>A3</td>
<td>Longitudinal Settlement of National Grid Wimbledon to Kensal Green Cable Tunnel – VL=0.85%</td>
<td>27</td>
</tr>
<tr>
<td>A4</td>
<td>Longitudinal Vertical Distortion of National Grid Wimbledon to Kensal Green Cable Tunnel – VL=0.85%</td>
<td>27</td>
</tr>
<tr>
<td>A5</td>
<td>Longitudinal Imposed Radius of Curvature of National Grid Wimbledon to Kensal Green Cable Tunnel – VL=1%</td>
<td>29</td>
</tr>
<tr>
<td>A6</td>
<td>Longitudinal Imposed Radius of Curvature of National Grid Wimbledon to Kensal Green Cable Tunnel – VL=0.85%</td>
<td>29</td>
</tr>
</tbody>
</table>
Figure A1: Longitudinal Settlement of National Grid Wimbledon to Kensal Green Cable Tunnel – VL=1%

Figure A2: Longitudinal Vertical Distortion of National Grid Wimbledon to Kensal Green Cable Tunnel – VL=1%
Figure A3: Longitudinal Settlement of National Grid Wimbledon to Kensal Green Cable Tunnel – VL=0.85%

Figure A4: Longitudinal Vertical Distortion of National Grid Wimbledon to Kensal Green Cable Tunnel – VL=0.85%
Radius of Curvature Determination

This note describes the technique employed to determine the radius of curvature for the longitudinal settlement curve at the invert of the tunnel asset. The technique determines the centre and corresponding radius for a given rolling three points (P₁, P₂ and P₃) along the settlement curve.

![Diagram of centre of circle for three points]

Figure 1: The centre of the circle for three points

Finding the Centre of the Circle

Two lines, \( a \) and \( b \), are drawn through the points \( P₁ \) and \( P₂ \) and \( P₂ \) and \( P₃ \) respectively (see Figure 1). The equations of the two lines are as follows:

\[
y_a = m_a(x-x_1) + y_1 \quad \text{and} \quad y_b = m_b(x-x_2) + y_2
\]

Where \( m \) is the gradient of the line:

\[
m_a = \frac{y_2 - y_1}{x_2 - x_1} \quad \text{and} \quad m_b = \frac{y_3 - y_2}{x_3 - x_2}
\]

The centre of the circle is the intersection of the perpendicular bisectors of the two lines. The equations of the perpendicular bisectors are given by:

\[
y'_a = \frac{1}{m_a}\left(x - \frac{x_1 + x_2}{2}\right) + \frac{y_1 + y_2}{2} \quad \text{and} \quad y'_b = \frac{1}{m_b}\left(x - \frac{x_2 + x_3}{2}\right) + \frac{y_2 + y_3}{2}
\]

The two lines intersect at the centre of the circle, \((x_c, y_c)\). Solving for \( x_c \) gives

\[
x_c = \frac{m_a m_b (y_1 - y_3) + m_b (x_1 + x_2) - m_a (x_2 + x_3)}{2(m_b = m_a)}
\]

The value of \( y_c \) can be determined by substituting \( x_c \) into either of the equations of the perpendicular bisectors.

Radius Determination

The radius is found by simply finding the distance between the centre of the circle and one of the points on the circle, in this case point \( P₂ \).
Figure A5: Longitudinal Imposed Radius of Curvature of National Grid Wimbledon to Kensal Green Cable Tunnel – VL=1%

Figure A6: Longitudinal Imposed Radius of Curvature of National Grid Wimbledon to Kensal Green Cable Tunnel – VL=0.85%
Appendices

Appendix B – Structural Assessment
Detailed Assessment Calculations for TU025 NG Wimbledon to Kensal Green Cable Tunnel at Wandsworth

i. Assessment Inputs

i.i Tunnel Properties and Geometry

OD := 3.55 m  
Tunnel external diameter

t := 190 mm  
Lining thickness

n := 6  
Number of segments

$E_{I_{long}} := 15\text{ GPa}$  
Long Term Elastic Modulus of Lining (Grade 50 concrete)

$E_{I_{short}} := 30\text{ GPa}$  
Short Term Elastic Modulus of Lining (Grade 50 concrete)

$\nu_{I} := 0.2$  
Poissons Ratio of Lining

i.ii Soil Properties and Geometry

$E_{G} := 50\text{ MPa}$  
Elastic Modulus of Ground

$K_{0} := 0.7$  
Earth Pressure Coefficient

$\gamma_{g} := 20\frac{\text{kN}}{\text{m}^3}$  
Bulk Unit Weight of Ground

$S := 75\text{kPa}$  
Surface surcharge

$Z := 27\text{ m}$  
Depth to Cable Tunnel axis level

$\nu_{G} := 0.1$  
Poisson's ratio of ground

i.iii Partial Factors

Partial factors are taken from Table 7 of London Underground Standard 1-055

$\gamma_{f_{soil}} := 1.2$  
Partial factor on super-imposed dead load (soil)

$\gamma_{f_{live}} := 1.4$  
Partial factor on live load
ii Lining Geometry Calculations

ii.1 Calculated Parameters

\[ I := \frac{1 \cdot m \cdot t^3}{12} \]

Moment of Inertia of Tunnel Lining Segment

\[ I = 5.716 \times 10^{-4} \, m^4 \]

\[ I_r := I \left( \frac{4}{n} \right)^2 \]

Reduced Moment of Inertia of Tunnel Lining Segment

(after Muir Wood, 1975)

\[ I_r = 2.54 \times 10^{-4} \, m^4 \]

\[ I_{rx} := \frac{I_r}{1 \cdot m} \]

Reduced Moment of Inertia per metre run

\[ I_{rx} = 2.54 \times 10^{-4} \frac{m^4}{m} \]

\[ \sigma_{v\_no\_surcharge} := \gamma' Z \cdot f_{\text{soil}} = 648 \cdot \text{kPa} \]

\[ \sigma_{v\_surcharge} := \gamma' Z (\gamma' f_{\text{soil}} + S \cdot f_{\text{live}}) = 753 \cdot \text{kPa} \]

A := 1 \cdot m \cdot t = 0.19 \, m^2

R := \frac{(OD - t)}{2} = 1.68 \, m

Mean Radius

R_{\text{internal}} := \frac{(OD - 2t)}{2} = 1.585 \, m

Internal Radius

\[ A_{\text{rx}} := \frac{A}{1 \cdot m} = 0.19 \frac{m^2}{m} \]

\[ E := \frac{E_1 \cdot \text{long}}{\left( 1 - \nu_1^2 \right)} = 15.625 \cdot \text{GPa} \]

Modified Young’s Modulus for lining after Muir Wood (1975)
1 - Assessment of Ground Loads on Primary Lining

1.1 Primary Lining - 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.

\[
M_{\text{no surcharge}} := \sigma_{v, \text{no surcharge}} \left(1 - K_0\right) R^2 \frac{1}{4 + \frac{3 - 2 \nu_g}{3 \left(1 + \nu_g\right) \left(3 - 4 \nu_g\right)} \frac{E_c R^3}{E_i I_{rx}}}
\]

\[
M_{\text{no surcharge}} = 23.356 \text{ kNm/m}
\]

\[
N_{1, \text{no surcharge}} := \sigma_{v, \text{no surcharge}} \left(1 + K_0\right) R \cdot \frac{1}{2 + \frac{2}{1 + \nu_g} \frac{E_c R}{E_{i, \text{long}} A_{rx}}}
\]

\[
N_{1, \text{no surcharge}} = 901.197 \text{ kN/m}
\]

\[
N_{2, \text{no surcharge}} := \sigma_{v, \text{no surcharge}} \left(1 - K_0\right) R \cdot \left[1 + \frac{1}{12 \left(1 + \nu_g\right)} \frac{E_c R^3}{E_{i, \text{long}} I_{rx}}\right] \cdot \frac{E_c R^3}{6 \left(1 + \nu_g\right) \left(3 - 4 \nu_g\right)} \frac{E_{i, \text{long}} I_{rx}}{E_i I_{rx}}
\]

\[
N_{2, \text{no surcharge}} = 153.552 \text{ kN/m}
\]

\[
N_{\text{max, no surcharge}} := N_{1, \text{no surcharge}} + N_{2, \text{no surcharge}} = 1054.749 \text{ kN/m} \quad \text{Maximum hoop force}
\]

\[
N_{\text{min, no surcharge}} := N_{1, \text{no surcharge}} - N_{2, \text{no surcharge}} = 747.645 \text{ kN/m} \quad \text{Minimum hoop force}
\]

ULS partial factors are applied to M, Nmax, and Nmin during the lining assessment in accordance with London Underground Standard 1-055.
1.2 Bending Moment due to As-Built Imperfections

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

\[ u_{\text{max}} = \frac{1}{100} \times \text{OD} = 35.5 \, \text{mm} \]

Radial distortion due to existing ovalisation/squat

\[ \text{Mod. Factor} = \frac{M_{\text{no surcharge}}}{0.25 \cdot \sigma_{\text{no surcharge}} \cdot (1 - K_p) \cdot P_{\text{internal}}^2} = 0.191 \]

\[ M_{\text{as built}} = N_{\max \text{ no surcharge}} \cdot u_{\max} \cdot \text{Mod. Factor} = 7.163 \frac{1}{m} \, \text{kNm} \]

1.3 Bending Moment Induced due to Thames Tunnel Construction

The construction of the Thames Tunnel beneath the National Grid Wimbledon to Kensal Green Cable Tunnel will distort the Cable Tunnel and induce bending

\[ \delta_d = 5.4 \, \text{mm} \]

Diametrical distortion - difference between greenfield movements at crown and invert

\[ \delta_r = \frac{\delta_d}{2} = 2.7 \, \text{mm} \]

Radial distortion

\[ \Delta M = \left( \frac{3E \cdot I_x \cdot \delta_r}{P_{\text{internal}}^2} \right) f_{\text{soil}} = 15.358 \frac{\text{kN} \cdot \text{m}}{\text{m}} \]

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

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

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

\[ M_{\text{existing}} = M_{\text{no surcharge}} + M_{\text{as built}} = 30.519 \frac{1}{m} \, \text{kNm} \]

Assumed final bending moment in tunnel lining following Thames Tunnel construction

\[ M_{\text{final}} = M_{\text{no surcharge}} + \Delta M + M_{\text{as built}} = 45.876 \frac{1}{m} \, \text{kNm} \]

\[ N_{\max \text{ no surcharge}} = 1054.749 \frac{1}{m} \, \text{kN} \]

Maximum hoop force

\[ N_{\min \text{ no surcharge}} = 747.645 \frac{1}{m} \, \text{kN} \]

Minimum hoop force
2 - Assessment of Ground Loads with 75KPa Surcharge on Primary Lining

2.1 Primary Lining - Existing Bending Moment and Hoop Forces due to Ground Load with 75KPa Surcharge

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.

\[ M_{\text{surcharge}} := \frac{\sigma_v \cdot \text{surcharge}}{R^2} \cdot \frac{1}{1 - K_0} \cdot \frac{1}{E_c R^3} \cdot \frac{3 - 2 \cdot \nu_g}{3 \left(1 + \nu_g\right) \left(3 - 4 \cdot \nu_g\right)} \cdot \frac{E_c}{E_{I_{rx}}} \]

\[ M_{\text{surcharge}} = 27.141 \, \frac{kNm}{m} \]

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

\[ N_{1_{\text{surcharge}}} = 1.047 \times 10^3 \, \frac{kN}{m} \]

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

\[ N_{2_{\text{surcharge}}} = 178.433 \, \frac{kN}{m} \]

\[ N_{\text{max_{surcharge}}} := N_{1_{\text{surcharge}}} + N_{2_{\text{surcharge}}} = 1225.657 \, \frac{kN}{m} \quad \text{Maximum hoop force} \]

\[ N_{\text{min_{surcharge}}} := N_{1_{\text{surcharge}}} - N_{2_{\text{surcharge}}} = 868.792 \, \frac{kN}{m} \quad \text{Minimum hoop force} \]

ULS partial factors are applied to M, Nmax, and Nmin during the lining assessment in accordance with London Underground Standard 1-055.
2.2 Bending Moment due to As-Built Imperfections

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

\[ u_{\text{max}} = \frac{10}{100} \cdot \text{OD} = 35.5 \text{ mm} \]

Radial distortion due to existing ovalisation/squat

\[ \text{Mod Factor} = \frac{M_{\text{surcharge}}}{0.25 \cdot \sigma_y \cdot \text{no surcharge} \cdot (1 - K_0) \cdot R_{\text{internal}}}^2 = 0.222 \]

\[ M_{\text{as built}} := N_{\text{max \ no surcharge}} \cdot u_{\text{max}} \cdot \text{Mod Factor} = 8.323 \frac{1}{m} \text{ kNm} \]

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

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

\[ M_{\text{existing}} := M_{\text{surcharge}} + M_{\text{as built}} = 35.464 \frac{1}{m} \text{ kNm} \]

Assumed final bending moment in tunnel lining following Thames Tunnel construction

\[ M_{\text{final}} := M_{\text{surcharge}} + \Delta M + M_{\text{as built}} = 50.822 \frac{1}{m} \text{ kNm} \]

\[ N_{\text{max surf}} = 1225.657 \frac{1}{m} \text{ kN} \]

Maximum hoop force

\[ N_{\text{min surf}} = 868.792 \frac{1}{m} \text{ kN} \]

Minimum hoop force

Notes

1. There is no Secondary Lining to this tunnel.
## Section Data

<table>
<thead>
<tr>
<th>Concrete Grade ($f_{ck}$)</th>
<th>50 MPa</th>
<th>Fibres</th>
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<tr>
<td>Steel ($f_y$)</td>
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<tr>
<td>Steel Elastic Modulus ($E_s$)</td>
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<td>Flexural tensile strength ($f_{tud}$)</td>
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<tr>
<td>Tensile $\sigma_t$</td>
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<tr>
<td>Maximum residual $\sigma$</td>
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<tr>
<td>Minimum residual $\sigma$</td>
<td>1.54</td>
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<tr>
<td>Effective Tensile Strain Limit</td>
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</tbody>
</table>

**Factored Yield Stress**: 434.78 MPa  
**Material factor**: 1.5

**Width of section (b)**: 1000 mm  
**Depth (h)**: 190 mm

**Reinforcement**:  
- **Tension Bar 1**: 0 mm  
- **Tension Bar 2**: 0 mm  
- **Compression Bar 1**: 0 mm  
- **Compression Bar 2**: 0 mm  

**Cover to bar**:  
- **d-1**: 190 mm  
- **d-2**: 190 mm  
- **Ast1**: 0 mm  
- **Ast2**: 0 mm  

**Section Effective depth ($d_e$)**: 190 mm  
**Tension Steel Ratios**:  
- **Actual**: 0.00%  
- **Minimum for Reinforced**: 0.21%  

### Concrete grade
G50/60 D 0.5 S -1,5
after BS EN 14487-1

### Moment Interaction Diagram

- **SFRC Capacity**
- **Full Compression**
- **Existing No surcharge, Nmin**
- **Existing surcharge, Nmin**
- **Existing surcharge, Nmax**
- **Post construction no surcharge, Nmin**
- **Post construction no surcharge, Nmax**
- **Post construction surcharge, Nmin**
- **Post construction surcharge, Nmax**

N.B. Cover-to-bar is to the tension or compression bar itself, not just the specified minimum cover to rebar generally.
Detailed Assessment Calculations for TU025 NG Wimbledon to Kensal Green Cable Tunnel at Wandsworth

The excavation of the Thames Tunnel will result in a change in vertical stress at the level of the National Grid Wimbledon to Kensal Green Cable Tunnel. The magnitude of the change in stress directly above the Thames Tunnel crossing has been estimated using the Kirsch Equations for the stresses surrounding a circular hole in a stressed elastic body.

![Diagram of stress distribution](image)

\[ \text{OD}_{\text{asset}} = 3.55 \text{ m} \]

Tunnel external diameter of asset

\[ \text{OD}_{\text{Thames Tunnel}} = 8.8 \text{ m} \]

Thames Tunnel Excavated diameter

\[ k = 0.7 \]

Earth Pressure Coefficient

\[ \gamma_g = 20 \text{ kN/m}^3 \]

Bulk Unit Weight of Ground

\[ \nu_g = 0.1 \]

Poisson's ratio of ground

\[ S = 75 \text{kPa} \]

Surface surcharge

\[ Z_{TT} = 38.2 \text{ m} \]

Depth from riverbed level to Thames Tunnel Axis Level

\[ \text{separation} = 6 \text{ m} \]

The vertical separation between the NG Cable Tunnel and the Thames Tunnel

\[ p_z = \gamma_g Z_{TT} = 764 \text{kPa} \]

Vertical stress in the "infinite plate" - no surface surcharge

Initial conditions

\[ \sigma_1 = p_z = 764 \text{kPa} \]

\[ \sigma_2 = p_z k = 534.8 \text{kPa} \]
Thames Tunnel excavated

\[ a := \frac{OD_{\text{Thames Tunnel}}}{2} = 4.4 \text{ m} \]  
Excavated radius of Thames Tunnel

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

\[ r := 0 \quad \text{separation} + \frac{OD_{\text{Thames Tunnel}}}{2} + \frac{OD_{\text{asset}}}{2} = 12.175 \text{ m} \]

The stress components are given by the Kirsch Equations

Radial

\[ \sigma_r = \frac{1}{2} p_z \left[ (1 + k) \left( 1 - \frac{a^2}{r^2} \right) + (1 - k) \left( 1 - 4 \frac{a^2}{r^2} + 3 \frac{a^4}{r^4} \right) \cos (2\theta) \right] = 625.178 \text{ kPa} \]

Tangential

\[ \sigma_\theta = \frac{1}{2} p_z \left[ (1 + k) \left( 1 + \frac{a^2}{r^2} \right) - (1 - k) \left( 1 + 3 \frac{a^4}{r^4} \right) \cos (2\theta) \right] = 613.752 \text{ kPa} \]

Shear

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

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

maximum

\[ \sigma_{1\text{-after}} := \frac{1}{2} (\sigma_r + \sigma_\theta) + \left[ \frac{1}{4} (\sigma_r - \sigma_\theta)^2 + \tau_{r\theta} \right]^{1/2} = 625.178 \text{ kPa} \]

minimum

\[ \sigma_{2\text{-after}} := \frac{1}{2} (\sigma_r + \sigma_\theta) - \left[ \frac{1}{4} (\sigma_r - \sigma_\theta)^2 + \tau_{r\theta} \right]^{1/2} = 613.752 \text{ kPa} \]

Change in stress at the National Grid Wimbledon to Kensal Green Cable Tunnel axis level due to construction of the Thames Tunnel are as follows:

\[ \Delta \sigma_1 := \sigma_{1\text{-after}} - \sigma_1 = -138.822 \text{ kPa} \]  
Change in vertical stress

\[ \Delta \sigma_2 := \sigma_{2\text{-after}} - \sigma_2 = 78.952 \text{ kPa} \]  
Change in horizontal stress in plane of page

\[ \Delta \sigma_3 := \nu_g (\Delta \sigma_1 + \Delta \sigma_2) = -5.987 \text{ kPa} \]  
Change in horizontal stress into/out of plane of page
p_z := \gamma g \cdot Z_{TT} + S = 839 \text{ kPa}

Vertical stress in the "infinite plate" with surface surcharge

Initial conditions

\sigma_1 := p_z = 839 \text{ kPa}
\sigma_2 := p_z \cdot k = 587.3 \text{ kPa}

Thames Tunnel excavated

\alpha := \frac{OD_{Thames\ Tunnel}}{2} = 4.4 \text{ m}

Excavated radius of Thames Tunnel

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

\theta := 0
r := \text{ separation} + \frac{OD_{Thames\ Tunnel}}{2} + \frac{OD_{asset}}{2} = 12.175 \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 - \frac{4 a^2}{r^2} + \frac{3 a^4}{r^4} \right) \cos(2\theta) \right] = 686.55 \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 + \frac{3 a^4}{r^4} \right) \cos(2\theta) \right] = 674.002 \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(2\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) + \frac{1}{4} \left( \sigma_r - \sigma_\theta \right)^2 + \tau_{r\theta}^2 \right)^{\frac{1}{2}} = 686.55 \text{ kPa}

minimum

\sigma_{2\text{ after}} := \frac{1}{2} \left( \sigma_r + \sigma_\theta \right) - \frac{1}{4} \left( \sigma_r - \sigma_\theta \right)^2 + \tau_{r\theta}^2 \right)^{\frac{1}{2}} = 674.002 \text{ kPa}
Change in stress at the National Grid Wimbledon to Kensal Green Cable Tunnel axis level due to construction of the Thames Tunnel are as follows:

\[ \Delta \sigma_1 := \sigma_{1\text{ after}} - \sigma_1 = 152.45 \text{ kPa} \]  
Change in vertical stress

\[ \Delta \sigma_2 := \sigma_{2\text{ after}} - \sigma_2 = 86.702 \text{ kPa} \]  
Change in horizontal stress in of plane of page

\[ \Delta \sigma_3 := \nu (\Delta \sigma_1 + \Delta \sigma_2) = -6.575 \text{ kPa} \]  
Change in horizontal stress into/out of plane of page

Therefore changes in hoop load are such that it can be assumed for assessment purposes that hoop load is largely unchanged following the tunnelling-induced ground movements.
Appendix C– Mitigation Measures
Mott MacDonald

Assessment of the Impact of the Excavation of the Thames Tunnel on the NG Wimbledon to Kensal Green Cable Tunnel at Wandsworth

Mitigation Measure Design: Resilient LDPE Packers for 190mm thick wedge block tunnel lining

CONTENTS

1 - TUNNEL DESIGN DATA
2 - PACKER PROPERTIES
3 - TBM THRUST RAM EFFECT
4 - CHECK ON CIRCLE JOINT CAPACITY
5 - CHECK ON RADIUS OF CURVATURE OF TUNNEL

APPENDIX A - DRAWING 78-HAL-00030-21282-XXX-CIV

[Signature]
19/3/12
OBJECTIVE - To quantify the benefit of fitting resilient packers, in this case 6mm thick LDPE, in the circle joints of the NG Wimbledon to Kensal Green Cable Tunnel at Wandsworth. The results of the impact assessment indicate that the anticipated greenfield ground movements resulting from the construction of the Thames Tunnel beneath the NG Cable Tunnel at this location will result in radii of curvature less than that which is acceptable in the absence of mitigation measures.

1.0 - TUNNEL DESIGN DATA

1.1 Concrete with steel fibres

Cube strength \( f_{cu} := 60 \text{MPa} \)

Cylinder strength \( f_{ck} := 50 \text{MPa} \)

Mean compressive strength \( f_{cm} := 48 \text{MPa} \)

Characteristic tensile strength \( f_{ck} := 3.7 \text{MPa} \)

Material factor \( \gamma_c := 1.5 \)

Additional tensile factor \( \alpha_{ct} := 1 \)

Design compressive strength \( f_{cd} := \frac{0.67 \cdot f_{cu}}{\gamma_c} = 26.8 \cdot \text{MPa} \)

Design tensile strength \( f_{ctd} := \frac{\alpha_{ct} \cdot f_{ck}}{\gamma_c} = 2.47 \cdot \text{MPa} \)

Young's modulus for concrete \( E_c := 34 \text{GPa} \)
1.2 Tunnel and Segment Geometry

Internal diameter \( \text{ID} := 3160 \text{mm} \)

Segment thickness \( t_s := 190 \text{mm} \)

External diameter \( \text{OD} := \text{ID} + 2 \cdot t_s = 3540 \text{mm} \)

Mean radius \( R_{av} := \frac{\text{ID} + t_s}{2} = 1675 \text{mm} \)

Ring length \( L_{ring} := 1200 \text{mm} \)

Number of segments (excluding key) \( n_s := 6 \)

Segment angle (leading edge) \( \theta := 52.9475^\circ = 0.924 \text{ rad} \)

Segment circumferential length \( L_{circ} := \theta \cdot R_{av} = 1548 \text{ mm} \)

Radial joint extrados chamfer depth \( \text{ed}_r := 25 \text{ mm} \)

Circle joint extrados packer rebate \( \text{ed}_c := 20 \text{ mm} \)

Radial joint caulking chamfer depth \( \text{cgd}_r := 25 \text{ mm} \)

Circle joint caulking chamfer depth \( \text{cgd}_c := 30 \text{ mm} \)

1.3 TBM Data

Number of shoes on counter key segment \( n_{shoes} := 2 \)

Maximum thrust per shoe \( T_{stated} := 753 \text{kN} \)

Ram load factor \( \gamma_{ram} := 1.0 \)

As the TBM maximum thrust capacity is used

Design total ram thrust on segment \( T_{total} := T_{stated} \cdot n_{shoes} \cdot \gamma_{ram} = 1506 \text{kN} \)
2.0 PACKER PROPERTIES

Packer width

\[ W_p := t_s - e_d - cgd_c = 140 \text{ mm} \]

Side rebates to prevent edge contact

\[ S_r := 50 \text{ mm} \]

Packer length

\[ L_p := L_{\text{circ}} - S_r - S_r = 1.448 \text{ m} \]

Packer mean radii

\[ R_p := \frac{(OD - e_d_c + ID - cgd_c)}{4} = 1.662 \text{ m} \]

Packer outer radii

\[ R_{po} := \frac{(OD - 2e_d_c)}{2} = 1.75 \text{ m} \]

Packer inner radii

\[ R_{pi} := \frac{(ID + 2cgd_c)}{2} = 1.61 \text{ m} \]

3.0 TBM RAM THRUST EFFECT

Packer plan area

\[ \text{PACKERarea} := \left(\frac{\theta}{2}\right) \left( R_{po}^2 - R_{pi}^2 \right) - S_r 2W_p = 0.203 \text{ m}^2 \]

Concrete plan area

\[ \text{CONCarea} := \frac{\theta}{8} \left( OD^2 - ID^2 \right) = 0.294 \text{ m}^2 \]

Mean packer pressure

\[ \sigma_{prams} := \frac{T_{\text{total}}}{\text{PACKERarea}} = 7.406 \text{ MPa} \]

Mean concrete stress

\[ \sigma_{crams} := \frac{T_{\text{total}}}{\text{CONCarea}} = 5.121 \text{ MPa} \]

4.0 CHECK ON CIRCLE JOINT CAPACITY

Bursting stresses checked according to MM Joint Design Manual which is based on joint tests carried out for the Victoria Line and Channel Tunnel.

Design Joint as unreinforced concrete

The ultimate load capacity at no joint eccentricity

\[ N_u = f_{cd} \cdot L_{\text{circ}} \cdot t_s \cdot \frac{\beta}{\alpha} \]

Where

\[ N_u = \text{Failure load} \]

\[ f_{cd} = \text{Tensile strength of concrete} \]

\[ t_s = \text{Segment thickness} \]

\[ L_{\text{circ}} = \text{Length of segment} \]

\[ \beta := 1.6 \]
\[ \alpha := 0.44 - \frac{\text{PACKERarea} \cdot 0.4}{\text{CONCarea}} = 0.163 \]

\[ \text{Nuo} := f_{ctd} \cdot L_{circ} \cdot t_s \cdot \frac{\beta}{\alpha} = 7.102 \times 10^3 \cdot \text{kN} \]

Ultimate load at 0.05ts is given by \( \text{Nu5} = 0.75 \cdot \text{Nuo} \)

\[ \text{Nu5} := 0.75 \cdot \text{Nuo} = 5.327 \times 10^3 \cdot \text{kN} \]

Where the eccentricity exceeds 0.05ts the ultimate load is given by \( \text{Nue} = 0.75 \cdot \text{Nuo} \times \tau \)

\[ \frac{e}{h} \quad \tau \]

\[
\begin{array}{c|c|c|c|c}
\hline
\text{ } & 0.05 & 1.0 & 0.1 & 0.85 \\
\hline
\frac{e}{h} & \tau & \tau & \tau & \tau \\
\hline
\end{array}
\]

Eccentricity induced in the circle joint due to bad build inducing steps ASSUMED to be less than 10mm

Circumferential joint design capacity = \( \text{Nue} \)

\[ e_c := 10 \text{mm} \]

\[ \tau := 1.0 - (1 - 0.85) \cdot \frac{(0.1 - 0.05)}{(0.1 - 0.05)} = \]

\[ \text{Nue} := 0.75 \cdot \text{Nuo} \times \tau = 5.285 \times 10^3 \cdot \text{kN} \]

Therefore limit maximum force in segment to 5285kN

5.0 CHECK ON RADIUS OF CURVATURE OF TUNNEL WITH LDPE PACKERS INCLUDED IN THE CIRCLE JOINTS

Allowable mean longitudinal Stress in concrete segment

\[ \sigma_{\text{seg lim}} := \frac{\text{Nue}}{\text{CONCarea}} = 17.969 \cdot \text{MPa} \]

equivalent stress in packer

\[ \sigma_{\text{packer lim}} := \frac{\text{Nue}}{\text{PACKERarea}} = 25.988 \cdot \text{MPa} \]

Initial compression on segment due to jacking force

\[ \delta_{0.\text{seg}} := \sigma_{\text{rams}} \cdot \frac{L_{\text{ring}}}{E_c} = 0.181 \cdot \text{mm} \]
Based on compression test results for 3.2mm thick LDPE (tests carried out on 150mm square sample). Test results provided by Tunnelling Accessories.

**Test Results for 3.2mm Thick LDPE Packer**

![Compression test graph](image)

**Compression mm**

For packer thicknesses greater than 3mm, the respective packer properties are multiplied by the corresponding number of 3mm thick layers making up the overall packer thickness. In this case 6mm thick packers are being considered, i.e. the packer properties are multiplied by \( n = 2 \).

Number of 3mm LDPE packers

\[
n := 2
\]

\[
\delta_{0,\text{packer}} := n \left[ 0.185 \text{mm} + \frac{\sigma_{\text{prams}} - 4.44 \text{MPa}}{44.44 \text{MPa} - 4.44 \text{MPa}} (0.413 \text{mm} - 0.185 \text{mm}) \right] = 0.404 \text{mm}
\]

Total compression under jacks

\[
\delta_0 := \delta_{0,\text{seg}} + \delta_{0,\text{packer}} = 0.585 \text{mm}
\]

Compression at maximum stress in lining:

\[
\delta_{1,\text{seg}} := \sigma_{\text{seg lim}} \frac{L_{\text{ring}}}{E\text{c}} = 0.634 \text{mm}
\]

\[
\delta_{1,\text{packer}} := n \left[ 0.185 \text{mm} + \frac{\sigma_{\text{packer lim}} - 4.44 \text{MPa}}{44.44 \text{MPa} - 4.44 \text{MPa}} (0.413 \text{mm} - 0.185 \text{mm}) \right] = 0.616 \text{mm}
\]

Total compression per ring

\[
\delta_1 := \delta_{1,\text{seg}} + \delta_{1,\text{packer}} = 1.25 \text{mm}
\]

Allowable length change per ring

\[
\delta_{\text{ring}} := \delta_1 - \delta_0 = 0.665 \text{mm}
\]

Allowable minimum radius

\[
R_{\text{curvature}} := R_{\text{av}} \frac{L_{\text{ring}}}{\delta_{\text{ring}}} = 3021 \text{m}
\]

**CONCLUSION -** The inclusion of 6mm thick LDPE packers in the circle joints of the tunnel lining result in allowable curvatures of 3km.
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