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Simulating the effects of braced excavation on the adjacent tunnel using numerical method

Shun YI[1, 2, 3, 4], Wenhui KE[5], Xiangguo HUANG[5], Mingzhao XIAO[5], Jian CHEN[1, 2, 3, 4*] and Juehao HUANG[1, 2, 3, 4]

[1]State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan, Hubei 430071, China

[2]University of Chinese Academy of Sciences, Beijing 100049, China

[3]Hubei Key Laboratory of Geo-Environmental Engineering, Wuhan 430071, People's Republic of China

[4]The Soft Soil Research Center in Ningbo University of Technology, State Key Laboratory of Geomechanics and Geotechnical Engineering, Ningbo 315211, People's Republic of China

[5]Wuhan Municipal Construction Group Co. Ltd, Wuhan, Hubei 430023, China

[*]Corresponding author's e-mail: jchen@whrsm.ac.cn

Abstract: It is inevitable that the construction of braced excavation is in the vicinity of existing tunnels. Therefore, it is necessary to assess the influence of braced excavation on the nearby tunnel. Using two-dimensional (2D) numerical method, this study is conducted to investigate the response of existing tunnel induced by overlying excavation. A series of scenarios are carried out, with consideration of relative locations of tunnel with respect to overlying excavation. The results demonstrate that different distortion of the tunnel will occur with the variety of relative locations between the tunnel and the braced excavation. Additionally, the excavation-induced tunnel responses show a decrease trend with an increase distance between the tunnel and excavation. In this regard, the study can provide a useful reference for evaluating the influence of braced excavations on nearby structures.

1. Introduction

With the development and utilization of city underground space, more and more braced excavations will be constructed, and many of them are inevitably in the vicinity of existing tunnels. In this regard, attention should be paid to the influence of the braced excavations on nearby tunnels.

A number of numerical analyses [1-5] have been carried out to study the interaction between braced excavations and tunnels. However, it should be noted that almost all these numerical analyses didn't take account of the small strain behaviour in soil induced by construction disturbance. Lots of studies [6-9] have demonstrated that the small-strain stiffness of soil has a significant influence on deformation caused by excavation. As illustrated in the reference [10], the model considering the soil small-strain stiffness does well in predicting the excavation-induced deformation. The figure 1 shows the available strain range in different engineering applications. It can be known that the soil stiffness decreases with its strain increasing and soil in braced excavation lies in the range of small strain.

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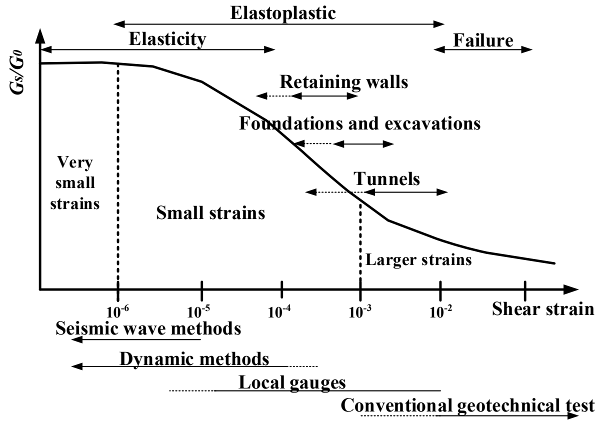


Figure 1. The available strain range in different engineering applications

In order to study the influence of excavations on adjacent tunnels in an effective way, the Plastic Hardening-Small Strain (PH-SS) model [11] is used in this paper. This paper takes the relative position between the tunnel and the excavation as the focus, and further study the tunnel responses caused by excavations in different scenarios. This study provides a useful reference for the evaluation of the effects of braced excavation on existing structures in soft areas.

2. The Plastic Small Strain model

Based on the hardening soil model, the PH-SS model takes account of the soil small strain characteristics by embedding the parameters G (small strain stiffness) and γ_{70} (shear strain) into the finite difference program. The relation between G and γ_{70} is written as following.

$$\frac{G}{G_0}=\frac{1}{\left(1+0.385\gamma/\gamma_{70}\right)^2} \tag{1}$$

where γ_{70} indicates the shear strain corresponding to its shear stiffness attenuation to 70% of initial shear stiffness. The initial shear stiffness G_0 can be obtained from the stiffness G_0^{ref} under the reference pressure at a very small strain level, as shown below.

$$G_0=G_0^{ref}\left(\frac{c' \cos\phi' + \sigma_3' \sin\phi'}{c' \cos\phi' + p^{ref} \sin\phi'}\right)^m \tag{2}$$

where c' is the effective cohesion, ϕ' is the effective friction angle, σ_3' represents the third effective stress, and p^{ref} denotes the reference pressure.

It can be acknowledged from the Equation 1 that the soil stiffness shows a decrease trend with an increase of the shear strain, corresponding to the conclusion shown in figure 1.

3. Numerical analyses

3.1. Numerical model and calculation parameters

A general-purpose finite difference program FLAC^{3D} was used in this study. Different locations of tunnel with respect to excavation in a series of typical scenarios were taken into account to investigate the interactions between existing tunnel and braced excavation. Table 1 provides the scenario definitions with consideration of the relative positions between tunnel and excavation. In the scenarios from Case 1 to Case 9, the excavation width is 14m and the retaining wall depth is 12m. Tunnels in Case 1~Case 5 lie at the central line under the bottom of excavation. The location of tunnel in Case 6 is under the base of retaining wall. Tunnel with respect to excavation in the Case 7, Case 8 and Case 9 are all outside of the retaining wall. Taking the Case 1 as the example shown as the figure 2, the 2D numerical model size lies in 90m (x-axis) × 40m (z-axis). Figure 3 shows the tunnel locations in Case 6, Case 7, Case 8 and Case 9.

Table 1. Different scenarios considering the tunnel locations

Scenarios	Diameter (m)	D_x	D_z
Case 1	6.2	0	1.0D
Case 2	6.2	0	1.5D
Case 3	6.2	0	2.0D
Case 4	6.2	0	2.5D
Case 5	6.2	0	3.0D
Case 6	6.2	0.5B	2.0D
Case 7	6.2	1.0B	2.0D
Case 8	6.2	1.5B	2.0D
Case 9	6.2	1.0B	0.5D

Note: D_x indicates horizontal distance from tunnel axis to excavation axis; D_z is vertical distance from tunnel axis to excavation bottom; D=6.2m, represents the diameter of tunnel; B=14m, is the width of the excavation.

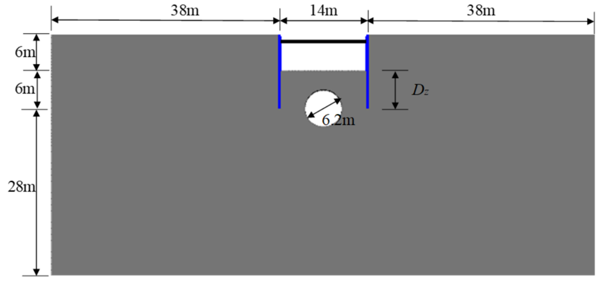
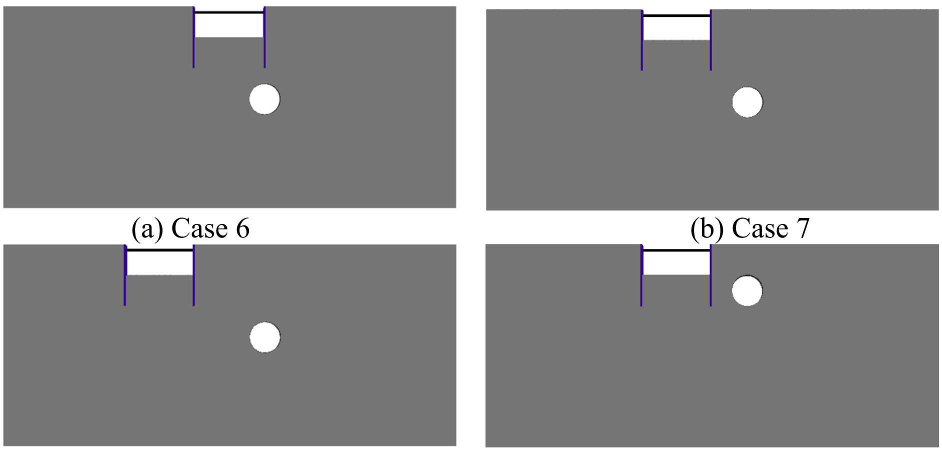


Figure 2. The model size including braced excavation and existing tunnel (Case 1 as the example)



(a) Case 6 (b) Case 7

(c) Case 8 (d) Case 9

Figure 3. The relative positions between tunnels and excavations for the four typical scenarios.

In order to simplify the complicated problems, the soil was assumed to be a uniform soft clay layer. Meanwhile, the influence of joints on tunnel lining was not taken into account in calculations.

The retaining wall is simulated by lining elements and the internal support is simulated by beam elements. The clay parameters are provided in Table 2 with the references [11-12]. The parameters of related structural elements are shown in Table 3 and Table 4.

Table 2. Soil and material parameters

Layer	φ/°	c/kPa	Ψ/°	E_{50}^{ref}/MPa	E_{ur}^{ref}/MPa	E_{oed}^{ref} /MPa	υ	m	p^{ref}/kPa	G_0^{ref}/MPa	γ_{70}
Clay	20	13	0	4.5	13.5	4.5	0.35	0.9	100	40.5	2e^{-4}

Table 3. Parameters of diaphragm

Attributes	Density/kg·m^{-3}	Young's modulus/GPa	Poisson's ratio	Equivalent thickness/m
Values	2500	24	0.2	0.51

Table 4. Parameters of internal support

Attributes	Density/kg·m^{-3}	Young's modulus/GPa	Poisson's ratio
Values	3000	30	0.2

3.2. Result analysis

3.2.1. Analysis of existing tunnel deformation

The existing tunnel may be inevitably affected by the braced excavation, including its deformation. Figure 4 shows the tunnel deformation in different scenarios. In order to make a better description, the results for tunnel deformation were enlarged 200 times. It can be obtained that the location of tunnel has important influence on the deformation of existing tunnel. When the tunnel is below the axis of excavation, it doesn't show any displacement in horizon direction for the whole tunnel and the heave decreases with the relative distance of tunnel increasing. When the tunnel is directly under the base of retaining wall, its deformation will experience distortion, as illustrated in figure 4(d). When the tunnel lies outsides of the retaining wall, the tunnel shows obvious responses both in vertical and horizontal directions, especially its deformation toward to the excavation base due to the unloading.

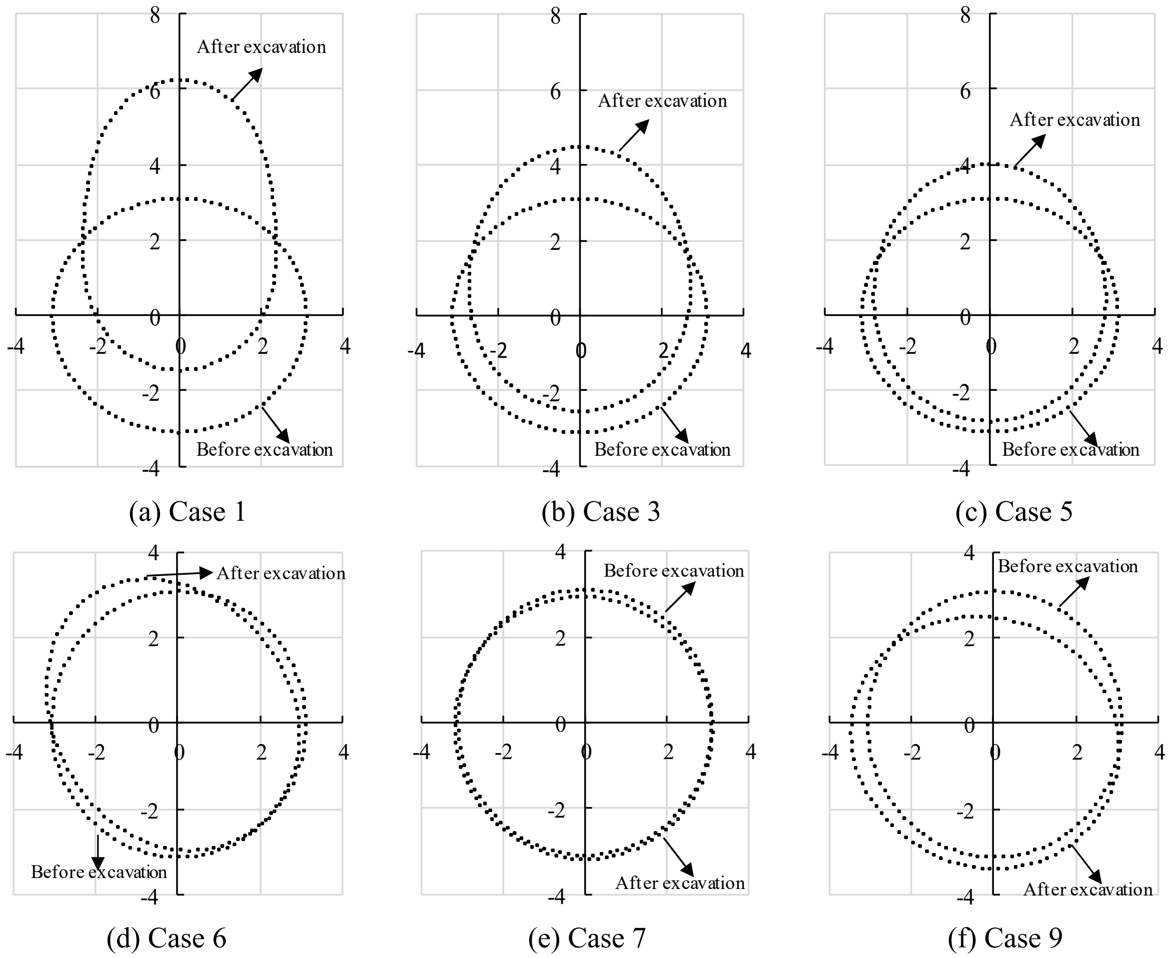


Figure 4. The tunnel deformation induced by excavation in typical cases (Enlarge the tunnel deformation 200 times).

For the safety of tunnel, circumferential deformation should be paid enough attention. The tunnel crown, invert and the location at the springline are studied in the paper. Figure 5 provides the deformation at tunnel typical locations both in horizontal and vertical directions. It can be obtained that the results for deformation show a decrease trend with an increase of the relative distance between

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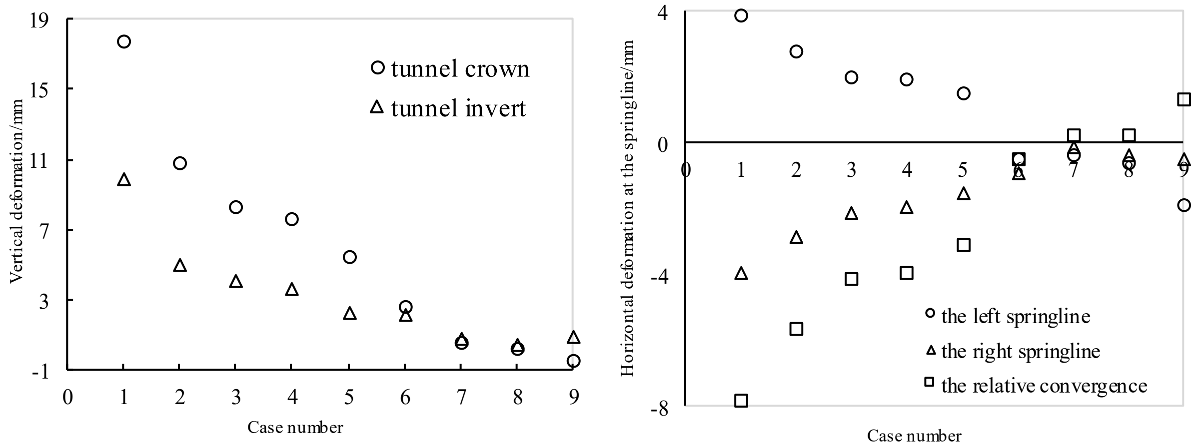
braced excavation and existing tunnel. For the Case 1 ~ Case 5, the deformation at the tunnel crown is not consistent with that of the tunnel invert and the deformation at the left springline and the right springline show an opposite trend, which demonstrates that the existing tunnel is vertically elongated and horizontally compressed. In additional, the result at tunnel crown is lower than that at the invert and the tunnel relative convergence may show a positive value, as shown in the Case 9. In this regard, the existing tunnel may be vertically compressed and horizontally elongated when the tunnel is outside the retain wall.

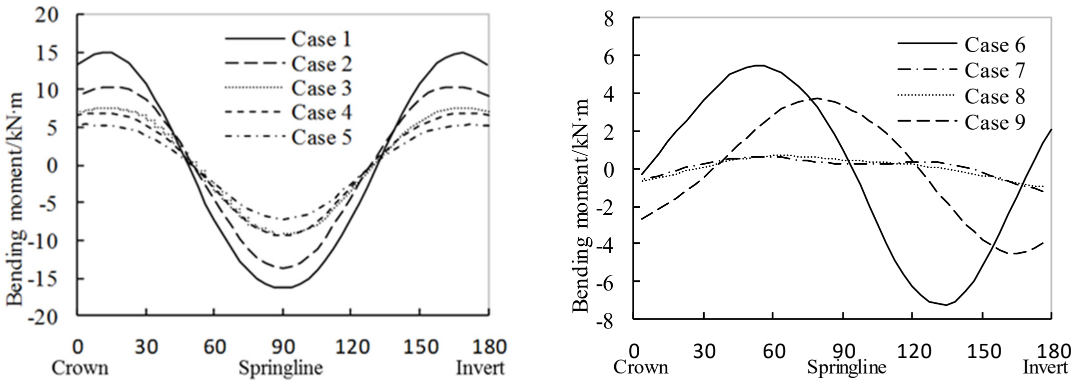


(a) the deformation at the crown and invert (b) the deformation at the springline

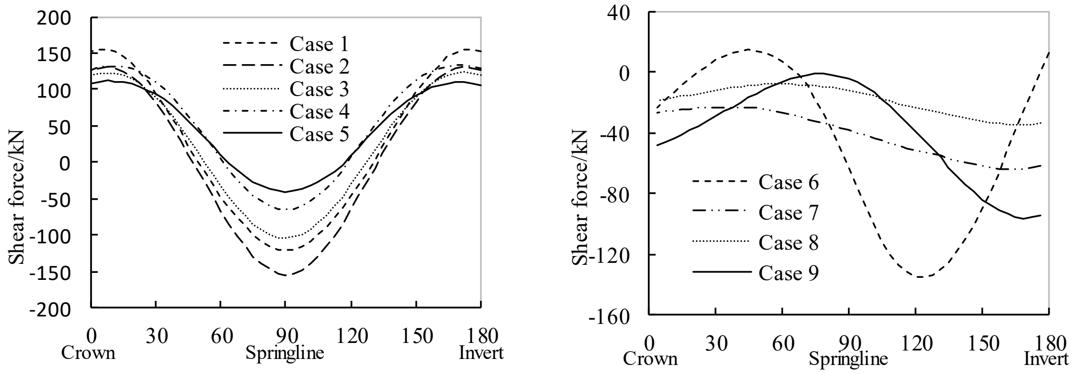
Figure 5. The tunnel deformation both in horizontal and vertical directions.

3.2.2. Analysis of existing tunnel inner force

The inner force (i.e. the bending moment and the shear force) should be attached important attention for a better tunnel protection. Figure 6(a) and (b) shows the inner force of the half tunnel lining in different cases. It is noted that both the magnitudes of the bending moment and the shear force increase due to the excavation-induced unloading. Additional, for the Case 1 to Case 5, the unloading doesn't have any influence on the positions of the maximum positive and negative inner force. Overall, the magnitudes of the inner force show a decrease trend with an increase of the relative distance between the existing tunnel and the braced excavation. When the tunnel is outside of the retaining wall, the bending moment and the shear force show the forms of asymmetrical distributions.



(a) circumferential bending moment (from Case 1 to Case 9).



(b) circumferential shear force (from Case 1 to Case 9).
Figure 6. Influence of the location of tunnel on the inner forces of the lining.

4. Conclusions
With consideration of the soil small strain, the Plastic Hardening-Small Strain (PH-SS) model is used to investigate the excavation-induced tunnel responses. The deformations and inner forces of the existing tunnel are studied in this paper. A series of conclusions are obtained as follows:

(1) Different distortion of the tunnel will occur with the variety of relative locations between the tunnel and the braced excavation.

(2) When the tunnel is below the base of excavation, the existing tunnel is vertically elongated and horizontally compressed; When the tunnel is outside the retain wall, the tunnel may be vertically compressed and horizontally elongated.

(3) When the tunnel is directly below the axis of the excavation base, the excavation-induced unloading doesn’t have any influence on the positions of the maximum positive and negative inner force. Overall, the magnitudes of the inner force show a decrease trend with an increase of the relative distance between the existing tunnel and the braced excavation. When the tunnel is outside of the retaining wall, the bending moment and the shear force show the forms of asymmetrical distributions.

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