J. Cent. South Univ. Technol. (2008) 15(s2): 069−075
DOI: 10.1007/s11771−008−0438−4

Springer

Numerical analyses of influence of overlying pit excavation on existing tunnels

ZHENG Gang(郑 刚), WEI Shao-wei(魏少伟)

(Department of Civil Engineering, Tianjin University, Tianjin 300072, China)

Abstract: The response of existing tunnel due to overlying excavation was studied using 2D FEM (Finite element method). Three typical locations of tunnel with respect to excavation, namely at the central line under the excavation bottom, directly under the base of diaphragm wall and outside of diaphragm, were considered. The variation of tunnel response with the change of location of tunnel was analyzed. The stress path of soil surrounding tunnel during the process of excavation was compared. Numerical analysis results indicate that the underlying tunnels at different locations under the excavation will experience convergence and divergence due to overlying excavation. Moreover, the tunnel located below base of diaphragm wall will experience distortion. The deformation is mainly due to the uneven changes of ground contact pressure on tunnel linings. Both the vertical and horizontal displacement of the tunnel decrease with the increase of the tunnel embedded depth beneath the formation of excavation.

Key words: pit; excavation; tunnel response; FEM

1 Introduction

Metro tunnels is the life line of city transport, its security is extremely important. However, it is inevitable that some constructions is carried out near the existing tunnels. This may include excavation above existing tunnels. The overlying excavation will impose significant influence on the tunnel linings, including changes of stress and deformation. Meanwhile, different stresses and deformations changes will occur in tunnel linings in different locations under excavation formation due to the “space effect” of excavation.

Many researchers have performed field monitoring and numerical simulation to investigate the impact of excavation on adjacent tunnel. However, the effects on existing underlying tunnel due to the overlying excavation were studied. BURFORD[1] reported there was the recorded tunnel displacement due to overlying excavation in London. The maximum heave measured in the tunnel lining is about 50 mm and the rate of heave shows little sign of decreasing although the excavation took place over 27 years. LO and RAMSAY[2] conducted a back analysis based on field measurement during the whole process of excavation in Toronto. The results show that the methods employed in the case may be applied in other urban tunnel situations. DOLEZALOVA[3] carried out a plain strain numerical FEM analysis and compared the results with field measurement data. SHARMA et al[4] reported a large excavation close to two parallel tunnels in Singapore and the field measurement results indicate the significant effects of excavation on tunnel. Based on field measurements in Shanghai, HU et al[5−6] studied the effects of construction measures such as pumping inside the pit, installation of cement-soil mixing columns and excavation regime. This study shows that the measures concerned can reduce the effect of excavation on existing tunnel linings. These construction measures were also proved to be effective based on field measurements of some analogous projects in Shanghai[7] and Nanjing[8]. WISSER et al[9−10] discussed the effect of grouting technique on the tunnel linings based on numerical analyses. KARKI[11] presented a study of the effects of deep excavations on adjacent metro or utility tunnel in soft to medium soil. Design charts for estimation of effects of deep excavation on adjacent existing tunnels were established using FEM (finite element method).

Most of the researches mentioned above are based on field measurement and there are few theoretical analysis concerned in detail. To further understand the influence of overlying excavation on existing tunnels, 2D FEM method was used to study the effect of overlying excavation on existing tunnels, and then the influences of parameters, such as vertical distance from the tunnel to the diaphragm wall and horizontal distance from tunnel center to excavation center, were investigated.

2 Analysis of effect of excavation on underlying tunnels

2.1 FEM model and parameters

A general-purpose finite element program ABAQUS/

Foundation item: Project (07FDZDSF01200) supported by Tianjin Science and Technology Innovation Special Funds
Received date: 2008−09−05; **Accepted date**: 2008−10−18
Corresponding author: ZHENG Gang, Professor; Tel: +86-13820381880; E-mail: zhengzige2004@yahoo.com.cn

Standard[12] was used in this study. Three typical cases where the locations of tunnel with respect to excavation, namely at the central line under the bottom of excavation, under the base of diaphragm and outside of diaphragm, were considered to investigate the influences of tunnel responses, as shown in Fig.1. The tunnel diameter was 6 m and the lining thickness was 0.3 m.

With the excavation carried on, the soil inside the pit will move upward and the soil outside the soil moves towards the excavation. This excavation-induced movement will consequently impose different influences on tunnel linings with different locations.

To avoid undue complication in this study, soil was assumed to be a uniform silty clay layer and the pit was assumed to be sufficiently long enough that a two dimensional plane-strain model was applicable. Also the effect of joints on tunnel lining was not taken into consideration in numerical analyses.

The parameters are also shown in Fig.1, where B is excavation width and h_e is excavation depth, H is total thickness of soil layer and h_s is spacing between struts, B_w and h_w are wall width and length, respectively. B_t is vertical distance from the tunnel to the wall and h_t is horizontal distance from the tunnel centerline to excavation centerline.

The finite element meshes where the tunnel locates close to excavation centerline (Tunnel 1 in Fig.1) is shown in Fig.2. Plain-strain model was adopted and 4 node bilinear quadrilateral, incompatible plain-strain elements were used to model the soil, diaphragm walls and the tunnels.

Goodman interface elements were introduced to model the interaction between soil and walls, and soil and tunnel linings. The friction coefficients were respectively assumed to be 0.2 between soil and walls and 0.3 between soil and tunnel linings. Linear stress—

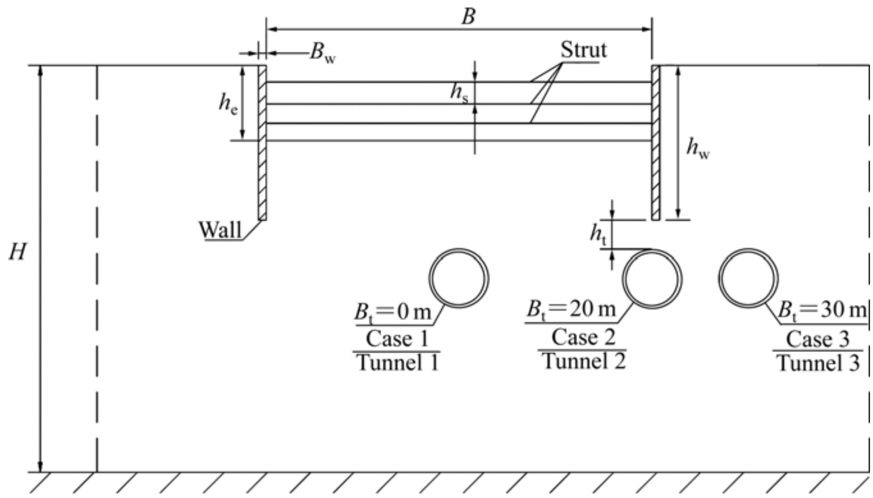

Fig.1 Typical locations of tunnel with respect to excavation and diaphragm: B=40 m; H=70 m; h_e=8 m; h_s=2 m; h_c=3 m; h_w=16 m; B_w=0.8 m

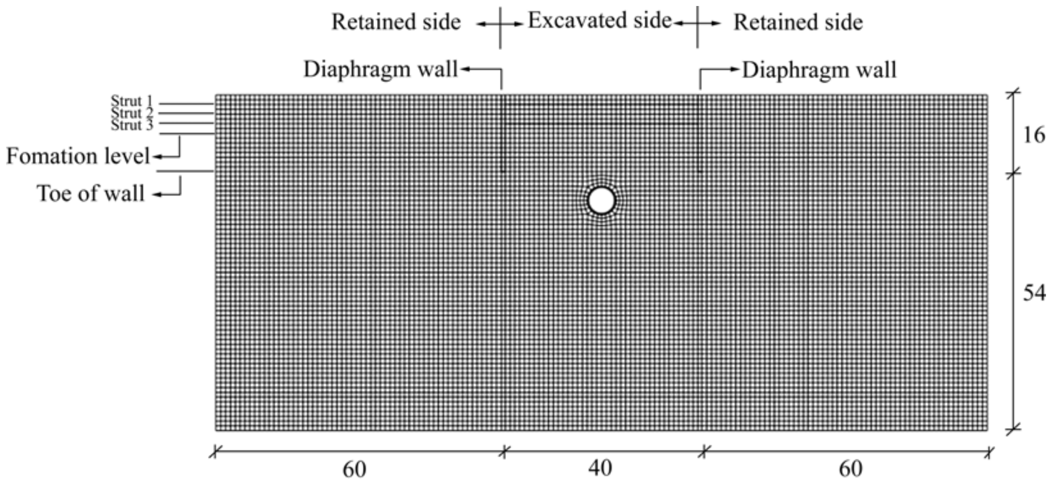

Fig.2 Finite element mesh of case that tunnel located close to excavation centerline (Unit: m)

displacement truss elements were used to model the struts. Modified Cam-clay model was used to simulate the stress—strain relation of the soils and simplified linear elastic model was used to simulate the diaphragm walls and the tunnel linings. The material properties were listed in Tables 1 and 2. Diaphragm walls were wished-in-place and the influence on the diaphragm walls due to the tunnel construction was ignored.

Table 1 Properties of non-soil materials

Material	strut	Diaphragm wall	Tunnel lining
Elastic modulus/10^{10} Pa	0.2	2.0	2.0
Poisson's ratio v	0.2	0.17	0.17

Table 2 Properties of soil

Soil type	M	λ	κ	e_0	ρ/(kg·m^{-3})	v
Silty clay	1.1	0.07	0.004	0.72	1 860	0.3

2.2 Excavation regime

Based on the simulation of tunnel construction, excavation was carried out in 4 steps and the simulation steps were as follows:

Step 1: excavation to −2 m below the ground surface;

Step 2: excavation to −4 m below the ground surface and installation of the first strut;

Step 3: excavation to −6 m below the ground surface and installation of the second strut;

Step 4: excavation to −8 m below the ground surface and installation of the third strut.

3 Results and analysis

3.1 Tunnel deformations

For the safe operation of metro tunnels, restriction standards were set up in some regions. The allowable deformations of existing tunnel were specified[7] and include: (1) The absolute displacement of tunnels should be less than 20 mm; (2) the heave displacement of tunnel invert should be less than 15 mm; (3) the distortion ratio should be less than 1/2 500.

For tunnel located at the three typical positions mentioned hereinbefore, the computed vertical displacement of the tunnel inverts for the four excavation steps is shown in Fig.3. The computed horizontal displacement of the tunnel centers is shown in Fig.4.

It can be seen from Fig.3 that all the vertical displacements of the tunnel inverts in the three cases increase when excavation and the vertical displacement in case 1 (Tunnel 1) is much larger than those in cases 2 (Tunnel 2) and 3 (Tunnel 3). As shown in Fig.4, significant horizontal displacements towards excavation

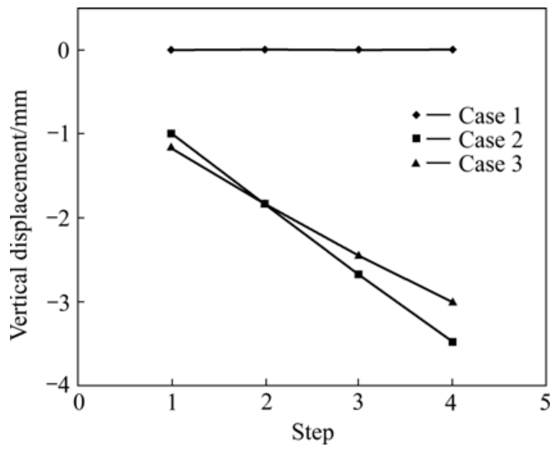

Fig.3 Computed vertical displacements (with reference to tunnel construction, positive represents moving upward)

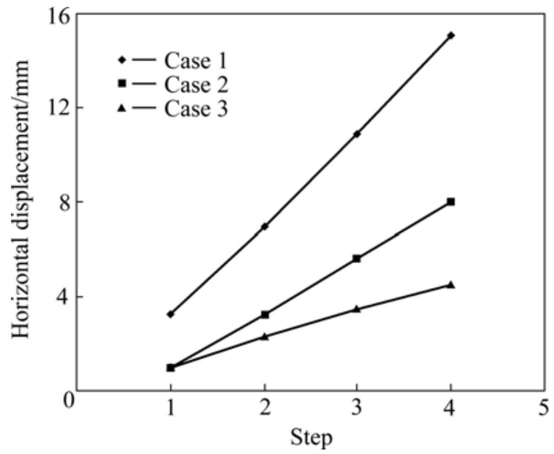

Fig.4 Computed horizontal displacements (with reference to tunnel construction, negative represents moving towards excavated area)

occur in tunnels 2 and 3 during excavation. Tunnel 1 mainly moves upward, and for tunnels 2 and 3, horizontal displacements is larger but vertical displacements is smaller during excavation. Generally speaking, the tunnel displacement in the three cases coincide with excavation-induced soil movement around the tunnels.

The deformed shapes of the tunnels in the three cases in different steps are shown in Fig.5. The shaded areas represent the shape changes of the tunnels due to excavation. It can be seen from Fig.5 that diameter of tunnel at all directions changes in all the three tunnels after excavation but only significantly distortion occurs in tunnel 2.

For tunnel 1, the maximum diameter increase due to excavation is about 5.8 mm in vertical direction, whereas the maximum reduction approximately 5.2 mm in horizontal direction is.

Tunnel 2 which locates beneath the tip of diaphragm wall will experience complicated deformation. The

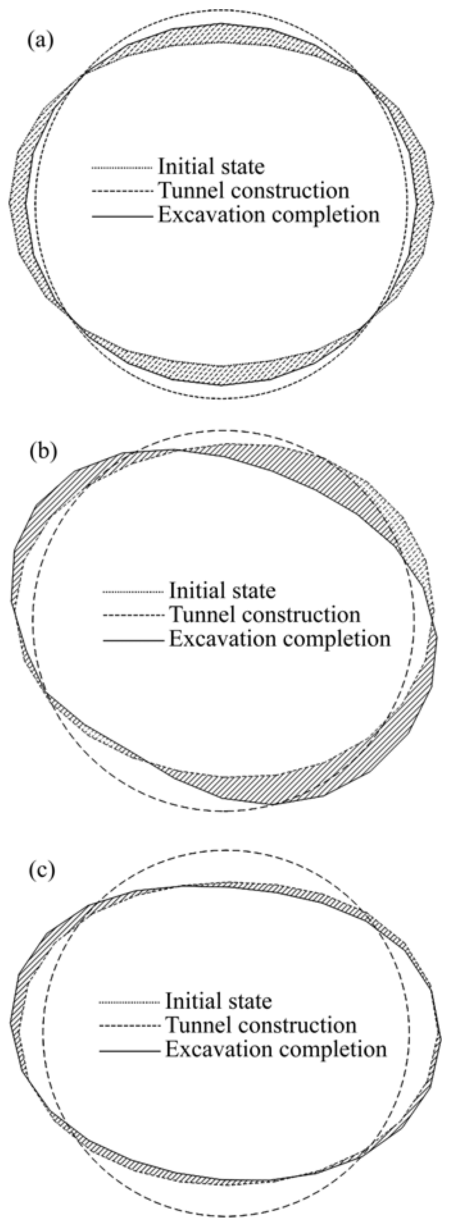

Fig.5 Deformed shapes of tunnels: (a) Tunnel 1; (b) Tunnel 2; (c) Tunnel 3

maximum increase in the tunnel diameter due to excavation is about 5.02 mm and occurs at 30˚ in a clockwise direction from the horizontal，whereas the maximum reduction is about 6 mm and occurs at 30˚ in a clockwise direction from the vertical.

For tunnel 3, which locates outside the wall, slight distortion is observed due to less soil stress relief compared with others.

The different deformations of tunnel are obviously induced by different interactions between soil and tunnels due to the "space effect" of excavation.

3.2 Contact pressure changes on tunnel linings

Fig.6 shows polar plots of change of contract pressures between soil and tunnel linings during excavation. For convenience, positive sign and negative sign were introduced to denote increase and decrease of contact pressures during excavation, respectively.

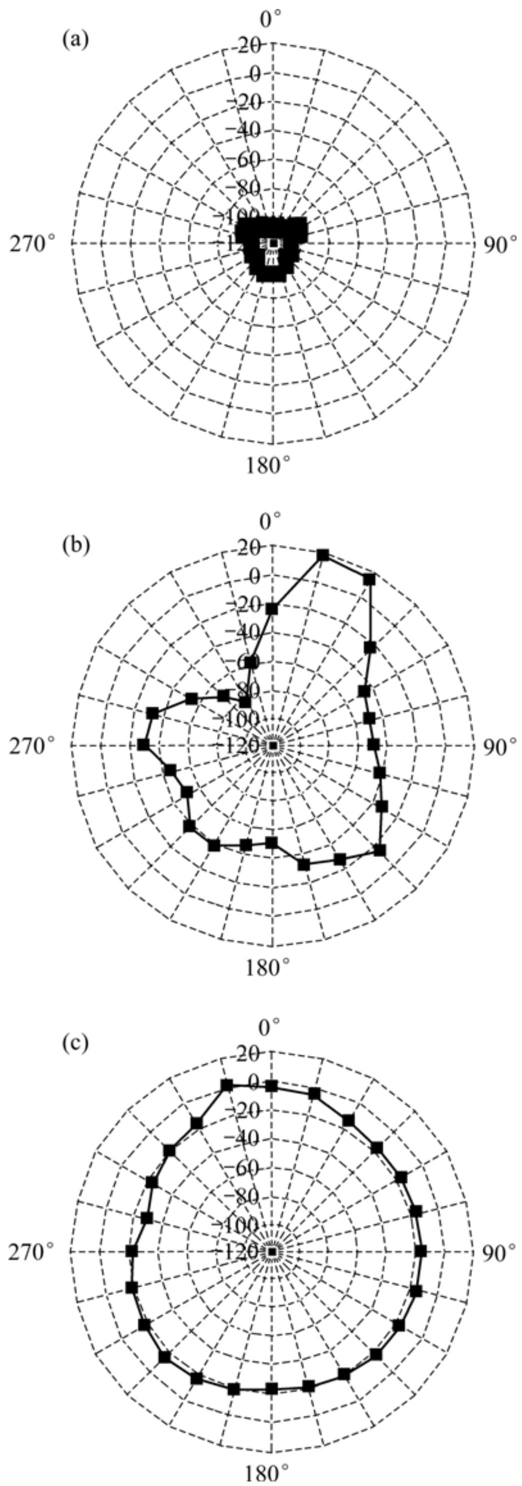

Fig.6 Polar plots of changes of contact pressures during excavation: (a) Tunnel 1; (b) Tunnel 2; (c) Tunnel 3

It can be seen from Fig.6 that contact pressure on tunnel 1 decreases dramatically with an average magnitude of 102 kPa. Contact pressure on tunnel 3 reduces slightly in the process of excavation, with a maximum magnitude of 30 kPa. For tunnel 2, the change of contact pressure is more complicated. At the left shoulder, the contact pressure decreases significantly, but at the right shoulder the contact pressure only increases slightly due to the excavation-induced soil movement. The contact pressure on tunnel linings of tunnel located inside of diaphragm wall reduces more significantly compared with that outside the wall. Due to this irregular change of contact pressure, the deformations of tunnel in the three cases are different, as shown in Fig.5.

3.3 Stress path analysis

The stress path analysis is an effective tool to study the complex interaction between soil and structures. FUNATSU et al[13−14] used the stress path analysis to study the soil and tunnel interactions based on numerical modeling and a better insight into the problems were obtained.

In order to further understand the mechanism of tunnel responses induced by the excavation activities, 8 critical points were selected to observe the stress paths during the construction period. The locations and stress paths of these points are shown in Figs.7 and 8, respectively.

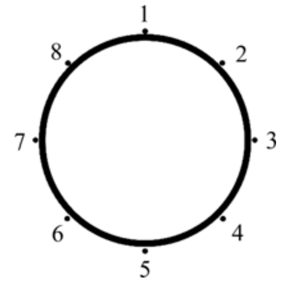

Fig.7 Locations of critical points for stress path analysis

For all the 8 nodes, the stress paths of the soil surrounding tunnels in these three cases during tunnel constructions are similar. Significant unloading in both vertical and horizontal directions occurs at Nodes 1 (crown) and 5 (invert). At nodes 3 (right springline) and 7 (left springline), there are significant increase in horizontal stress. That the stress changes around tunnels are consistent with the oval-shape deformations of tunnel due to excavation.

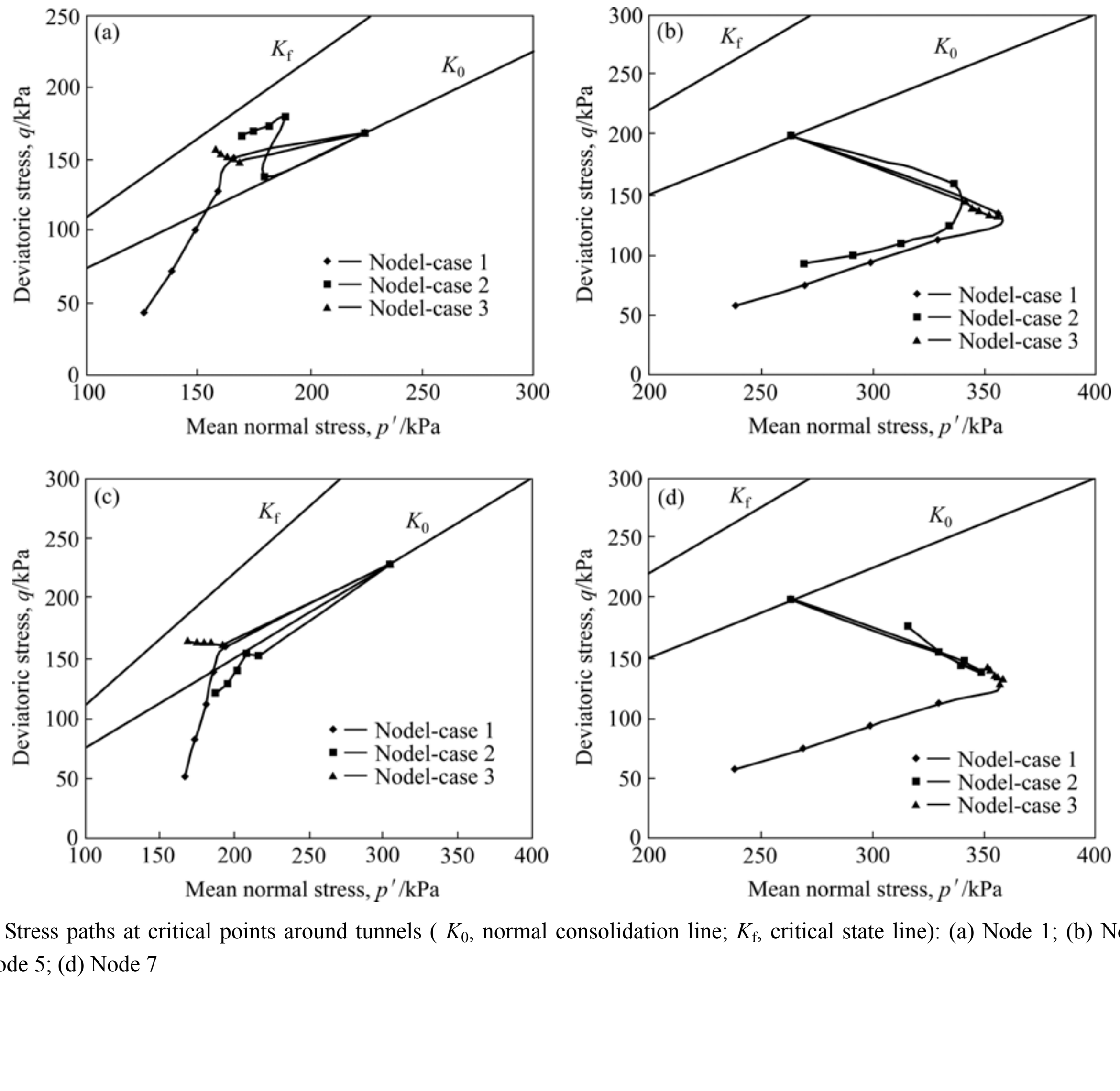

Fig.8 Stress paths at critical points around tunnels (K_0, normal consolidation line; K_f, critical state line): (a) Node 1; (b) Node 3; (c) Node 5; (d) Node 7

For tunnel 1, larger vertical stress release and less decrease of horizontal stress take place at Nodes 1 and 5 during excavation. The stress paths of nodes 3 and 7 decrease when gradients approximate to the K_0 curve, which means that stress reduction occurs in both horizontal and vertical directions during excavation. Meanwhile the magnitudes of the stress release in vertical direction at nodes 1 and 5 are much larger than those in horizontal direction at nodes 3 and 7, which leads decrease of diameter in horizontal direction and increase of diameter in vertical direction during excavation.

The stress change in soil surrounding tunnel 3 is slight with maximal magnitude at nodes 1, 3, 5 and 7 about 15 kPa during excavation. Overlying excavation produces much less influence on the tunnels located outside the pit.

The stress change of the soil around tunnel 2 is much more complicated. At node 1, the stress path goes upward first due to diaphragm wall installation and drops down during excavation. At nodes 3 and 5 stress releases occur in both vertical and horizontal directions during excavation. At node 7 there is a vertical stress increase along with a decrease in horizontal direction during excavation.

The stress paths of nodes 2 (right shoulder), 4 (right heel), 6 (left heel) and 8 (left shoulder) of tunnel 2 are shown in Fig.9. From Fig.9 it can be seen that the stress paths of nodes 4 and 8 drop down with gradients approximately to the k_o curve during excavation. Horizontal stress at node 2 increases while the vertical stress decreases. The soil stress at node 6 changes slightly.

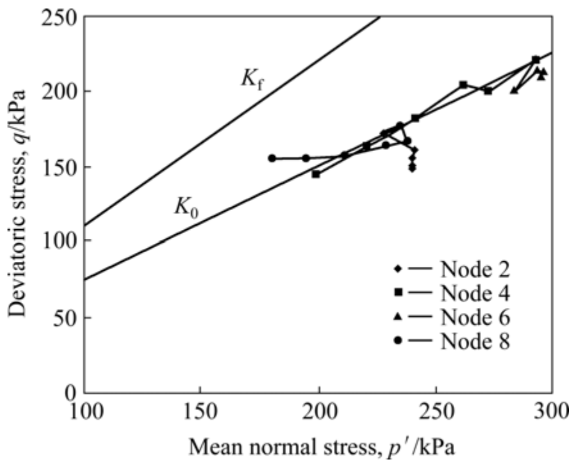

Fig.9 Stress paths at critical points around tunnel 2 (K_0, normal consolidation line; K_f, critical state line)

The way that the soil stress changes around tunnel 2 results in that the contact pressure on the right shoulder and left heel during excavation are much larger than those at left shoulder and right heel. This can be used to best explain the distortion of the tunnel 2 in the process of excavation as shown in Fig.5(b).

4 Parametric study and analysis

To study the effect of tunnel location change with respect to that in cases 1, 2 and 3 on tunnel responses, parameter study including vertical distance from the wall to the tunnel (h_t), and horizontal distance from excavation centerline to tunnel centerline (B_t) was performed.

The computed vertical displacements of tunnel invert and horizontal displacements of tunnel center are shown in Figs.10 and 11, respectively. From Fig.10 it can be seen that the vertical displacements of the tunnel decrease with the increase of B_t. From Fig.11 it can be seen that the maximum horizontal displacement occurs at the half way between pit centerline and diaphragm.

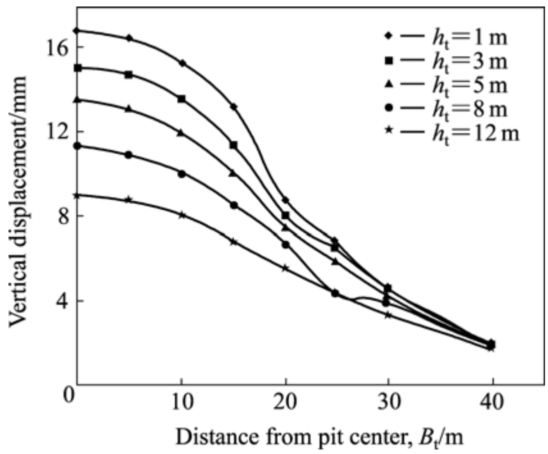

Fig.10 Vertical displacement versus B_t

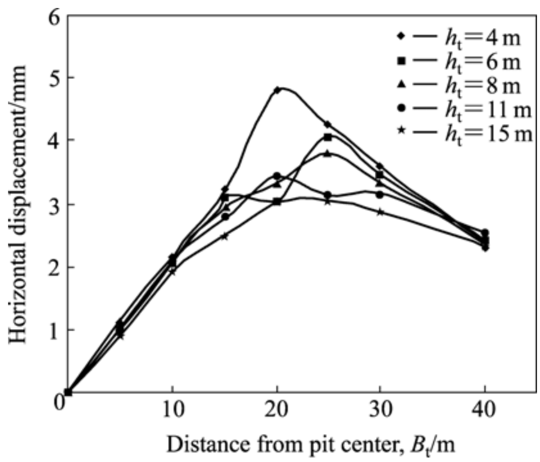

Fig.11 Horizontal displacement versus B_t

It should be noted that the maximum horizontal displacement is much smaller compared to the vertical displacement. Both vertical and horizontal displacements of the tunnels decrease with the increase of the tunnel embedded depth.

5 Conclusions

1) Excavation can cause deformation of underlying existing tunnel and change of contact pressure between lining and surrounding soil to underlying existing tunnel. Tunnel at different locations with respect to pit and diaphragm wall will experience different deformations and contact pressure changes.

2) For tunnel located inside diaphragm wall, large convergence occurs in horizontal direction when the tunnel is located close to excavation centerline, while for the tunnel located directly under the base of diaphragm walls, large convergence occurs at 30˚ in a clockwise direction from the vertical, and divergence occurs at 30˚ in a clockwise direction from the horizontal. For Tunnels located outside the wall, it experiences more slight distortions due to more slight soil stress changes during excavation.

3) The contact pressure on tunnel linings of tunnel located inside of diaphragm wall reduces more significantly compared with that outside the wall.

References

[1] BURFORD D. Heave of tunnels beneath the Shell Center, London, 1959−1986[J].Geotechnique, 1988, 38(1): 135−137.

[2] LO K Y, RAMSAY J A. The effect of construction on existing subway tunnels—a case study from Toronto[J]. Tunnels and Deep Space, 1991, 6(3): 287−297.

[3] DOLEZALOVA M. Tunnel complex unloaded by a deep excavation[J]. Computers and Geotechnics, 2001, 28(3): 469−493.

[4] SHARMA J A, HEFNY A M, ZHAO J, CHAN C W. Effect of large excavation on deformation of adjacent MRT tunnels[J]. Tunnelling and Underground Space Technology, 2001, 16: 93−98.

[5] HU Z F, YUE Z Q, ZHOU J, THAM L G. Design and construction of a deep excavation in soft soils adjacent to the Shanghai Metro tunnels[J]. Canadian Geotechnical Journal, 2003, 40(5): 933−948.

[6] JIA Jian. Study of controlling measures on the deflection of metro tunnels due to overlying excavation[J]. Underground Construction and Ground Movement, ASCE, 2006, 26(s): 158−163.

[7] MAO Chao-hui, LIU Guo-bin. Measures of preventing the in use tunnel disaster caused by overhead excavation[J]. Journal of Zhejiang University of Technology, 2005, 33(5): 534−537. (in Chinese).

[8] YANG Ting, WANG Xin-lian, XU Qiong-he, WANG Yi. Analysis and design aiming at control of upwarping deformation of existed tunnel under new tunnel's excavation[J]. Rock and Soil Mechanics, 2005, 26: 187−192. (in Chinese).

[9] WISSER C, AUGARDE C E, BURD H J. Numerical modeling of compensation grouting above shallow tunnels[J]. Int J Numer Anal Meth Geomech, 2005, 29: 443−471.

[10] KASPER T, MESCHKE G. A numerical study of the effect of soil and grout material properties and cover depth in shield tunneling[J]. Computers and Geotechnics, 2006, 33: 234−247.

[11] KARKI R. Effects of deep excavations on circular tunnels in fine-grained soils[D]. Canada: University of Saskatchewan, 2006.

[12] HIBBITT, KARLSSON, SORENSEN Inc. ABAQUS User's Manual, version 6.5[M]. 2004.

[13] FUNATSU T, HOSHINO T, SAWAE H, SHIMIZU N. Numerical analysis to better understand the mechanism of the effects of ground supports and reinforcements on the stability of tunnels using the distinct element method[J]. Tunnelling and Underground Space Technology, 2008, 23(5): 508−521.

[14] LIAO S M, GAO L Q, ZHU H H. Soft ground movement under small disturbance of shield driving[J]. Geotechnical Special Publication, 2006, 150: 62−69.

(Edited by CHEN Can-hua)