The influence of non-uniform soil deformation on tunnel induced ground movement

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Abstract

Tunnel construction in soft ground will inevitably result in deformation in the neighborhood ground. The soil deformation around the tunnel can be characterized by the sum of three basic modes: a uniform radial contraction due to ground loss, a pure distortion of tunnel ovalization and a vertical deformation with no volume loss. The extension of considering this non-uniform boundary condition and the complex soil material requires numerical analysis. This paper use two-dimensional finite element (FE) analysis for modeling the influence of non-uniform soil deformation on tunnel induced ground movement. The role of tunnel deforming patterns on the resulting field of ground movements is demonstrated by means of a parametric study on an idealized tunnelling problem. The applicability of the proposed method is then checked with field data.
1 Introduction

The effect of tunnel induced ground movements on existing infrastructures has always been one of major issues in tunnel design in urban area. The prediction of ground movement is complex as it involves diverse tunnel boundary condition and complex soil constitutive law as well as soil-structure interaction. A rational way to estimate ground movements induced by tunnelling should be based on the use of numerical simulation such as finite element (FE) method. In practice, as full three-dimensional analyses are usually expensive and time-consuming, the use of 2D FE analysis is of great value in parametric studies, particularly if there are significant changes in tunnel geometry and boundary conditions, and ground conditions.

2 Tunnel deformation patterns

The soil deformation around the tunnel are often associated with the concept of “ground loss”, usually expressed as the percentage of ground volume loss to the theoretical volume of the tunnel excavated per unit length (ground volume loss parameter $V_l$). This parameter can be obtained from empirical observation or other methods considering aspects such as soil stability, tunnelling method and tunnel configuration [1, 2]. Meanwhile, It is manifested that a uniform radial soil loss is not realistic for the tunnel deformation patterns [3 - 6]. The tunnel deformation can be summarized as the sum of three deformation modes [6]: a uniform radial contraction with ground loss with, $u_0$; a pure distortion of tunnel ovalization, $u_\theta$; and a vertical deformation with no ground loss, $u_v$; shown in Fig.1.

![Fig.1. Modes of tunnel deformation](image)

3 Modelling of tunnel deformation using 2D FE analysis

3.1 Model description and analysis procedure

A series of assumed tunnel excavation in soft ground has been carried out in two-dimensional plane strain analysis to assess the effects of tunnel deformation pattern on the resulting field of ground displacement. The numerical analysis has been performed with the widely used FE code ABAQUS (ABAQUS, 6.10). This software provides a user subroutine so called DISP which enables to define the magnitude of complex prescribed boundary conditions. The assumed tunnel excavation is based on a case history of shield tunnel construction in Frankfurt subway [3]. The model dimension, tunnel geometry and ground condition are shown in Fig.2 and Table 1. In order
to take the three deforming modes into account, the non-uniform boundary condition around the tunnel is represented by the following formula based on the polar coordinate in Figure 1, given by

$$u = -u_0(1 - \rho \cos 2\theta + \eta \sin \theta)$$

(1)

where the first term, $u_0 = R_0(1 - \sqrt{1 - V_0})$, represent the uniform radial contraction; the second term denotes the tunnel ovalization, $\rho = u_{0=0.2}/u_0$; the third term accounts for the vertical deformation of the tunnel, $\eta = u_y/u_0$.

<table>
<thead>
<tr>
<th>soil</th>
<th>$\gamma$ (kN/m$^3$)</th>
<th>E (MPa)</th>
<th>$\nu$</th>
<th>$c$ (kPa)</th>
<th>$\phi$</th>
<th>$\psi$</th>
<th>Soil condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil-1</td>
<td>20</td>
<td>50+7</td>
<td>0.2</td>
<td>0</td>
<td>36</td>
<td>5</td>
<td>Mohr Coulomb, Undrained</td>
</tr>
<tr>
<td>Soil-2</td>
<td>19</td>
<td>21+7</td>
<td>0.15</td>
<td>20</td>
<td>22</td>
<td>0</td>
<td>Mohr Coulomb, Undrained</td>
</tr>
</tbody>
</table>

Table 1 Soil parameters adopted for FE analysis

In this parametrical study, $u_0$ is determined by assuming a ground volume loss parameter equal to 1.66%. The relative ovalization parameter $\rho$ ranges from 0 to 1.5 and the non-dimensional ratio $\eta$ varies from -0.5 to 1 for a parametric study.

### 3.2 Evaluation of results

Nine FE analyses have been carried out with the same amount of ground volume loss, and the computed results of surface settlements are shown in Figs 3 and 4. On the one hand, in Fig. 3, the surface settlements are computed from different values of $\eta$ with no influence of ovalization. It is apparent that the increase of the value of $\eta$ results in a net increment of surface settlement and there is no evident change in the total width of the settlement trough. For $\eta$ equal to 1.5 the maximum settlement is coincident with that predicted by the empirical Gaussian error curve, but the computed settlement trough width is much wider and the slope of the settlement profile is dramatically more gradual than the Gaussian error curve. On the other hand, in Fig. 4, the surface settlements are computed from different values of the relative ovalization factor $\rho$ without vertical deformation. Obviously, an ovalization of the tunnel induces a significant narrow surface settlement trough. The maximum surface settlement also increases with the increase of the ovalization parameter $\rho$ but, in an opposite way, a reduction of the settlement trough width is
accompanied. Hence, in a real situation, the settlement profile should be the combined results of tunnel ovalization and vertical deformation.

Fig. 5 shows the computed surface settlement for the tunnel excavation in the Frankfurt subway with a relative ovalization parameter $\rho = 1.7$ and a vertical deformation factor $\eta = 0.5$. The results are also compared with results from empirical Gaussian error curve and measured field data. It is found that the computed surface settlements are in a good agreement with the measured data. Moreover, in the convex part of the settlement profile, the computed settlement is even more accurate than the settlement predicted by the empirical Gaussian error curve.

4 Summary

A procedure of 2D FE analysis is suggested for modeling tunnel induced ground movements. The influence of the tunnel deformation modes on the resulting field of surface settlements is investigated by means of parametric studies on an idealized tunnelling problem. The rationality and applicability of the proposed procedure are then checked with published field data. It is apparent that, except tunnel uniform contraction, both the tunnel ovalization and the tunnel vertical deformation have a significant influence on the resulting field of ground movements. Therefore, it is suggested that a combination of these three deformation modes for modeling tunnel induced ground movements using FE analysis can give more realistic results.

References


