Stacked Tunnelling Induced Settlements in Soft Soil
– A Case Study

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Abstract

The growing demand for public and sustainable transport in heavily urbanized areas like Singapore requires construction of an increasing numbers of Metro Lines. Complicated technical challenges are associated to such an activity while constructing underground infrastructure below existing buildings and structures. This was particularly a significant problem in Contract 933 of Downtown Line 3 which passes between Bendemeer Station and Jalan Besar Station, where many old buildings are situated on shallow foundations in Kallang formation. These buildings are particularly very sensitive to settlements induced by excavation. In such situations, settlement prediction models play a key role in assessing the tunnelling-related risk assessments and planning mitigation techniques. Although a significant amount of research has been performed to study the settlements induced by side-by-side twin tunnels, the settlement prediction of stacked tunneling has been, relatively, very limited.

In this paper, stacked tunnelling induced settlements are predicted using 2D numerical simulation. The extensive data from the instrumentation measurements collected during the construction of tunnels between Bendemeer Station and Jalan Besar Station have been used to compare the settlement troughs and to study the validity of the principle of superposition for stacked tunnels. Actual volume loss in TBM tunnelling is obtained by integrating the observed settlement trough and compared with the design volume loss to understand the influence of operational parameters (like face pressure, grouting pressure etc). Key observations are presented by comparing empirical, numerical and actual field settlement data. Based on the field settlement data and using Monte-Carlo simulation technique, the empirical trough parameter is back calculated to fit the actual settlements observed in Kallang formation. This could be used for future settlement predictions in similar ground conditions.

1. Introduction

Singapore has been expanding the Mass Rapid Transit system in the recent years. The current project in progress is the Downtown Line (DTL) which is the Fifth MRT line in Singapore and on completion it will be Singapore’s longest automated underground line. This will connect the north western and eastern regions of Singapore to the Central Business District and Marina Bay area comprising of 32 stations and 43 Km long. The whole project is being constructed in three stages as shown in Figure 1.

As on date, DTL Stage 1 is completed and is in operation whereas DTL Stage 2 and DTL Stage 3 are still in the construction phase. Downtown Line Stage 3 is divided further into 3 Packages. This paper discusses about the stacked tunnelling induced settlement based on the DTL Stage
3 Package A - Contract Bendemeer Station (C933). Contract C933 has 4 EPB drives from Bendemeer station, 2 drives each on east and west side. Bendemeer station is being built under Kallang Bahru Road and will serve commuters accessing to the commercial and industrial buildings in the area.

The tunnel alignment on the west drive (towards Jalan Besar station) runs under a number of public roads including Jalan Besar, Lavender Street whereas east side has to undercross Kallang River. Due to various site constraints along the alignment a significant section of these tunnels have to be stacked. The ground conditions show both tunnels are in Old Alluvium (OA) strata on west side and Kallang strata on east side (as shown in Figure 3) and Kallang strata consists of isolated pockets of F1 layers. Because of the sensitivity of the ground and adjacent critical structure along the alignment, an extensive instrumentation regime has been implemented. Location of instrumentation arrays installed along the alignment is shown in Figure 4.
2. TBM Face Pressure

TBM face pressures are estimated using the available empirical methods [1] and in these estimations, surcharge due to shop houses were considered. Figure 5 shows the target face pressure and actual pressure along the alignment for Tunnel 1 (BP bound tunnel) and Tunnel 2 (Expo bound tunnel). Since the overburden of the two tunnels are different, normalized face pressure is presented in Figure 6 for comparison of TBM face pressure in both the drives. Table 1 shows the face pressure at different Chainage locations together with the nearest instrumentation array. Based on the settlement observations, estimated volume loss at the end of the drive seemed to be less than the predicted values. Along the OA strata, the volume loss is observed to be about 0.5% and moving further into Kallang higher volume (around 2%) loss was observed.
Table 1 Details of TBM Face Pressure at array locations

<table>
<thead>
<tr>
<th>Ring</th>
<th>Instrumentation Array</th>
<th>Actual Face Pressure [bar]</th>
</tr>
</thead>
<tbody>
<tr>
<td>142</td>
<td>D</td>
<td>3.1</td>
</tr>
<tr>
<td>255</td>
<td>P1</td>
<td>2.65</td>
</tr>
<tr>
<td>438</td>
<td>C1</td>
<td>2.5</td>
</tr>
<tr>
<td>488</td>
<td>C2</td>
<td>2.6</td>
</tr>
<tr>
<td>545</td>
<td>C</td>
<td>4.8</td>
</tr>
<tr>
<td>635</td>
<td>B</td>
<td>4.7</td>
</tr>
<tr>
<td>115</td>
<td>D</td>
<td>2.4</td>
</tr>
<tr>
<td>215</td>
<td>P1</td>
<td>1.9</td>
</tr>
<tr>
<td>398</td>
<td>C1</td>
<td>1.7</td>
</tr>
<tr>
<td>448</td>
<td>C2</td>
<td>2.5</td>
</tr>
<tr>
<td>505</td>
<td>C</td>
<td>3.1</td>
</tr>
<tr>
<td>611</td>
<td>B</td>
<td>3.1</td>
</tr>
</tbody>
</table>

3. Evaluation of Settlements

3.1. Empirical Methods

With the recent advancement in numerical modelling capability, finite element modelling has become very popular tool in prediction of tunnelling induced ground settlement. However, the use of numerical modelling always required understanding of constitutive material models selection to represent soil behaviour. Thus, there has always been an emphasis on simple but reliable method for estimation of tunnelling induced settlements. The empirical formulation commonly utilised in engineering practice is developed by Peck [2] and Schmidt [3]. Peck [2][4] assumed that the transverse ground settlement trough can be reasonably represented by a Gaussian (or Normal) distribution curve as shown in Figure 7.
From the Gaussian distribution curve, the empirical equation for settlement is given below

\[ S = S_{\text{max}} e^{-\frac{x^2}{2i^2}} \]

where \( S \) is the ground surface settlement at a distance ‘\( x \)’ from the tunnel centre, \( S_{\text{max}} \) is the maximum ground settlement at the vertical tunnel axis. Trough width parameter \( i \), is the distance from the tunnel center line to the point of inflexion of the trough. Mair [5] suggested that the total half width of the settlement trough is about 2.5i.

As an improvement to Peck’s empirical method, Oteo [6] proposed a modified Peck’s error curve to consider some additional tunnel and ground parameters like young’s modulus and poison’s ratio. Romo-Diaz (1980) proposed an empirical formula derived from finite element analysis which considers additional parameters like horizontal stress, face pressure acting at the excavation face and the average value of strain at the failure [7].

### 3.2. Analytical Methods

Sagaseta [8] proposed a closed form solution obtained by combining fluid flow with elastic solution for half space. This method allows the strain field evaluation in an initially isotropic and homogeneous incompressible soil. Later, Verruijt et al [9] presented an analytical solution using generalisation of the Sagaseta’s solution. This method allows for the computation surface vertical displacements as well as vertical displacements at different depths below ground level and horizontal displacements along a cross-section to the exaction direction.

Loganathan and Poulos [10] presented a modified form of Verruijt et al. [9] by suggesting the use of a modified equivalent ground loss parameter. The surface settlement and lateral displacement can be obtained as
Lateral displacement \( u_{x,z=0} \) = \(-\frac{4gR + g^2}{2} e^{\left(-\frac{1.33g^2x^2}{(H+R)^2}\right)} \frac{x}{x^2 + H^2}\)

Surface settlement \( u_{z=0} \) = \(\frac{4gR + g^2}{2} e^{\left(-\frac{1.33g^2x^2}{(H+R)^2}\right)} \frac{H}{x^2 + H^2}\)

where, g is the gap parameter, H is the depth of tunnel from ground surface, R is the radius of the tunnel, z is the depth measure from ground surface and x is the lateral distance from the tunnel centre line.

3.3. Numerical Methods

Tunnelling process is a three dimensional problem which involves stress change and deformation in all the three directions. However for the simplified modelling, it is reasonable to assume a plane strain or two dimensional model for long tunnel section in studying tunnelling induced settlements. In order to simulate tunnel excavation in 2D FE analysis, the effect of the missing third dimension has in some way to be included. Figure 9 shows the 3D arch around the unsupported tunnel heading by displaying rotated principal stress directions. This arch is able to carry the vertical ground loads by transferring them around the unsupported cut stretch.

Figure 9 3D arch support and 2D FE approximation with support pressure

When using 2D numerical analysis to simulate tunnel excavation consideration must be given to the ground in front of the shield machine, which will move both radially and axially towards the tunnel face. To simulate shield tunnelling 2D FE analysis are frequently used and different methods are used to simulate the ground loss and settlement [11]. Table 2 lists the different methods possible for simulating the TBM installation in 2D model. Detailed explanation of all the methods are beyond the scope of this paper. In this study, grout pressure method is found suitable for estimating the settlement troughs based on TBM face pressure and is adopted for our analysis.

Table 2 2D FEM simulations methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Scheme</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gap Method</td>
<td><img src="image" alt="Gap Method" /></td>
<td>Rowe et al (1983)</td>
</tr>
<tr>
<td>Stress Reduction</td>
<td><img src="image" alt="Stress Reduction" /></td>
<td>Addenbrooke et al (1997)</td>
</tr>
</tbody>
</table>
Mohr-Coulomb’s failure criterion is used to model the behaviour of soils involved in the analysis. The soil parameters used for this study are based on the C933 contract GIBR. The soil parameters used in the PLAXIS analysis are tabulated in Table 3.

Table 3 Soil parameters used in this study

<table>
<thead>
<tr>
<th>Soil layer</th>
<th>Unit weight [kN/m³]</th>
<th>Young’s modulus, E [MPa]</th>
<th>Cohesion c’ [kPa]</th>
<th>Angle of friction phi’ [degree]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fill</td>
<td>19</td>
<td>8</td>
<td>0</td>
<td>30</td>
</tr>
<tr>
<td>Kallang – Marine (Lower)</td>
<td>16.5</td>
<td>7.5</td>
<td>0</td>
<td>22</td>
</tr>
<tr>
<td>Kallang – Marine (Upper)</td>
<td>16.5</td>
<td>16.5</td>
<td>0</td>
<td>22</td>
</tr>
<tr>
<td>Kallang – Fluvial (Lower)</td>
<td>19</td>
<td>9.2</td>
<td>0</td>
<td>24</td>
</tr>
<tr>
<td>Kallang – Fluvial (Upper)</td>
<td>19</td>
<td>16.5</td>
<td>0</td>
<td>24</td>
</tr>
<tr>
<td>Old Alluvium</td>
<td>20</td>
<td>150</td>
<td>10</td>
<td>32</td>
</tr>
</tbody>
</table>

In order to back assess the actual volume loss during the tunnel drive, the numerical analysis is carried out with the corresponding face pressure. Ground water is considered at ground level. After obtaining the initial stresses, all the nodal displacements were then reset to zero prior to the exaction of tunnels. The analysis for this study typically involved the following stages. Stage 1 involved initialization of the stresses. Stage 2 involved the excavation of the first tunnel and subsequent installation of its lining elements. The tunnel lining is simulated as a flexible impermeable membrane (with low flexural and axial stiffness). The impermeable membrane ensures to prevent any dissipation of applied face pressure. The pore-water pressure inside the tunnel is modified to simulate the TBM face pressure (based on actual face pressure used for the TBM driving at that particular chainage). Stage 3 involved the excavation of the second tunnel and installation of its lining parameters. The pore-pressure is similarly set to simulate the TBM operating face pressure. The settlement trough at the end of stage 2 and stage 3 is extracted from the Plaxis output. This settlement trough integrated to obtain the equivalent volume loss caused by Tunnel 1 and combined volume loss caused by Tunnel 1 + Tunnel 2.

3.4. Actual Settlement (Field Measurement)

A total of six monitoring arrays were installed at ground surface along the stretch under discussion. Each array consists of 11 to 16 numbers of settlements markers to monitor the transverse ground settlement during and after the excavation of stacked tunnels. The details of these settlement markers is shown in Figure 10. Table 4 presents the details of the instrumentation arrays used for the settlement back analysis along with the relevant dates during when the TBM crossed these arrays.
The development of transverse ground surface settlement troughs of each array during the tunnelling is shown in Figure 11. The maximum ground surface settlement observed from this study ranged between 5mm to 15mm. Comparison of above estimates are performed at the six array location along the stretch under study. The corresponding ground information and tunnel alignment data are represented in the Figure 10.

Table 4 Instrumentation array details

<table>
<thead>
<tr>
<th>Chainage (approx.)</th>
<th>Array Name</th>
<th>Nos. of Settlement Markers</th>
<th>Date when TBM1 crossed the Array</th>
<th>Date when TBM2 crossed the Array</th>
</tr>
</thead>
<tbody>
<tr>
<td>32+050</td>
<td>D</td>
<td>11</td>
<td>21/11/2013</td>
<td>06/01/2014</td>
</tr>
<tr>
<td>32+200</td>
<td>P1</td>
<td>11</td>
<td>13/01/2014</td>
<td>16/02/2014</td>
</tr>
<tr>
<td>32+450</td>
<td>C1</td>
<td>11</td>
<td>03/03/2014</td>
<td>15/03/2014</td>
</tr>
<tr>
<td>32+600</td>
<td>C</td>
<td>16</td>
<td>27/04/2014</td>
<td>03/05/2014</td>
</tr>
<tr>
<td>32+750</td>
<td>B</td>
<td>16</td>
<td>11/05/2014</td>
<td>25/05/2014</td>
</tr>
</tbody>
</table>

Table 5 Comparison of actual and design Volume Loss

<table>
<thead>
<tr>
<th>Array</th>
<th>Design Volume Loss [%]</th>
<th>Expected Volume loss for the applied face pressure [%]</th>
<th>Actual Volume Loss (back calculated based on actual trough) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Numerical</td>
<td>Observed</td>
</tr>
<tr>
<td>P1</td>
<td>1</td>
<td>0.75</td>
<td>0.17</td>
</tr>
<tr>
<td>C1</td>
<td>1</td>
<td>0.88</td>
<td>0.12</td>
</tr>
<tr>
<td>C</td>
<td>3</td>
<td>1.4</td>
<td>1.24</td>
</tr>
<tr>
<td>D</td>
<td>1</td>
<td>0.6</td>
<td>0.1</td>
</tr>
<tr>
<td>B</td>
<td>3</td>
<td>1.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Figure 10 Ground Information and array arrangement
Figure 11 shows settlement prediction based on two methods (analytical, numerical) and also shows the actual field settlement data. Analytical estimate of settlement pattern is shown in solid line (blue and red, blue line indicates the settlement due to T1 alone whereas red line indicates the combined settlement due to T1 and T2). Dotted line represents the settlement trough from numerical simulation. Table 5 presents the comparison of design volume loss, expected volume loss and actual volume loss. Expected volume loss is calculated by integrating the settlement trough obtained from the numerical analysis.

Among the five array sections studied, three sections (Array C, C1 and P1) are the sections in which the tunnels are stacked almost one over the other. Surface settlements at these sections over a period of six months are studied and presented in Figure 12. Settlement vs time plot for the tunnels passing through old alluvium soil (array P1 and C1) do not indicate any particular pattern. However, the settlement vs time plot in marine clay (array C) clearly indicates that most of the ground movement occurs immediately after the mining of first tunnel. Longitudinal ground settlement profile in marine clay is represented using scattered plot in Figure 13. From the (polynomial) trend line, it can be clearly noted that the ground settlement...
starts much ahead of the TBM excavation face and the settlement continues even after the TBM has passed the monitored section.

4. Results and Discussion

4.1. Stacked Tunnel Settlements

The results presented in Figure 11 indicate the surface settlement trough using numerical analysis and Peck’s formulation. In general, the trend of the settlement trough is similar in all the scenarios. Most of the ground movement seems to occur during the excavation of the first tunnel and the total volume loss is observed to be less than the summation of the volume loss of two tunnels separately. Peck’s empirical estimation (for the given trough parameter), which
are based on the Gaussian form, seemed to overestimate the settlements. Numerical analysis for the exact TBM face pressure predicted closer settlement pattern.

The width of the settlement trough is more appropriately predicted by the numerical analysis because the exact face pressure is used to predict the settlement pattern. It is to be noted that Rowe and Kack [12] have reported that the numerical analysis overestimates the width of the settlement trough if the settlement trough is calculated based on the contraction parameter in Plaxis software. It is demonstrated in this study that the use of actual face pressure in estimating the deformations results in realistic settlement trough.

4.2. Applicability of Peck’s empirical formula

This study examines the validity of the principle of superposition and appropriateness of the trough parameter k prescribed in LTA CDC guidelines for the encountered soil in this project. Although the Pecks equation is more superior in estimating the transverse ground surface settlements induced by tunnelling than the cumbersome FE analysis [13], the choice of trough parameters plays a key role in estimating the settlement pattern which is closer to reality. In the present analysis, the trough parameter is set as per LTA CDC guidelines and is observed that the assumed trough parameter (k) does not represent the realistic settlement trough. Available field data is used to curve fit and back calculate the appropriate parameter for the Kallang formation and presented in Table 6. In order to achieve a good Gaussian curve fit, Monte Carlo simulation with a large number of fictitious k values are performed to determine Root mean square error for each of the fictitious k values. The median value of k with the least error is chosen as the appropriate trough parameter for the selected soil type.

<table>
<thead>
<tr>
<th>Soil layer</th>
<th>Trough parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kallang Formation</td>
<td>0.7 - 0.8</td>
</tr>
</tbody>
</table>

4.3. Excavation parameters influencing surface settlements

The role of TBM operating pressure and grouting pressure in the volume loss has been reported in recent projects [14], [15], [16], [17]. In this study an attempt was made to explore relationship between volume loss and to face pressure (based on available monitoring data). The correlation data is presented in Figure 14. The data is mostly dispersed however it signifies the role of face pressure and grouting pressure in mitigating settlements and hence reducing volume loss.

![Figure 14 Observed trend between operating pressures and volume loss](image)
5. Conclusions

This paper focused on the settlements of stacked tunnels of C933 Contract in Downtown Line 3 in Singapore MRT System, constructed using EPB machine. A series of ground settlement analyses have been carried out for a stacked tunnel using empirical equation (that assumed principle of super imposition) as well as numerical simulation and were compared with the actual field settlement data. Key observations are presented based on this comparison. It is demonstrated in this study that the use of TBM face pressure in the numerical simulation of settlement troughs (i.e using “grout pressure” method instead of “contraction” method) results in realistic settlement prediction. Further, based on the field settlement data and using Monte-Carlo simulation technique, the empirical trough parameter is back calculated to fit the actual settlements observed in Kallang formation. This could be used for future settlement predictions in similar ground conditions.

References: