Settlement due to Two Bored Tunnels in Mixed Soil Conditions

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1. INTRODUCTION

The stratigraphy in the Perth CBD (central business district) comprises three formations. The bedrock or the Kings Park Formation (KPF) underlies the over consolidated ‘Perth Formation’ (comprising inter bedded layers of clay silt and sand); normally consolidated Spearwood (aeolian) sand overlies the ‘Perth Formation’. Figure 1 shows the alignment of the two 6900mm diameter (D) bored tunnels as well as the geotechnical investigation and instrumentation locations relative to the five Railway Tracks (which are the main focus of this paper). The distance between Track 1 and Track 5 was about 46m. As may be seen, investigations took place north of Track 5 and about 120m further away on the southern side of Track 1. Consequently, no investigation data at the track locations were available and, in the following, two soil profiles are considered, namely the North and South profiles.

Figure 1 Geotechnical Investigation Locations near the Railway Lines

The borehole information and stratigraphical profiling based on the Ic index [1] derived from the CPT data together with Io index from dilatometer tests were used to establish the profiles shown on Figure 2. The best estimate average CPT end resistance (qc) value for each soil layer is also shown in the corresponding profiles. Figure 2 (a) indicates that the tunnels are primarily in the Spearwood Sand in the North. However, in the South, the tunnels are located in the sand and clay layers of ‘Perth Formation’. The water table was at 9.2m AHD, which is about 3m below the existing ground surface. The relevant section of Tunnel 1 was bored between 16th May 2006 and 23rd May 2006 while that for Tunnel 2 was bored between 27th September 2006 and 2nd October 2006.
Figure 2 Soil Profile and Location of Tunnel

**2. FIELD MEASUREMENT**

Rail Settlement Points (RSPs) and Electro Level beams (EL beams) were used to monitor three of the five existing railway tracks. RSPs took the form of retro reflective targets because of access difficulties caused by trains, which continued to run throughout the tunnelling project.

EL beams are used to monitor either rotation or tilt if used as a single beam. Figure 3 shows the typical view of the EL beam. By linking end to end, the beam sensors can monitor differential movement; total movements are established if the movement of one of the sensors (typical one at the end of the string) is known.

Figure 1 shows the location of EL Beams on the railway lines. Both longitudinal as well as transverse EL Beams were used and these were installed, as shown on Figure 4, on the sleepers between the two rails. It is clear from Figure 1 that the Railway Tracks were not orthogonal to the tunnels and thus to the EL Beams; this is shown schematically in Figure 5. Transverse surface settlement troughs were therefore derived using the procedure illustrated on Figure 5, which involved converting the distance along the railway track into an equivalent transverse distance. Consider points A, B and C marked in the figure. EL Beams are aligned along AC and the transverse distance (orthogonal distance) is BC. It may be assumed that there is little difference between the soil properties at A and B and hence the final settlement at B was taken equal to that at A.

The vertical ground movement of ‘greenfield’ (free field) site (where there is no interaction effect of any structures) is the focus of this paper. Hence the observations related to the transverse settlement troughs measured using both RSPs and EL beams are summarised in the following sections.
2.1 Displacement and Tilt Measurements

A summary of maximum soil surface heave generated during tunnelling and of the maximum settlement recorded after tunnelling was completed, as indicated by RSPs, is provided in Table 1. One of the (perhaps surprising) features of the data was the amount of short term heave generated during tunnelling. Such heave is presumed to have arisen due to the application of relatively large pressures (typically 195 ± 15kPa) at the tunnel face or the grout pressure (180±40kPa) at the tail of the TBM. Although all of the three monitored tracks experienced heave during tunnelling, incremental movements after the TBM cutter face had passed any given location were always downwards and resulting final ground movements were also downwards (i.e. settlements), varying between 2mm and 9mm. As indicated on Figure 6, there appears to be a general trend for greater settlement to take place when preceded by greater heave, suggesting that the benefits of settlement reduction caused by application of high face pressures are only short term.

It was also noted that the settlement stabilised very rapidly (within a few days) and hence long term (consolidation) settlements were insignificant. Such an absence of long term movements is consistent with the predominance of dense sandy soils at the tunnel locations. Because of the insignificance of long term movements, to avoid errors associated with instrumentation drift, all RSPs and EL beams were re-zeroed prior to the Tunnel 2 drive.

<table>
<thead>
<tr>
<th>Track</th>
<th>Max. Heave (mm)</th>
<th>Max. Settlemnt (mm)</th>
<th>Max. Heave (mm)</th>
<th>Max. Settlement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tunnel 1 alone</td>
<td>3</td>
<td>4.5</td>
<td>1.5</td>
<td>2.2</td>
</tr>
<tr>
<td>Tunnel 2 alone</td>
<td>6</td>
<td>8.9</td>
<td>1.8</td>
<td>6.0</td>
</tr>
<tr>
<td>Track 5</td>
<td>9.5</td>
<td>6.2</td>
<td>8.4</td>
<td>3.2</td>
</tr>
</tbody>
</table>

Table 1 Variation of Heave and Settlement for each Track after the Tunnel Boring
Relative settlements from the EL-beams were obtained by integrating the tilt readings from one end of the string of beams. These relative values were converted to absolute values using measurements from RSPs located at the ends of the strings.

2.2 Transverse Settlement Troughs

The movements (settlement/heave) indicated by the RSPs and EL-beams were in close agreement for both tunnel runs and therefore the final transverse settlement troughs shown in Figure 7 were taken as the average of the two measurement sets. The characteristics of these troughs, as recorded at the three track locations, are summarised in Table 2 and discussed below.

2.2.1 Settlement

It is evident from Figure 7 that:

- The settlement induced by boring of the second tunnel (Tunnel 2) was less than that for the first tunnel (Tunnel 1) for all three tracks; this trend contrasts with trends reported in the literature ([2], [3]).
- The settlement of Track 3 was largest and that of Track 1 was lowest for both tunnel drives. It is possible that this situation arose because of localised variations in soil stiffness.

![Figure 7 Separate Transverse Settlement Troughs due to Tunnel 1 and Tunnel 2](image)

2.2.2 Trough Width

The width of the transverse settlement trough at ground level on either side of the tunnel axis was assessed from the observed field data, assuming the trough extended to a distance where the settlement was less than about 0.1 mm. These widths are listed in Table 2 and indicate that:

- The settlement troughs were symmetrical during Tunnel 1 boring.
- The settlement troughs induced by Tunnel 2 were not symmetrical and indicated a reduced trough width on East side of the Tunnel axis and a larger trough width on the West side. Given the overall lower settlements induced during Tunnel 2, the trend on the east side is likely to be due to an increase in ground stiffness due to the presence of the stiff lining of Tunnel 1 and increases in the in-situ mean effective stress.

2.2.3 Volume Loss

The additional soil that has to be excavated over and above the volume associated with the tunnel area is referred to as the volume loss and is usually expressed as a ratio of the area of
the surface settlement trough to the nominal area (=Volume per unit length) of the tunnel bore. The areas of the settlement troughs indicated on Figure 7 is used to derive the volume losses summarised in Table 2. It is evident that:

- All three tracks showed lower volume losses during Tunnel 2 boring than during Tunnel 1 boring. On average the volume losses for Tunnel 1 and Tunnel 2 were 0.18% and 0.1% respectively.
- Tracks 1 and 5 experienced comparable and relatively low volume losses, whereas Track 3 experienced significantly larger volume losses during both tunnel bores.
- Although the maximum settlement at Track 1 and 5 differ, the volume loss calculated from the respective settlement troughs remained the same. This is because Track 5 had a narrower and deeper settlement trough compared to Track 1 for both Tunnel 1 and Tunnel 2 boring.

3. COMPARISON OF OBSERVED TRANSVERSE SETTLEMENT TROUGHS WITH GAUSSIAN APPROACH

This section examines the applicability of the widely used Gaussian Method to predict the shapes of Greenfield troughs observed during tunnel boring. Best fit parameters for use of this method in ground conditions similar to those existing in Perth CBD are established. The equation for the Gaussian profile is,

\[ S_v = S_{\text{max}} e^{-y^2/2i^2} \]  

Equation 1

Where,

- \( S_{\text{max}} \) - Maximum settlement,
- \( S_v \) - Settlement at an offset \( y \) from the tunnel centre line
- \( i \) - The transverse horizontal distance from the centre-line of the tunnel to the point of inflection of the settlement trough

Equation 1 can be re-arranged to allow derivation of \( i \) (Equation 2), if the maximum settlement and the settlement at an offset distance, \( y \), is known:

\[ i = \sqrt{\frac{1}{2 \ln \left( \frac{S_v}{S_{\text{max}}} \right)} y^2} \]  

Equation 2

If the settlement profile is of Gaussian nature, then \( \ln \left( \frac{S_v}{S_{\text{max}}} \right) \) should be proportional to \( y^2 \) and \( i \) can be estimated from the constant of proportionality. Typical linear regression lines between \( \ln \left( \frac{S_v}{S_{\text{max}}} \right) \) and \( y^2 \) (based on the field measurements for Track 1) are given in Figure 8. Values of \( i \) determined in this way are presented in Table 3. The good linear fit apparent for the data on Figure 8 confirms that the measured settlement troughs for Tunnel 1 are of Gaussian nature. The settlement troughs associated with Tunnel 2 were asymmetrical, as discussed above, but Equation 2 indicated that both the east and west profiles were well represented using the Gaussian form, except with different \( i \) values on either side (see Table 3).
4. DISCUSSION

This section discusses the nature of transverse settlement troughs observed at three locations close to each other and also provides recommendations for the trough width parameter ($K$) appropriate to the ground conditions in Perth CBD. The relationship between the parameter $i$, tunnel depth and tunnel diameter is also examined.

4.1 Nature of Settlement Trough

The surface settlements normalised by the respective maximum settlements for Tunnel 1 are shown in Figure 9. These indicate that, as the tunnel moves Northwards (from Track 1 to Track 5); there is a general trend for the width of the settlement trough to reduce. Similar trend was also observed for Tunnel 2 except at Track 3. This trend is consistent with the inference from Figure 2 that the tunnel moves progressively out of the Perth Formation and into the Spearwood dune sand as it moves northwards. A narrower trough width in sand has been seen in centrifuge model tests, which, with sufficient volume loss, ultimately leads to a failure mechanism involving a “chimney” propagating vertically from the tunnel to the surface ([4],[5]).

The $K$ values corresponding to the $i$ values shown in Table 3 are summarised in Table 4 and lines of constant $K$ are plotted along with the $i$ values on Figure 10 (For Tunnel 2, only west side is plotted except Track 3); this figure also shows the range of $i$ values recommended by Mair and Taylor [6] in sands and gravels. It is apparent that the observations are in keeping with these recommendations, noting that the decreasing $K$ values (or slopes on Figure 10) arise in deposits with reducing quantities of clay.

<table>
<thead>
<tr>
<th>Track 1 ($i$) (m)</th>
<th>Tunnel 1 ($i$) (m)</th>
<th>Tunnel 2 ($i$) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>East</td>
<td>West</td>
</tr>
<tr>
<td>Track 1</td>
<td>5.01</td>
<td>5.03</td>
</tr>
<tr>
<td>Track 3</td>
<td>4.2</td>
<td>3.8</td>
</tr>
<tr>
<td>Track 5</td>
<td>3.4</td>
<td>3.5</td>
</tr>
</tbody>
</table>

Table 3 Estimated $i$ values
Table 4 \( i \) and \( K \) estimated for the three Tracks for Tunnel 1 and Tunnel 2

<table>
<thead>
<tr>
<th>Track</th>
<th>( z_0 ) (m)</th>
<th>Tunnel 1</th>
<th>Tunnel 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track 1</td>
<td>11</td>
<td>0.46</td>
<td>0.42</td>
</tr>
<tr>
<td>Track 3</td>
<td>10.5</td>
<td>0.41</td>
<td>0.57</td>
</tr>
<tr>
<td>Track 5</td>
<td>10</td>
<td>0.34</td>
<td>0.35</td>
</tr>
</tbody>
</table>

4.2 Relationship between \( i \), Tunnel Depth and Tunnel Diameter

Peck [7] suggested a relationship, shown in Figure 11, between the parameter \( i \) and tunnel depth \( (z_0) \) for different ground conditions. The observed relationships between \( 2i/D \) and \( z_0/D \) are, for both tunnel drives, seen fall under the category of sands above water table (which is in the same category as rock and hard clays). Although the tunnels were below water table, the effect of ground water on the settlement trough could be assumed negligible because of the fact that the water flow into the Tunnel was prevented or significantly reduced by maintaining the face pressure above the hydrostatic water pressures. Also the pore water pressure difference between inside the cutter head and the point of muck release onto the TBM’s belt conveyor was maintained by keeping a soil plug within the screw conveyor using appropriate soil conditioning agents. The joints between the linings were also fully water proofed to avoid any leak into the tunnel.

Figure 11 Relation between \( i \), Tunnel depth and Diameter for Different Ground Conditions (Peck, 1969 [7])

5. SUMMARY

The observed patterns of Greenfield movement due to the EPB boring of two adjacent tunnels are discussed in this paper. The main findings are as follows:
• The average volume losses of 0.18% and 0.1% for Tunnels 1 and 2 respectively are within the range of expectations of the earth pressure balancing technique employed.

• No long term settlement occurred in the predominantly sandy conditions present at the site.

• Larger volume losses occurred consistently at one location for both tunnel drives (at the location of Track 3) indicating the presence of localised weaker soil and the need for thorough site investigations in advance of tunneling projects.

• The width of the transverse settlement trough associated with a second tunnel drive was lower than the Greenfield value due to the influence of the first tunnels’ stiff lining and possibly also due to increased soil stiffness.

• The trough width parameter $K$ estimated from the observed settlement troughs at the three locations is in agreement with past observations made in similar ground conditions around the world.

6. ACKNOWLEDGMENTS

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7. REFERENCES


