Consolidation settlements caused by a shield tunnel for the Taipei Mass Rapid Transit System

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Abstract This paper describes the use of elasto-plastic finite element modelling to predict the ground surface settlements due to a shield driven tunnel. Settlement readings of a case study are used to be compared with the numerical results. The predictions are mainly concerned with the consolidation settlement. The modified Cam-clay model, coupled with pore water pressure estimated using Biot’s equation, is adopted to analysis the consolidation behaviour. Comparisons are presented between measured and predicted behaviour. Generally it appears that the prediction of consolidation settlement, is in acceptable agreement with the actual value.

INTRODUCTION

It is a basic requirement of tunnelling in the downtown of the city that the construction should not cause damages to any surrounding or overlying structure. In order to satisfy this requirement, the method of shield tunnelling is adopted in the construction of the Taipei Mass Rapid Transit System. In general, the ground settlement due to the construction of the shield tunnel can be divided into two stages:

(a) Ground (or immediate) loss: The immediate settlement occurs as the tunnelling face is advanced under the settlement point, and the transverse array has the form of an error function curve (Peck, 1969; Schmidt, 1974; Chen, 1993). The ground loss takes place in a short time. In general, the closure of tail void is the main cause of the immediate settlement.

(b) Consolidation settlements: The consolidated settlements are often associated with the removal of compressed air from a tunnel. The soil at the top of the tunnel face is compressed during the removal of compressed air from a tunnel and excess pore pressure is generated. The dissipation of the excess pore pressure leads to the consolidation settlements. The completed time of the consolidation depends on the permeability constant of the soil stratum.

Peck’s approach is usually followed to evaluate the ground settlement. In consideration of the geological condition for the Taipei basin, Chen (1993) presents an another approach to assess the ground loss. However, both do not reflect the consolidation settlement which can usually take a long time.

Many causes may induce the pore pressure. The immediate gap of a tunnel lining within the tailpiece of protective shield is the vital factor to result in the excess pore pressure generated and it is of major concern in this paper. A modified Cam-clay model
coupled with pore water pressure, estimated using Biot's equation (Biot, 1941), is adopted to analyse the deformation and consolidation behaviour due to the shield tunnelling. Numerical predictions of consolidation settlement are compared with the measured behaviour. Also, the possible reasons are given for the differences found.

DATA

Gap parameter

In accordance with foregoing studies (Peck, 1969; Schmidt, 1974; Chen et al., 1993), the ground surface subsidence is strongly related to the buried depth, the diameter of the shield tunnel and the gap parameter (Rowe & Lo, 1983; Rowe & Kack, 1983). With the advance of the tunnelling machine, soil in front of the heading will move both radially and axially towards the face. In the shield driven tunnel, the installation of a new lining within the protective tail results in the conditions shown in (Fig. 1(a)). The annular void is equal to the difference between the diameter of the excavated surface and the lining. As the shield driven advances, the weight of lining will cause it to rest on the excavated surface as shown in (Fig. 1(b)). If the invert of the tunnel lining rests on the underlying soil then the gap parameter $g$ is the vertical distance between the crown of the tunnel lining and the crown of the excavated surface prior to removal of the tunnel traction. It is also equal to the difference between the diameter of excavated surface ($D_m$) and the tunnel lining ($D_l$), (Rowe et al., 1983), the so-called gap parameter: $g = D_m - D_l$.

Construction effects can be approximately incorporated in terms of the gap parameter. For instance, the effect of the grouting may be expected to decrease settlements. It is equivalent to the decrease of the gap parameter which would be employed in the finite element analysis.

![Fig. 1 Definition of gap parameter (Rowe, 1983).](image)

Geotechnical data

The geotechnical characteristics of soils in Taipei basin have been studied for more than 25 years. A comprehensive collection of geotechnical data has been conducted by MAA in 1987 and the results of study have been published (Huang et al., 1987; Cheng, 1987, 1988). In general, the Taipei basin is a tectonic basin covered with more than 200 m of Quaternary sedimentary deposits overlying the Tertiary bedrock. The Quaternary deposits can be classified into three major formations in which the Sungshan Formation is generally located at the town centre of Taipei City. Hung (1966) proposed that Sungshan Formation can be subdivided into six layers. The thickness of each sub layer
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Table 1 Geotechnical properties of the Taipei basin.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness (m)</th>
<th>$E$ (MPa)</th>
<th>$c$ (MPa)</th>
<th>$\phi$ (°)</th>
<th>$\mu$ Poisson ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>VI</td>
<td>4.5</td>
<td>13.2</td>
<td>0.0</td>
<td>33.6</td>
<td>0.35</td>
</tr>
<tr>
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<td>29.0</td>
<td>-</td>
<td>32.5</td>
<td>0.3</td>
</tr>
<tr>
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<td>18.0</td>
<td>0.0</td>
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<td>0.32</td>
</tr>
<tr>
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<td>29.0</td>
<td>-</td>
<td>33.3</td>
<td>0.3</td>
</tr>
<tr>
<td>II</td>
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<td>-</td>
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<td>35.5</td>
<td>0.3</td>
</tr>
<tr>
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<td>4.5</td>
<td>-</td>
<td>-</td>
<td>33.3</td>
<td>0.3</td>
</tr>
</tbody>
</table>

may vary from area to area in the basin. The site is located at the $T_2$ zone of Taipei basin. Typical soil properties of the $T_2$ zone are given in Table 1.

Implementation of finite element analyses

The actual behaviour of the subsoil is very complex. A simplified soil profile of Taipei basin and a typical finite element mesh used to model the behaviour of the shield driven tunnel is shown in (Fig. 2). The modified Cam-clay model coupled with Biot’s equation, provide a set of equations. The finite element method will be applied to equations (1) and (2), using displacements and pore pressure as the basic parameters.

\[
[K] \{u\} - [Q] \{p_w\} = \{F_1\} \tag{1}
\]

\[
[Q]^T \{u\} + [S] \{p_w\} + [H] \{p_w\} = \{F_2\} \tag{2}
\]

$[K]$, $[Q]$, $[S]$ and $[H]$ are the matrices of stiffness, coupling, compressibility and seepage, respectively. In which,
\[ [K] = \int_\Omega [B]^T [D] [B] d\Omega \]

the constitutive matrix of modified Camclay \([D]\) is employed in the analysis. \(\{F_1\}\) and \(\{F_2\}\) are the nodal force and flow vector, respectively; \(\{u\}\) is the displacement vector and \(\{p_w\}\) is the pore water pressure. The complete set of equations is used in the time-stepping procedure outlined above to determine the value \(\{u\}\) and \(\{p_w\}\) at any point in the time relating to their initial values. In the nonlinear cases some or all matrices \([K]\), \([Q]\), \([S]\) and \(\{F_1\}\) and \(\{F_2\}\) are dependent on the values of unknown, \(\{u\}\) and \(\{p_w\}\), so that theoretically iterations within each time step are required.

**Comparisons between predicted and measured behaviour**

A case study of the Taipei Rapid System was conducted by Moh & Associates Inc. (Hwang *et al.*, 1995). Settlement readings obtained at the centre of the shield tunnel are

![Fig. 3](image3.png)

Fig. 3 Ground surface settlements in the cross-section of the tunnel against time.

![Fig. 4](image4.png)

Fig. 4 Ground surface settlements in the longitudinal direction of the tunnel against time.
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shown in Fig. 4. It can be seen that a 20 mm surface settlement suddenly took place as the tail passed. The prediction of the ground surface settlement in the finite element analysis is strongly related to the gap parameter, which can be obtained from the difference between the excavated surface and the tunnel. The outer diameter of the shield is 605 cm and that of the lined tunnel is 590 cm. In consideration of the condition for grouting, the gap parameter 10 cm is employed in FEM analysis. The soil parameters were chosen primarily from available published literature of Taipei basin. The effective Young's modulus \(E\) and Poisson's ratio of the various soil types for the effective finite element analysis are shown in Table 1. The coefficient of permeability for vertical flow is around \(k_v = 1.0 \times 10^{-6} \text{ m s}^{-1}\). The horizontal coefficient of permeability values were assumed to be 1.5 times higher than the vertical value.

Figure 3 shows the predicted settlement profile beneath the ground surface. Figure 4 compares the predicted and observed surface settlement at centre of the shield driven tunnel. The general shape of the settlement profile is predicted reasonably, but at the ground (immediate) loss, the predicted surface settlements exceed the measured values. The larger predicted values of the ground loss reflect a too big gap parameter value used in the analysis. It is also likely that the values of Young's modulus adopted in the predictions were too low. However, the amount of the consolidation deformation lies around 30% of the total settlement and shows a reasonable agreement with the measured data.

Acknowledgement The authors would like to express their sincere thanks to Dr C. C. Liang for his explanation of settlement readings and for invaluable instructions.

REFERENCES


