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Numerical Analysis of Excavation on the Adjacent Existed Tunnel Considering Soil Spatial Variability

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Abstract: With the rapid development of urbanization, it is becoming increasingly popular to have excavation adjacent existed tunnel. It is necessary to predict the tunnel displacement induced by nearby excavation to evaluate the tunnel safety. Although the effect of excavation on adjacent existed tunnel has been studied extensively in homogeneous soil, the effect of the spatial variability in soil strength on the soil-tunnel-excavation interaction have received little attention so far. This study presents a random finite difference method (RFDM) for assessing the response of tunnel embedded in spatially varied soft soils to nearby excavation. Random fields are generated and mapped into a non-linear finite difference analysis to reveal the interaction of soil-tunnel-excavation in spatially varied soft soils. The influences of soil spatial variability on the responses of existed tunnel to adjacent excavations are investigated and quantified. The results indicate that ignoring the spatial variability of soil strength, the most dangerous situation may be ignored which will result in the conservative consequence. The conclusions drawn from this study should provide practical and useful references for engineers to assess the performance of tunnel embedded in spatially varied soils affected by adjacent excavations.

Keywords: Adjacent tunnel; excavation; spatial variability; random field.

1 Introduction

Tunnel and excavation are engineering activities in urban construction. More and more excavation is located above or on both sides of the tunnel. Large excavations will present considerable threats to the operation of adjacent metro facilities. The adjacent excavation construction will inevitably affect the existing tunnel. Because the subway vehicles are very sensitive to the deformation of the tunnel, the tunnel deformation requirements are very strict. Excavation will have an impact on the deformation of existing subway tunnels. The most essential reason is the unloading of excavation. Therefore, it is very important to master the deformation characteristics of existing subway tunnels in the process of excavation.

For the past few years, there are many efforts have been made to study the effects of excavation on adjacent tunnels. Numerical analysis is one effective way to study complex problems in deep excavation and tunneling. Huang et al. (2013) used the numerical analyses method to evaluate the deformation response of an existing tunnel due to nearby excavation. Chen et al. (2016) analyzed the responses of the ground and left tunnel due to the adjacent excavation employing a three dimensional numerical simulations. Liu et al. (2016) conducted case histories to investigate the performance of a deep excavation and its effect on adjacent tunnels in Shanghai soft clay. Zheng et al. (2018) proposed a simplified prediction method for evaluating tunnel displacement induced by laterally adjacent excavations using the finite element analysis.

However, in geotechnical engineering practice, it is more common to assume that soil is homogeneous. In spite of great efforts, what we got is still a state of the mean. The average level of results may miss the true failure mechanisms and ignore the weakest part of soils in the sense of randomness of soil properties. Hence, the question of how this type of uncertainty affects the response of excavation to adjacent tunnels remains unanswered. Therefore, it is necessary to consider the soil spatial variability on probabilistic analysis. Huang et al. (2017) analyzed the influence of spatial variability of soil Young's modulus on tunnel convergence in soft soils. Luo et al. (2018) presented the effect of spatial variability of soft clays on the geotechnical serviceability assessment of braced excavations. However, few previous researches have been devoted to the effect of excavation on adjacent tunnel considering soil spatial variability.

This paper is organized as follows. First, the FDM for modeling tunnel and excavation are presented. Second, the automation procedure of RFDM program and assessment deformation method used in this study is introduced. Third, several cases are implemented to demonstrate how the tunnel responses under the adjacent excavation considering the spatial variability of soil properties. Last, some conclusions are obtained.
2 Methodology

2.1 Development of the finite difference model
To generate artificial data on tunnel responses, an FDM model with a Mohr-Coulomb constitutive relationship was established. Fig. 1 illustrates the configuration and mesh of the numerical model. The width of the excavation was assumed to be 16 m. The diaphragm wall and tunnel lining were modeled as consisting of a linear elastic material with a Young’s modulus of 34.5 and 30 GPa. Meanwhile the Poisson’s ratio was 0.2 and 0.167, their density were 2500 kg/m$^3$. The struts were assumed to be linear elastic beam structural elements. In this paper, A shield tunnel with its outer diameter $D=6.2$ m, internal diameter 5.5m, thickness 0.35m and depth $H=12$m is considered. The excavation depth was 12 m which is common in Shanghai. In this study, the width of excavation is set as 16m. As shown in Fig. 1, the soil domain is set as 12.2 D in width and 7.26 D in depth to avoid the boundary effects and minimize effects on the analysis results. The plane-strain condition is assumed for this finite difference method analysis. The drained condition is assumed for the soils in this paper. There are 5006 soil zones and 10568 grid points. The soil in this paper is modeled as an elastic-plastic medium, following the Mohr-Coulomb yield criterion, which is most widely used in numerical simulations (Huang et al. 2017). The tunnel and the soil are connected through interface elements. Details of input parameters used in the numerical analyses are summarized in Table 1.

Table 1. Soil parameters adopted in finite difference modeling.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Notation</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic modulus</td>
<td>$E_s$</td>
<td>25</td>
<td>MPa</td>
</tr>
<tr>
<td>Cohesion</td>
<td>$c$</td>
<td>17</td>
<td>kPa</td>
</tr>
<tr>
<td>Friction angle</td>
<td>$\phi$</td>
<td>15</td>
<td>$^\circ$</td>
</tr>
<tr>
<td>Density</td>
<td>$\rho_s$</td>
<td>1800</td>
<td>kg/m$^3$</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>$\nu_s$</td>
<td>0.3</td>
<td>–</td>
</tr>
</tbody>
</table>

In accordance with the stages of the actual construction process, the finite difference calculations were performed following the steps listed below:
1. Generate the initial stress.
2. Activate the elements of the tunnel lining and calculate to balance.
3. Clear the displacement field, the velocity field, and activate the elements of the diaphragm wall.
4. Excavate to a depth of 1 m and construct the first-level concrete strut.
5. Excavate to a depth of 4 m and construct the second-level steel strut.
6. Excavate to a depth of 4 m and construct the second-level steel strut.
7. Excavate to the bottom of the excavation.

2.2 Generation of random field
There is a lot of uncertainty in the construction of tunnel engineering. Traditional design method usually adopts single safety factor to consider many uncertainty factors. It is fails to consider the effect of spatial variability on engineering safety risk. Scale of fluctuation is an important concept of geotechnical parameters in the random field modeling. It can well reflect the spatial variability of the soil. In this study, the correlation matrix is built with the anisotropic exponential autocorrelation function:
\[
\rho(\Delta x, \Delta y) = \exp\left[-2\left(\frac{\Delta x}{\delta_x} + \frac{\Delta y}{\delta_y}\right)^2\right]
\]

where \(\Delta x\) and \(\Delta y\) are horizontal and vertical distances between the two points, respectively, \(\delta_x\) and \(\delta_y\) are correlation distances in horizontal and vertical direction, respectively, and \(\rho(\Delta x, \Delta y)\) is the correlation coefficient between two points; The correlation distance quantifies the distance within which the soil properties exhibits relatively strong correlation. A smaller correlation distance indicates a stronger spatial variability. The Karhunen-Loeve expansion technique is used to discretize the random field in this study.

In this study, only the elastic modulus \(E_s\) is considered to be a spatially random property. Random fields of soil \(E_s\) are generated and mapped into finite difference analysis. As soil properties tend to be more similar in the horizontal direction than in the vertical direction, \(d_h\) is usually larger than the \(d_v\) (Phoon et al. 2016). In order to analysis the effect of soil spatial variability, the cases are set as shown in the table 2.

Table 2. Scales of fluctuation in anisotropic random fields.

<table>
<thead>
<tr>
<th>Case</th>
<th>COV</th>
<th>Scale of fluctuation</th>
<th>Anisotropic ratio</th>
<th>(\delta_h/D)</th>
<th>(\delta_v/D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case1</td>
<td>0.3</td>
<td>30 30 30</td>
<td>30</td>
<td>4.84</td>
<td>0.08</td>
</tr>
<tr>
<td>Case2</td>
<td>0.3</td>
<td>30 30 10</td>
<td>10</td>
<td>4.84</td>
<td>0.24</td>
</tr>
<tr>
<td>Case3</td>
<td>0.3</td>
<td>30 12 7.5</td>
<td>7.5</td>
<td>4.84</td>
<td>0.65</td>
</tr>
<tr>
<td>Case4</td>
<td>0.3</td>
<td>30 30 1</td>
<td>1</td>
<td>4.84</td>
<td>4.84</td>
</tr>
</tbody>
</table>

2.3 Automation of random finite difference modeling

The automation procedure to realize random field difference method program in this study is shown in Fig. 6. The framework of this program for predicting the effect of excavation on adjacent tunnel considering soil spatial variability can be summarized in the following steps:

Step 1 is to define the tunnel prediction problem caused by adjacent excavation and establish the numerical model. Meanwhile, the random field parameter should be selected in this step.

Step 2 is to discrete the random field parameter using the K-L expansion technique. In order to realize the goal, the center coordinates of grid units in the FDM model should be extracted. In this step, \(N\) times simulations (random field parameter) should be finished. A converged run number means that the COV of generated data is not sensitive to the run number. In this study, it is about 300 in this sense (Zhang et al. 2018).

Step 3 is to map the random field parameter into the FDM model. Then, using the FLAC software to calculate the model and get the result. In this step, 300 times calculations should be finished.

Step 4 is to manage the result using the MATLAB code and output the result files.

Figure 2. Flow chart for automating random finite difference modeling.

2.4 Assessment method

An assessment method of tunnel deformation is proposed to reflect the effect of the adjacent excavation on the exist tunnel. In this problem, the tunnel not only undergoes convergence deformation, but also due to the excavation unloading impact, the tunnel will have a horizontal movement towards the excavation. Convergence indicates the difference between the distance between the maximum deformation point after the deformation of the tunnel and the two points before the deformation. Therefore, the convergence index consists of horizontal convergence \((\Delta D_h)\) and the vertical convergence \((\Delta D_v)\). The horizontal displacement \((\delta_{Th})\) of tunnel indicates the
movement of the tunnel in horizontal direction. And, there's a corresponding vertical displacement of tunnel \( \delta_{Tv} \). The horizontal displacement \( \delta_{Th} \) may be a significant index in this problem which will cause dislocation of tunnel especially in spatially varied soil. In this sense, the four evaluated index can be calculated as shown in Fig. 3.

![Figure 3](image)

**Figure 3.** The schematic of the assessment method for tunnel deformation proposed in this study.

### 3 Results and Discussion

#### 3.1 The tunnel deformation of deterministic analysis

The displacement vector diagram is a good method to study how the displacement of soil changes. Fig. 4 shows the displacement vector distribution in the soil near the tunnel and the excavation. It can be seen from the figure that, the displacement field of the soil mass in the pit after excavation is offset to the side of the tunnel to some extent, instead of being symmetrical about the excavation. At first, the displacement vector of the four regions around the tunnel all has the trend of moving towards the bottom of the pit, but the change is not the same. The displacement vector in region 1 is mainly dominated by horizontal displacement, accompanied by upward movement. The reason is that region 1 is the area closest to the excavation, so the overall displacement is towards the bottom of the excavation. Meanwhile, the displacement vector in region 2 and 4 are mainly upward, accompanied by horizontal movement. Region 3 has a relatively small impact because it is far away from the excavation area. According to the displacement of soil in the four regions, the tunnel will not only have a relatively obvious horizontal movement, but also easily cause the rotation of the tunnel because of the unsymmetrical deformation. As shown in Fig. 4, the tunnel will have a counterclockwise rotation in this study. The tunnel deformation contour after excavation is shown in the lower right corner of Fig. 4. Consequently, the stress relief induced by the excavation led to the horizontal displacement and rotation of the tunnel. Therefore, in practical engineering, we should pay more attention to the tunnel section near the excavation.

![Figure 4](image)

**Figure 4.** The displacement vector diagram after the excavation.

#### 3.2 Correlation between maximum lateral wall deflection and maximum tunnel horizontal displacement

The correlation between the maximum lateral wall deflection and the corresponding depth where the maximum deflection occurs was explored in this study. This correlation is shown in Fig. 5 for different levels of \( d \). Fig. 5 illustrates a clear trend of correlation, and a larger \( d \) indicates greater scatter. It is shown in Fig. 5 that most of the maximum lateral wall deflection in the simulations occurs at depth from 15m to 18 m at various levels of soil spatial variability.

Figure 6 shows the correlation between maximum lateral wall deflections \( \delta_{lmax} \) and maximum horizontal displacement \( \delta_{th} \) of tunnel for all simulations at four levels of \( d \). It can be easily observed that at lower levels of \( d \), the sample points are concentrated in a small area. However, when the \( d \) is larger, the sample points
disperse into a larger area. Furthermore, the correlation function between the $\delta_{R_{\text{max}}}$ and $\delta_{T_{v}}$ is also shown in Fig. 6. For all levels of $\delta_{v}$, it can be found that when the $\delta_{R_{\text{max}}}$ is large, $\delta_{T_{v}}$ tends to be large as well. It is clear that the $\delta_{T_{v}}$ has a positive linear correlation with the $\delta_{R_{\text{max}}}$, regardless of the spatial effect. The data points for each level of $\delta_{v}$ are shown to fit well into the regression equation resulting from all data points.

![Figure 5](image1.png)  ![Figure 6](image2.png)

**Figure 5.** Correlation between maximum lateral wall deflection and critical depth at various levels of $\delta_{v}$.

**Figure 6.** Correlation between maximum lateral wall deflection and tunnel horizontal displacement at various levels of $\delta_{v}$.

### 3.3 Effect of vertical SOF on the horizontal convergence of adjacent tunnel

Figure 7 shows the histogram of increasing horizontal convergence of tunnel in different vertical SOF. Since the displacement generated by tunnel excavation is removed in the calculation, the convergence values here are all caused by excavation. The horizontal SOF is same in the four cases and the COV is all 0.3. As shown in Fig. 14(a), when the $\delta_{v}$=1m, the mean value is 14.30mm, the range of distribution is about 11-17mm. As shown in Fig. 14(b), when the $\delta_{v}$=3m, the mean value is 14.28mm, the range of distribution is about 9-18mm. As shown in Fig. 14(c), when the $\delta_{v}$=12m, the mean value is 14.14mm, the range of distribution is about 5-23mm. As shown in Fig. 14(d), when the $\delta_{v}$=30m, the mean value is 13.83mm, the range of distribution is about 5-25mm. With the $\delta_{v}$ increases, the range of distribution is larger, which means the variability is more significant. If the spatial variability is neglected, the most dangerous situation may be ignored. The spatial variability of soil has a relatively small impact on the mean value and a relatively greater impact on the distribution.

### 4 Conclusion

This paper presents a numerical analysis of the excavation effect on adjacent exited tunnel considering the spatial variability of the soil. The spatial variability of the Young's modulus is modeled with random fields. Based on the results of numerical simulations, the following conclusions can be summarized as follows:

1. Spatial variability has a significant impact on the predicted wall and effect on adjacent tunnel. The vertical SOF of soil has a relatively small impact on the mean value and a relatively greater impact on the distribution pattern. If the spatial variability is neglected, the most dangerous situation may be ignored which will yield results on the unconservative side.

2. The locations of excavation-induced maximum lateral wall deflection is also critical for assessing the effect of the adjacent infrastructure. In these study case, the maximum lateral wall deflection mainly occurs at depths of 15–18 m.

3. The correlation between the maximum lateral wall deflection and the maximum horizontal displacement of tunnel is shown to be positively linear. Therefore, in engineering practice, the displacement of underground diaphragm wall should be strictly controlled to minimize the effect of the adjacent tunnels.

### Acknowledgments

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Figure 7. Histogram of $DA_h$ in different vertical SOF (a) $d_v=1m$; (b) $d_v=3m$; (c) $d_v=12m$; (d) $d_v=30m$.

References


