Twin tunnels and asymmetrical settlement troughs in soft soils.

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ABSTRACT: Numerous designs in twin tunnel projects assume the superposition of two Gaussian settlement curves as a method to evaluate the overall settlement induced by their excavation. In this paper we verify a quick method for settlement trough fitting and volume loss estimation for the second tunnel of a twin tunnel project, based on Peck’s formulation and using the data obtained in the first completed stretch of the Chennai Metro Rail Project. The analysis of the settlements developed in this project shows that not only the second tunnel volume loss is greater than first tunnel but also a wider and asymmetrical settlement trough associated exclusively to the second tunnel is produced. To examine this asymmetry, Gaussian curves are fitted separately to the left and right-hand sides of the settlement trough data. This allow us to better fit the actual data and avoid the shortcomings of the superposition of symmetrical Gaussian curves method in settlement evaluation.

1 INTRODUCTION
Irrespective of the method used, tunnel construction causes ground movements which have the potential to cause damage to existing structures. Current tunneling practice aims to reduce these movements to a minimum but, according to Divall (2013), there is still “a need for an improvement to the current understanding of twin bored tunnel settlements”.

The aim of this paper is to evaluate the actual settlements measured in the first finished section of the Chennai Metro Rail Project (CMRP) in Chennai, India.

The actual settlement fit provides a good tool to make accurate predictions about settlements in further sections to be excavated in this project. Beside this, this study is available for further designs and projects in similar geotechnical conditions.

2 PROJECT DESCRIPTION
The stretch under assessment is the first completed section of the twin tunnels excavated between the Washermanpet Station and Mannadi Station of the CMRP. This section belongs to the UAA-01 contract of this project, located in the northeast area of the city. It covers a length of approximately 1355 m.
increasing to a maximum of about 16.5 m in around chainage 1+000, then decreasing again as Mannadi station is approached, to a minimum value of about 11.3 m. As the excavation diameter is 6.63 m, it gives an overburden height to diameter ratio between 1.7 and 2.5.

2.1 Geological conditions

The whole part of TBM tunnel from Washermanpet station to Mannadi station is bored through mostly an alluvial formation represented by dense silty sand (SM) interbedded with layers of silt, clay and clayey sand. Underlying quaternary soil deposits, Charnockite rock is encountered at about 20-30 m below ground level. It is highly weathered in the upper part, with soil-like behavior. Assuming that the top of the bedrock is where weathering grade is IV or better, depth of the bedrock is around 25 to 35 m below ground level. Thus, no bedrock is encountered during TBM excavation.

A simplified geological sequence is illustrated in the Figure 2.

![Figure 2. Simplified ground profile.](image-url)

The water table varies from 2.9 to 6.2 m below the ground surface. The average permeability values of soil materials indicate that tunnel excavation occurs across low to very low permeable materials.

The geotechnical parameters of the different geological units along the alignment are reported on the Table 1.

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Elevation (mRL)</th>
<th>SPT “N”</th>
<th>c’ (kPa)</th>
<th>ϕ’ (º)</th>
<th>E’ (MPa)</th>
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<td>2.4</td>
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<td>15.6</td>
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<tr>
<td>SM below -13</td>
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<td>37</td>
<td>42.0</td>
<td></td>
</tr>
</tbody>
</table>

2.2 Tunnel excavation method

The running twin tunnels are bored with two identical Earth Pressure Balanced Tunnel Boring Machines in closed face mode.

Excavation diameter is 6.63 m and the final internal diameter of the tunnels is 5.8 m, with a segmental lining 275 mm thick.

The center-to-center spacing for the tunnels has a constant value of 14.05 m along all the section.

The tunnels are bored one after another. As shown in the Figure 3, within the major part of the section the excavation of the second tunnel is performed about 3 or 4 months after the first tunnel excavation.

![Figure 3. Time span between tunnels excavation.](image-url)

2.3 Settlement measurements

Precise leveling studs are installed on streets and paved areas in array perpendicular to tunnel
axis alignment when possible. These arrays extend to the outer edges of the 5 millimeters predicted settlement contour lines, up to about 25 m on both sides of the tunnels centreline.

Within the section under assessment in this paper, a total number of 27 leveling arrays are installed and measured. Each array has a minimum of 4 and a maximum of 14 leveling studs, with an average number of 9 studs per array. The schematic layout of the surface settlement markers in the arrays is shown in the Figure 4. The scheme of the settlement stud is shown in the Figure 5.

![Figure 4](image)

Figure 4. Surface marker schematic arrays for a 5 leveling stud array (top) and 13 leveling stud array (bottom). (CMRP, 2012)

![Figure 5](image)

Figure 5. Surface marker for ground settlement measurements. (CMRP, 2012)

The results obtained in the first leveling array, located at a minimum distance of 4.23 m from the launching station box diaphragm wall, are not taken into account because of the possible soil disturbance generated during the station excavation.

Because of the same reason, the two last leveling arrays neither can be considered. These are located 8.3 m and 1.9 m before the TBM reception box diaphragm wall.

Settlement measurements of a total number of 211 leveling studs, distributed in 24 transversal arrays constitute the database taken into account in this paper. Average distance between consecutive arrays is about 50 m.

Additional monitoring instrumentation is placed in the ground along the tunnel alignment, such as rod extensometers and piezometers. Building and other structures inside the influence area are monitored by leveling control through building settlement markers, tiltmeters and crackmeters. In some critical buildings horizontal displacements are also surveyed through optical targets and topographical measurements.

3 SETTLEMENT TROUGH PREDICTION METHODS

In this chapter we summarize the empirical equations for predicting movements above single tunnels in soft soil and how these equations are adapted in order to incorporate the ground movements measured above twin tunnels.

These equations will be the base for our further comparison with actual data obtained in CMRP and also other data coming from the literature.

3.1 Single tunnel induced ground movements.

Proposed by Peck (1969) and verified by many site measurements and centrifuge tests (Divall, 2013), the ground settlement profile induced by a single tunnel excavation in soft ground may be represented by a Gaussian distribution curve of the form shown in the Equation 1.

\[
S_v = S_{\text{max}} \exp \left( -\frac{x^2}{2i^2} \right),
\]

where \( S_{\text{max}} \) is the maximum settlement at the tunnel center line, \( x \) is the lateral distance from the tunnel center line and \( i \) is the lateral distance.

from the tunnel center line to the point of inflection in the Gaussian distribution curve.

3.2 Superposition method.
When predicting the combined effect of twin tunnel construction, the simplest assumption is to consider for the second tunnel the same settlement distribution as considered for the first tunnel. If a Gaussian distribution positioned over its center-line is assumed for the first tunnel, the superposition method considers the total settlement profile as the sum of two Gaussian distributions due to each tunnel, and each centered in its center-line. O’Reilly & New (1982) suggested the Equation 2 to estimate the combined settlement profile:

\[ S_v = S_{max} \left[ \exp \left( -\frac{x_A^2}{2t^2} \right) + \exp \left( \frac{(x_A - d)^2}{2t^2} \right) \right], \] (2)

where \( d \) is the lateral distance between the two tunnels centre-lines, \( x_A \) is the lateral distance from the center line of the first bored tunnel.

This expression assumes that the tunnels are parallel, have the same diameter and ignores any interaction between the tunnels, that is, the second tunnel is unaffected by the excavation of the first tunnel, and both have the same volume loss and the same settlement trough width.

According to Chapman et al. (2004), many authors have reported that this method is inaccurate for predicting settlements when there is some time delay between the excavation of each tunnel. This is also noticed from the CMRP measurements discussed in the chapter 4.

The second tunnel settlement trough shows in many cases an eccentric and larger maximum settlement.

3.3 Addenbrooke & Potts method
After a numerical study, Addenbrooke and Potts (2001) proposed a method for adjusting the predicted settlement profile related to the second tunnel excavation.

This method consists in finding the eccentricity of the maximum settlement and the increasing in volume loss of the second tunnel settlement profile. These two parameters are dependent on the pillar width, i.e. the center-to-center spacing of the tunnels minus the sum of their radii. The Figure 6 shows the design charts to find these parameters.

Then the total settlement induced by the excavation of both tunnels can be computed as the sum of the first tunnel settlement and the modified second tunnel settlement.

Even if this method takes into account the eccentricity of the maximum settlement point location for the second tunnel settlement trough, it still does not take into proper account the asymmetry of the second settlement distribution curve, as we will see in the next method and in the data from the CMRP as well.

![Figure 6. Design charts to find the increase in volume loss of the second tunnel's settlement profile (left) and an eccentricity of the maximum settlement (right) (After Addenbrooke & Potts, 2001).](image)

3.4 Modification Method by Hunt (2005)
Some authors showed that the magnitude of the maximum settlement above the second tunnel \( S_{max} \) is increased and eccentrically positioned towards the first tunnel.

Hunt (2005) proposed a modification factor to the semi-empirical tunneling-induced ground movements caused by a second tunnel. This method was developed after numerical analyses for tunnels excavated in London Clay.

This method takes into account an overlapping zone, shown in Figure 7, where it is assumed that the soil has been disturbed by the excavation of the first tunnel. The ground movements of the second tunnel are modified within this disturbed area.
The modified settlement related to the second tunnel excavation is computed according the following equations.

$$S_{mod} = F \cdot S_v,$$

where $S_{mod}$ is the modified settlement, $S_v$ is the unmodified settlement above the second tunnel computed by semi-empirical methods, and

$$F = \left\{1 + \left[ M \left(1 - \frac{d + x_d}{AK_sZ^*}\right)\right]\right\},$$

where $Z^*$ is the vertical distance from the tunnel center to the point where the settlement is computed ($Z_0+Z$), $A$ is the multiple of the trough width parameter (usually taken as 2.5 or 3.0) in a half settlement trough, $d$ is the center-to-center spacing of the tunnels, $K_s$ is the value of $K$ in the region of the first tunnel bored and $M$ is a maximum modification factor. This modification factor takes the maximum value $M=1$ in the center-line of the first tunnel, and reduces to zero at some lateral distance from the first tunnel.

![Diagram](image)

Figure 7. The modification factor for the settlement above the second tunnel (after Hunt, 2005).

3.5 Changes in $K$ parameter

As suggested and developed by some authors (Chapman et al. 2004) the estimation of the relative increases in the trough width for the second tunnel in a twin tunnel project can be based on an increase of the volume of the near limb relative to the remote limb of the second tunnel trough.

Given a maximum settlement value for the first tunnel $S_{max1}$ and a single $i$ value ($i_1$ in the Figure 8), settlement trough of the first tunnel can be computed by the equation 1 as usual. Regarding the second tunnel, given a maximum settlement $S_{max2}$, the settlement trough can be computed taking into account an $i$ value for the near limb ($i_{n2}$) in a half trough, greater than the $i$ value for the remote limb ($i_{r2}$) in the other half trough. This reverts in a different $K$ parameter for the second tunnel, i.e. $K_{n2}$ for the near limb of the half trough and $K_{r2}$ for the remote limb of the other half trough of the second tunnel.

![Diagram](image)

Figure 8. Increment of the near limb volume of the second tunnel settlement trough.

The volume loss of the second tunnel profile $V_2$ is therefore computed with the Equation 5.

$$V_2 = \sqrt{2\pi} \left(\frac{i_{n2} + i_{r2}}{2}\right),$$

$$\pi \cdot \left(\frac{D}{2}\right)^2,$$

where $i_{n2}$ is the lateral distance from the second tunnel center line to the point of inflection of the
limb near the first tunnel in the Gaussian distribution curve, \( i_{r2} \) is the lateral distance from the second tunnel center line to the point of inflection of the limb away from the first tunnel in the Gaussian distribution curve, and \( D \) is the tunnel diameter. The total profile is the sum of both settlement troughs.

This method does not take into account the possible eccentric position of the maximum settlement \( S_{max2} \) respect the center line of the second tunnel.

4 ACTUAL SETTLEMENT MEASUREMENTS

After the completion of the first section in the CMRP for both tunnels, a complete settlement analysis can be developed.

The charts in the Figure 9 show three representative ground settlement arrays measured in this section.

The settlement measurements taken after the first tunnel completion are shown in green round markers. The settlement measurements after the completion of the second tunnel are shown in red triangular markers. The blue square markers show the difference between the settlement measurements after the first tunnel excavation and after both tunnels excavation. It is assumed that this value is the settlement induced by the excavation of the second tunnel only.

The first tunnel settlement trough is matching with a Gaussian distribution curve aligned with the first tunnel center line. This Gaussian curve is represented by a green continuous line.

The settlements induced by the second tunnel excavation (blue square markers) are much larger than the settlements measured for the first one. Also the best fit of the settlement trough is not a symmetric Gaussian curve. We try to fit a modified settlement trough according the modification method proposed by Hunt (2005) and discussed above. With this method we get a slightly asymmetrical curve and an eccentricity for the maximum settlement on the second tunnel curve.

The central part and the limb away from tunnel 1 (what we call the remote limb of the curve) fit quite well with the actual data. However, the limb of the curve towards the tunnel 1 (what we call the near limb of the curve) is not fitting well with the actual data.

Figure 9. Settlements measured in three settlement arrays of the CMRP, and fitting curves applied.
Accordingly, the total settlement curve, computed as the sum of the Gaussian curve for the tunnel 1 and the modified curve for the tunnel 2, does not fit properly to the actual final settlements as well.

After this tentative we realized that a better fitting of the second tunnel-induced settlement trough can be achieved with the above discussed $K$ parameter modification method.

Therefore, we fit separately half a Gaussian to the left-hand side of the settlement trough data and to the right-hand side of the settlement trough data.

Thus, for the tunnel 1 settlement trough fit, as shown in the Figure 9, Equation 1 is used. For the tunnel 2 settlement trough fit, a different value of the $K$ parameter is tested to better fit each of the half sides of the Gaussian curve.

Regarding the eccentricity of the second settlement trough, in some settlement array can be inferred certain deviation of the maximum settlement point respect to the tunnel center alignment, as in the arrays in chainage 929 and 977, shown in the Figure 9. Due to the ground settlement markers location, this eccentricity cannot be accurately determined.

This approach has been done in all the ground marker arrays located in the captioned section. The main results obtained are shown in the Table 2.

### Table 2. Twin tunnel details in the section Washermanpet-Mannadi of the CMRP.

<table>
<thead>
<tr>
<th>Chainage (m)</th>
<th>Z (m)</th>
<th>$S_{\text{max1}}$ (mm)</th>
<th>$V_1$ (%)</th>
<th>$K_{n1}$ (-)</th>
<th>$K_{r1}$ (-)</th>
<th>$S_{\text{max2}}$ (mm)</th>
<th>$V_2$ (%)</th>
<th>$K_{n2}$ (-)</th>
<th>$K_{r2}$ (-)</th>
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<tr>
<td>247</td>
<td>14.6</td>
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<td>0.76</td>
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<td>0.28</td>
<td>0.28</td>
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</tr>
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<td>0.37</td>
<td>0.37</td>
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<td>1.55</td>
<td>0.54</td>
<td>0.34</td>
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<td>0.70</td>
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<td>0.40</td>
<td>-32</td>
<td>1.68</td>
<td>0.63</td>
<td>0.33</td>
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<td>-19</td>
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<td>0.53</td>
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<td>-38</td>
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<td>0.56</td>
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<td>1.32</td>
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<td>-31</td>
<td>1.71</td>
<td>0.67</td>
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</table>

Within the first completed section of the CMRP, the maximum settlement above the second tunnel is about 55% larger than the maximum measured above the first one.

Regarding the asymmetry of the settlement trough induced by the excavation of the second tunnel, it has been inferred a $K$ parameter in the near-to-first-tunnel limb ($K_{n2}$) about 81% larger than the $K$ parameter in the limb away from the first tunnel ($K_{r2}$).

As per volume loss, the average values computed after the excavation of the second tunnel ($V_2$) is about 61% larger than the computed after the first tunnel excavation ($V_1$).

The average parameters obtained in the first section of the CMRP can be incorporated in former available data from other similar
projects. Taken from the work of Chapman (2004), we show in the Table 3 a summary of the results from Lafayette Park in USA, St James Park and The Heathrow Express in the UK, in addition to the data obtained in the CMRP.

Table 3. Twin tunnel details in the CMRP and other similar projects (After Chapman et al, 2004)

<table>
<thead>
<tr>
<th>Location</th>
<th>Lafayette Park</th>
<th>St. James Park</th>
<th>Heathrow Express</th>
<th>Chennai (average)</th>
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<td>6.4</td>
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<tr>
<td>Z(m)</td>
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<td>14.6</td>
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<td>20.5</td>
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<tr>
<td>d(m)</td>
<td>-</td>
<td>-</td>
<td>-22.5</td>
<td>-</td>
</tr>
<tr>
<td>V(%)</td>
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<td>3.63</td>
<td>2</td>
<td>2.7</td>
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<tr>
<td>S_{max}(mm)</td>
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<td>69.6</td>
<td>18.48</td>
<td>22.6</td>
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<tr>
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<tr>
<td>Kr(-)</td>
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<td>0.35</td>
<td>0.4</td>
<td>0.4</td>
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</table>

Based on these results, some graphics are represented with a tentative correlation the parameters related to twin tunnel settlement trough.

Figure 10. Asymmetry of the settlement trough and distance between tunnels.

Nonetheless, the intuitive relation between the asymmetry of the second tunnel trough and the relation between tunnel depth and distance, which should be a good indicator of the amount of overlapping disturbed zone, does not show a clear correlation with the available data, as shown in the Figure 11.

5 CONCLUSION

At all the monitoring sections along the second tunnel record appears to have a larger settlement and volume loss than the generated by the first one. Beside this, it is shown an evident asymmetry of the settlement trough induced by the second tunnel excavation.

A rather quick and good qualitative fit of a settlement curve to the actual measurements is achieved by splitting the Gaussian curve into two halves and modifying the $K$ parameter values on each half of the curve. Therefore the Gaussian curve fitting the second tunnel settlements is defined by three parameters, that is the maximum settlement induced by the tunnel 2 excavation $S_{max2}$, the $K$ parameter for the half trough near the first tunnel $K_{n2}$, and the $K$ parameter for the remote limb of the half trough $K_{r2}$, away from the first tunnel.

The analysis of the settlement troughs carried out after the excavation of the first section of the Chennai Metro Rail Project provides a useful tool to review the expected settlements in the further sections to be excavated in similar geotechnical conditions. This can be extended to other tunneling works and can be taken into account for further multiple tunnel designs and projects.
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