Predicting the settlements above closely spaced triple tunnels constructions in soft ground

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ABSTRACT: In the UK the competition for underground space in the urban environment is increasing. In order to fulfil the requirement for improved transport links in London an increasing amount of tunnel constructions have been undertaken. The new tunnel constructions can disturb existing underground structures (i.e. pipes, tunnels and piles) and cause the movements in overlying buildings. For these reasons, methods for predicting movements above new tunnels are vital to practicing tunnelling engineers. This paper refers to previous work undertaken by the authors into the development of a modification factor to adapt empirical predictions based on the Gaussian curve equation for predicting vertical displacements above twin tunnels. It is shown how this method can be extended to incorporate the problem of triple tunnel analyses. The results are compared with those from a non-linear finite element analysis and sub-surface case history data collected during the construction of the Heathrow Express Tunnels in London. The results show a considerable improvement compared to the ‘unmodified’ empirical method. The role of construction sequence and the subsequent settlement profiles are also examined in the paper.

1 INTRODUCTION

Various papers have reported the changes to the settlement profile, which occur above a second tunnel construction in a side-by-side alignment (e.g. Cording and Hansmire, 1975, Addenbrooke, 1996). Chapman et al (2002) related these changes to a relative increase in settlement of approximately 60% always occurred above the centreline of the first tunnel driven when analysing side-by-side tunnels using the finite element method. Chapman et al (2004), based on the results of this earlier work, produced a modification method which could incorporated into existing predictive methods for finding vertical displacements above a second tunnel construction.

This paper extends the numerical model and improved predictive method, reported in this earlier work, to include the construction of a third tunnel. Two different construction sequences are considered here, referred to as SEQUENCE 1 and SEQUENCE 2 (Figure 1).

The triple tunnels reported here are assumed to be constructed consecutively (one after the other) in London Clay, with construction sequence 1 being representative of 26.0 m deep, 9.0 m diameter tunnels, constructed as part of the Heathrow Express at the Central Terminal Station (CTA) in the U.K. (Cooper and

Figure 1. Construction sequence and geometry of triple tunnels.
The depth and tunnel diameter are the same as those considered by Chapman et al. (2002) who conducted finite element analyses of side-by-side tunnels at various centre-to-centre spacings (i.e. 20.0, 30.0, 50.0, 80.0 and 120.0 m). The data shown in this paper supplements this earlier work by reporting the settlement profiles at a depth of 13.0 m below ground level (i.e. sub-surface) for side-by-side tunnels at a centre-to-centre spacing of 15.9 m and 36.8 m.

The paper shows the importance of construction sequence when considering triple tunnels in a side-by-side alignment.

2 MOVEMENTS ABOVE A SINGLE TUNNEL

2.1 Vertical movements

It is now well established and accepted that the surface settlement profile above a tunnel in soft soil may be represented by a Gaussian distribution curve of the form shown in Equation (1) (Peck, 1969 and O’Reilly and New, 1982).

\[ W(x) = W_{\text{max}} \exp \left( -\frac{x^2}{2i^2} \right) \]  

where \( W \) is the settlement and \( x \) is the distance from the tunnel centreline in the transverse direction. \( W_{\text{max}} \) is the maximum settlement and is determined given by Equation (2).

\[ W_{\text{max}} = 0.313V_l\sqrt{2\pi D^2} \]  

where \( V_l \) is the volume loss (%), \( D \) is the tunnel diameter and \( i \) is the distance to the inflection point of the curve, which has been defined by O’Reilly and New as \( i = KZ_o \), where \( Z_o \) is the depth of the tunnel and \( K \) is a dimensionless trough width parameter. On the basis of field data O’Reilly and New (1982) suggested a value of \( K = 0.5 \) for London Clay. Extending the assumption to sub-surface regions leads to underestimates of \( i \) with depth. Mair et al. (1993), on the basis of centrifuge and field data, found \( i \) to decrease linearly for sub-surface regions as shown in Equation (3).

\[ i/Z_o = 0.175 + 0.325(1 - Z/Z_o) \]  

Heath and West (1996) and others have proposed methods for predicting \( i \) assuming a non-linear variation for sub-surface regions.

3 MOVEMENTS ABOVE TWIN TUNNELS AND TRIPLE TUNNELS

3.1 Vertical displacements

The simplest method for predicting movements above twin and triple side-by-side tunnels is to assume greenfield profiles above each tunnel found by using Equation (1). The sub-surface settlement profiles are then calculated assuming Gaussian profiles and no volume change with depth (i.e. undrained behaviour). The total settlement profiles for surface and sub-surface levels are found by summing the separate profiles due to each tunnel. An equation for finding the total surface settlement profile above side-by-side twin tunnels was reported by O’Reilly and New (1991).

Cording and Hansmire (1975) reported an increased volume loss for a second tunnel driven which agrees with findings of Cooper and Chapman (1998) who also found increases above a second and third tunnel when considering triple tunnels constructed in London Clay. The authors also reported an apparent increase in trough width for the second tunnel driven on the side nearest the first tunnel driven. Cooper et al. (2002) provided methods of estimating the relative volumes of near and remote limbs of the settlement trough when considering twin tunnels. Mair and Taylor (1997) proposed that the behaviour is caused by the previous straining of soil in the vicinity of Tunnel 2, caused by the construction of Tunnel 1. This behaviour must also apply to triple tunnels when constructed consecutively and in close proximity to each other. The changes in soil stiffness due to this straining will be an important factor in the ground movements that occur.

The effect of pre-failure stiffness has also been highlighted in tunnelling problems when using finite element modelling by Addenbrooke et al. (1997) and Chapman et al. (2002). Chapman et al. (2002) reported increased horizontal and vertical displacements on the side of the first tunnel driven and based on the results of their numerical modelling, Chapman et al. (2003) proposed a new method for estimating the settlement profile above a second tunnel when considering twin side-by-side tunnels. The improvement could be achieved by applying a modification factor to a greenfield profile inside the overlapping zone of bounds to movement (Equation 4).

\[ W_{\text{mod}} = \left( 1 + M \left( 1 - \frac{d' + x}{AKZ^*} \right) \right) W_{\text{max}} \exp \left( -\frac{x^2}{2(KZ^*)^2} \right) \]  

where \( Z^* = (Z_o - Z) \), \( W_{\text{mod}} \) is the modified settlement, \( A \) is the number of trough width parameters in a half trough width (usually taken as 3) and \( d' \) is the spacing of the tunnels, \( K_2 \) is the value of \( K \) for the second tunnel, which can be given separate values for the near limb (\( K_n \)) and for the remote limb (\( K_r \)). The other symbols have their usual meaning. For settlements outside this zone Equation (1) applies. The equation is applicable to surface and sub-surface regions.
4 2D FINITE ELEMENT MODELLING

4.1 Type of analysis and geometry
The use of a 2D analysis was chosen in preference to a full 3D analysis due to the long run times expected and the parametric nature of the study. The analyses were performed with the finite element program, ABAQUS (Hibbit et al, 1997). The excavation of twin 9.0 m diameter tunnels was modelled using the mesh shown in Figure 2. It is important to note that the second tunnel (Tunnel 2) was constructed once the first tunnel (Tunnel 1) was completed and that the third tunnel (Tunnel 3) was only constructed once the second tunnel was completed.

4.2 Material properties
All the analyses were carried out using linear elastic properties for a typical London Clay which varied linearly with depth: 
$$E(Pa) = 1000000 \times (10 + 5.2Z)$$, Z being the depth in (m), leading to $E = 145.2$ MPa at the tunnel axis (Burland and Kalra, 1986). Poissons ratio was taken as 0.499. The undrained strength was assumed to vary linearly with depth according to 
$$Cu (Pa) = 1000 \times (50 + 8Z)$$ (Mott-MacDonald, 1991). The liners were assumed to be 200 mm thick with a unit weight of 24 kN/m$^3$ and Youngs Modulus of $28 \times 10^9$ (Pa).

4.3 Finite element analysis
In the analyses, 8 noded isoparametric elements with reduced integration were used to model the soil and the concrete liners. Shell elements were never used because the program does not allow these elements to be removed or added to the mesh during calculation (Tang et al, 2000). Each node had two degrees of freedom in displacement.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1120</td>
<td>$\alpha$</td>
<td>1.355</td>
</tr>
<tr>
<td>B</td>
<td>1016</td>
<td>$\epsilon_{\text{min-max}}$</td>
<td>0.05–0.15</td>
</tr>
<tr>
<td>C%</td>
<td>$1 \times 10^{-4}$</td>
<td>$\gamma$</td>
<td>0.617</td>
</tr>
</tbody>
</table>

The mesh shown in Figure 2 consisted of 5945 nodes and 2056 elements. The boundary was restrained in the horizontal plane at both sides and in both planes at the base. The boundaries were set at 105 m from the left boundary to the centreline of the nearest tunnel and 105 m from the right boundary to the centreline of the nearest tunnel. A boundary distance of >10D was found have negligible effect on the surface settlement profile (Chapman et al, 2002). The London Clay was modelled as non-linear elastic perfectly plastic employing the model of Jardine et al (1986), pre-yield, a Mohr Coulomb yield surface and plastic potential post-yield. The ‘Jardine et al’ model was input as a user subroutine in ABAQUS. The parameters are shown in Table 1.

The liner was modelled as a linear elastic isotropic material. The volume loss was created by using a modified ‘Gap Parameter’ (Chapman et al, 2002), derived from the gap parameter reported by Rowe et al (1983). For all tunnels in the analyses the volume of the void per metre length of construction was taken as 1.3% of the tunnel-face area.

5 TRIPLE TUNNEL RESULTS

5.1 Sub-surface settlements (Sequence 1)
Figure 3 shows the sub-surface settlement profile 13.0 m above Tunnel 2, a 9.0 m diameter tunnel constructed at a centre-to-centre spacing from Tunnel 1.
Figure 3. Sub-surface displacements above Tunnel 2 at 13.0 m below ground surface (SEQUENCE 1).

Figure 4. Sub-surface displacements above Tunnel 3 at 13.0 m below ground surface (SEQUENCE 1).

Figure 5. Sub-surface displacements above Tunnel 2 at 13.0 m below ground surface (SEQUENCE 2).

Figure 6. Sub-surface displacements above Tunnel 3 at 13.0 m below ground surface (SEQUENCE 2).

of 20.9 m. The settlement profile is compared to the profile which would have occurred if Tunnel 1 was not present (i.e. the ‘greenfield’ profile). The settlement profile has changed significantly from the greenfield profile, the maximum settlement being increased from 18.1 mm to 18.6 mm with its position being drawn towards the centreline of Tunnel 1 (i.e. positioned 5.9 m away from the centreline of Tunnel 2). This agrees with previous numerical work conducted by Chapman et al (2002) and closely resembles the behaviour of real tunnels reported by Cooper and Chapman (1998).

Figure 4 shows the sub-surface settlement profile above Tunnel 3, which is only 15.9 m from Tunnel 1, the maximum settlement is now increased to 19.6 mm (i.e. much larger than that for Tunnel 2) although the eccentricity is now only 5.0 m (less than the further spaced tunnel). Although not shown here the results for Tunnel 3 are almost identical to those that would have been obtained if Tunnel 2 had not been constructed (i.e. a twin tunnel result).

5.2 Sub-surface settlements (Sequence 2)

Figure 5 shows the sub-surface settlement profile 13.0 m above Tunnel 2, a 9.0 m diameter tunnel constructed at a centre-to-centre spacing of 36.8 m from Tunnel 1. When compared to the greenfield profile the maximum settlement has decreased from 18.1 mm to 15.4 mm with its position being located over the centreline of Tunnel 2. Figure 6 shows the sub-surface settlement profile above Tunnel 3, which is situated in between Tunnel 1 and Tunnel 2. The maximum settlement is now 21.0 mm, which shows an increased value from the 19.6 mm found for Sequence 2. Its position is eccentricity placed 2.2 m towards the nearer Tunnel 1. Increases in settlement seem to be occurring on both limbs of the settlement profile with decreases evident at a distance of 20 m on either side.

6 IMPROVING CURRENT PREDICTIVE METHODS FOR TRIPLE TUNNELS

Figure 7 shows the actual settlement data recorded inside the 4.1 m diameter Inner Piccadilly tunnel due to the construction of three underlying tunnels on the Heathrow Express by Cooper and Chapman (1998) [N.B. The geometry is the same as Sequence 2]. The displacement data for Tunnel 2 and Tunnel 3 includes those induced by a pilot tunnel and its subsequent enlargement. The figure shows the displacement data after the construction of Tunnel 1 [N.B. This first
Figure 7. Sub-surface settlement case history data (Inner Piccadilly tunnel) and predictions at the Heathrow Express, U.K.

Table 2. Parameters for curves in Figure 7.

<table>
<thead>
<tr>
<th>Curve</th>
<th>V_f (%)</th>
<th>W_max (mm)</th>
<th>K_n</th>
<th>K_r</th>
<th>M</th>
</tr>
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<tbody>
<tr>
<td>W1, W2, W3</td>
<td>1.2</td>
<td>29.3</td>
<td>0.8</td>
<td>0.8</td>
<td>N/A</td>
</tr>
<tr>
<td>W2a</td>
<td>1.6</td>
<td>34.7</td>
<td>0.8</td>
<td>0.8</td>
<td>0.6</td>
</tr>
<tr>
<td>W2b</td>
<td>1.8</td>
<td>35.0</td>
<td>1.2</td>
<td>0.8</td>
<td>0.6</td>
</tr>
<tr>
<td>W3a</td>
<td>1.7</td>
<td>39.1</td>
<td>0.8</td>
<td>0.8</td>
<td>0.6</td>
</tr>
</tbody>
</table>

The shape of this curve has been matched using a Gaussian curve predicted using the parameters for K and V_f shown in Table 2. The value of 0.8 is larger than the 0.68 estimated using Equation (3), which was reported to be due to the alignment (i.e. 70° skew) of the Inner Piccadilly tunnel to the new tunnels (Cooper and Chapman, 1998). The curve (W1) compares favourably with the case history data. This ‘greenfield’ curve shows little comparison to ‘actual’ data when superimposed over Tunnel 2 (W2) and Tunnel 3 (W3).

Figure 8 shows how the modification method reported by Chapman et al (2004) has been used to modify the curves above Tunnel 2 and Tunnel 3 to give an improved fit to the case history data. The ‘overlapping zones’ for the bounds to movement after the construction of Tunnel 2 and Tunnel 3 are shown in each case. The values used in Equation (4) are shown in Table 2. An M value of 0.6 was used in all cases.

For Tunnel 2 a much better fit to the case history data could be obtained by keeping the maximum settlement (greenfield) constant at 29.3 mm and increasing the value of K_n to 1.2 (i.e. increasing the volume of the near limb). The modification factor was applied to the increased overlapping zone shown by the new bounds to movement (W2b) in Figure 8.

Figure 9 shows the un-modified total settlement profile found by adding greenfield curves above Tunnel 1, Tunnel 2 and Tunnel 3 (i.e. W1 + W2 + W3) and compares this with a modified total settlement profile found from adding the greenfield curve above Tunnel 1 with modified curves for Tunnel 2 and Tunnel 3 (i.e. W1 + W2b + W3a).

7 CONCLUSIONS

This paper has shown how previous straining of soil and the effect of construction sequence for closely spaced multiple tunnel can alter the settlement profile for sub-surface movements when considering the construction of triple tunnels.
Figure 9. Case history total sub-surface settlement profile against predicted for the upline tunnel.

This paper has shown how finite element analyses can be used to assess the importance of construction sequence using the example of triple tunnels constructed on the Heathrow Express at CTA. The results showed that construction Sequence 1 resulted in lower vertical displacements above Tunnel 3, hence it can be concluded that this construction sequence was the correct one for this situation.

Use of the modification factor (Chapman et al, 2004) derived for twin tunnels is found to be applicable to triple tunnels when using Sequence 2 by assuming two separate twin tunnel analyses (i.e. Tunnel 1 with Tunnel 2 and Tunnel 1 with Tunnel 3). Significant improvements to the greenfield predictions were found when using this method, although further investigation is required into the variations in trough width parameter above multiple tunnels.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the Engineering and Physical Sciences Research Council in the UK for their support in the research project.

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