Investigation of response of metro tunnels due to adjacent large excavation and protective measures in soft soils

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Abstract: The inevitable influence of large excavation in soft soils on nearby tunnels is of great concern in practice. In this paper, the influence of a nearby large excavation on existing metro tunnels of the Ningbo Metro Line 1 in sensitive soft soils is investigated and presented. Considerable displacement in the left tunnel closer to the excavation induced by the nearby excavation was revealed by field monitoring. Visible cracks and leakages were observed in left tunnel linings. Three dimensional numerical simulations are conducted to investigate the responses of the ground and left tunnel due to the adjacent excavation. The development of bending moment and displacement of the left tunnel during different construction stages of the nearby excavation is obtained. Then the interaction mechanism between the nearby excavation, surrounding soils and existing twin tunnels is investigated, which is of significance to the interpretation of the influence of the nearby excavation on the existing twin tunnels. Several protective measures for alleviating the influence of

adjacent excavation on left tunnel are studied, including divided excavation, soil improvement and a cut-off wall. It is found that the left tunnel is influenced to varying degrees during different construction stages and the time effect is distinct for this large excavation in soft soils, which would be suggestive to engineers to pay more attention to the protection of adjacent tunnel during the crucial construction stages. The bending moment and displacement of the left tunnel is strongly related to the unloading effects and displacement of surrounding soils, which can be alleviated by means of proper improvement of excavation sequence. Comparatively, longitudinally divided excavation is more effective in protecting the left tunnel than soil improvement or a cut-off wall. This study is of certain reference value for protecting metro tunnels adjacent excavation in soft soils.

Keywords: Numerical analysis, Tunnel, Excavation, Displacement, Bending moment

1. INTRODUCTION

For the past few years, there has been rapid development of metros in many populous cities. Clearly, great attention needs to be paid to safety and serviceability. However, metro tunnels inevitably suffer various impacts caused by changes of the surrounding environment in urban cities. Nearby excavation is a major factor which can have a great impact. The unloading effects induced by excavation cause changes of the stress state and displacement of surrounding soils which will affect nearby metro tunnels. Visible cracks and leakages of linings will be observed if considerable deformations or internal forces occur in a tunnel.

Generally, soil excavation causes release of in situ stress and thus soil displacement (Chen et al., 2011a, 2011b, 2013), which inevitably exerts influence on existing structures. To better understand the influence of adjacent excavation on existing tunnels, theoretical analysis, numerical analysis and modeling tests have been conducted by many investigators. By analytical and semi-analytical methods, the excavation-soil-tunnel interaction mechanism was studied and the existing tunnel was assumed to be an elastic beam (Zhang et al., 2013a; Zhang et al., 2013b). Numerical analyses were conducted to evaluate the deformation response of an existing tunnel due to nearby excavation (Dolezalova, 2001; Sharma et al., 2001; Huang et al., 2013). In addition, Ng et al. (2013) conducted centrifuge tests of basement excavation effects on an existing tunnel in dry sand and carried out a numerical simulation for back-analysis. Ge (2002) studied the influence of an excavation on an adjacent existing metro tunnel systematically with analytical methods, field observation and numerical simulation. However, the above researches mainly focused on cases in which the existing tunnel was just underneath the excavation. The interaction between excavation and nearby tunnels was assumed to be plane-strain, which could not precisely reveal the actual effects of excavation on the nearby tunnel. Moreover, the studied excavations near existing tunnels were mostly small and could not cause an evident time-space effect.

Some typical protective measures, including soil improvement and cut-off walls, were studied to evaluate their effects on alleviating the impact of adjacent excavation on existing structures. Zhang et al. (2013a) studied the influence of divided

excavation on displacement of adjacent metro tunnels. Bai et al. (2014) investigated the effectiveness of several protection techniques, including cut-off walls and grouting reinforcement, on protecting nearby buildings during construction of the Bund Tunnel. Chen and Wang (2014) achieved satisfactory effectiveness in protecting existing twin tunnels near a deep excavation by combining isolation bored piles with triaxial soil-cement mixing piles. However, comparisons of the effectiveness of different protective measures were not carried out, as well as the varied responses of surrounding soils under different protective measures, which was beneficial to the interpretation of the mechanism of the distinct effectiveness of different protective measures.

In this study, three dimensional numerical simulations are conducted on the impacts of construction of a large adjacent excavation on existing twin tunnels in sensitive soft soils and we obtain the development of bending moment and displacement of the left tunnel during different construction stages of the nearby excavation. In addition, the excavation-soil-tunnel interaction mechanism is revealed. We also investigate the effect of divided excavation, soil improvement and a cut-off wall on alleviating the influence of the adjacent excavation on the existing left tunnel.

2. Ningbo Metro Line 1 and the adjacent excavation project

2.1. Ningbo Metro Line 1

Ningbo Metro Line 1 is the major line connecting the urban area of Ningbo east to west. As shown in Fig. 1, the studied section, consisting of two parallel tunnels, is

one of the sections of Line 1. The total length of this section is about 746.5 m. The twin tunnels of this section were driven by two earth pressure balanced shield machines (EPBS). As presented in Fig. 2, the horizontal distance between the centerlines of the twin tunnels ranges from 12 m to 15 m. The burial depth of the tunnel crown varies from 9 m to 15 m, and is 11.9 m on average. The internal and external diameters of tunnel linings are 5.5 m and 6.2 m respectively. The Young's modulus of concrete used for linings is 34.5 GPa. Each ring of linings consists of six 35 cm-thick prefabricated reinforced concrete segments with a width of 1.2 m. These segments are joined together by crooked bolts in both longitudinal and circumferential directions. The excavation of the left tunnel began on 28 February 2011. The shield machine arrived at Ring 36 (southeast corner of the nearby excavation) on 7 March 2011 and at Ring 280 (southwest corner of the nearby excavation) on 4 April 2011. The left tunnel was completed on 30 May 2011. The right tunnel began to be tunnelled on 6 July 2011 and was completed on 5 November 2011.

2.2. Adjacent excavation

As shown in Figs. 1 and 2, the excavation nearby the twin tunnels, named as C1-6 and C1-7, was retained by bored piles combined with two levels of reinforced concrete struts. The horizontal distance from the left tunnel to the nearby excavation ranged from 7.2 m to 13 m. The length of the excavation was about 240 m, while the width of the excavation ranged from 80 m to 120 m. The final excavation depth was 11.4 m on average. The length, diameter and spacing of bored piles were 22.8 m, 950

mm and 1100 mm, respectively. The lengths and widths of the cross-sections of struts varied at different zones and ranged from 600 mm to 1000 mm. The struts were supported in the vertical direction by steel lattice columns. The Young's modulus of bored piles and struts was all 30 GPa. As shown in Fig. 2, the soil excavation was conducted vertically in three steps to levels of -3.4 m, -7.9 m and -11.4 m. Consequently, two levels of reinforced concrete struts were installed at levels of -2.9 m and -7.4 m. Nearly one month after the completion of the right tunnel, the construction of the adjacent excavation commenced, on 1 December 2011. Concrete casting of the second level struts was completed on 11 January 2012. Thereafter, the 3rd excavation step was carried out from 11 March 2012 to 29 March 2012.

2.3. Geological conditions

The twin tunnels and excavation were constructed in typical soft soil strata. The groundwater level was at a depth of 1.0 m below the ground surface (GL-1.0 m). As shown in Fig. 2 and Table 1 (Shanghai Municipal Engineering Investigations & Design Co., Ltd, 2009), thick marine sedimentary soft soils characterized by high water content, high compressibility, high sensitivity and low strength are widely distributed in the construction site. The soil layers that shield machine tunneling mainly went through include mud (layer ②₁), muddy clay (layer ②₂), silty sand (layer ③₁) and silty clay (layer ③₂). Especially for layer ②₁, from GL-7.9 m to GL-11.4 m, i.e. mud, the void ratio and water content reach 1.558 and 55.6%, respectively. For the above soft clays, relatively lower undrained shear strength (S_u)

gained from vane shear tests is measured, the ratio of which to the effective vertical stress (σ'_v) at the corresponding depth is only about 0.14 (Li, 2015) compared with 0.22-0.3 gained from Taipei (Lim et al., 2010) and Hangzhou (Chen et al., 2014). Moreover, the sensitivities for soil layer ② (mud) and layer ② (muddy clay) reach 5.4 and 5.8 respectively (Shanghai Municipal Engineering Investigations & Design Co., Ltd, 2009). The mechanical properties of the above soils would be weakened severely after being disturbed by adjacent construction. The excavation inevitably caused disturbance to the surrounding soils and thus impacted on the nearby twin tunnels. Furthermore, soil layer ③₁ is a confined aquifer characterized by high water content and high water level. In this case, severe leakages would occur in any penetrating cracks in tunnel linings.

3. Field observation and monitoring

As shown in Fig. 3 (a), cracks and leakages at the invert region of the left tunnel were observed by workers on 13 March 2012. Afterwards, as shown in Fig. 3 (b), longitudinal cracks and leakages around the springline and invert regions of the left tunnel were observed on 19 March 2012. Ring 40 to Ring 414 of the left tunnel were damaged to varying degrees, including ring joints being stretched and dislocated and segments damaged.

Meanwhile, field monitoring also indicated that considerable deformation had occurred in the left tunnel which severely threatened its serviceability and safety. During the 3rd excavation step, the maximum increment of horizontal displacement

reached 33.5 mm at Ring 163. In addition, increments of horizontal convergence, vertical convergence and settlement of Ring 221 were 21.9 mm, 16 mm and 25.3 mm, respectively.

4. Numerical analysis details

In this study, the computer program, PLAXIS 3D (Brinkgreve et al., 2006), was used for evaluation. To eliminate the effects of model scope on the results, lateral boundaries are extended to more than 4 times the final excavation depth (Lim et al., 2010). Thus, the domain of the models is 360×260×40 m. Lateral boundaries are fixed in the horizontal direction and on the bottom boundary in both vertical and horizontal directions.

4.1. Analysis cases

To precisely reflect field construction procedure, the construction of the twin tunnels prior to the excavation was also simulated. The main object of this study is focused on the net influence of nearby excavation on the existing tunnel. The time interval between the completion of left tunnel and beginning of excavation work was nearly six months. And the excess pore water pressure generated by the tunnel construction dissipated almost completely just before excavation. In order to investigate the net influence of the nearby excavation, the tunnel construction simulation was simplified compared with step-wise manner (Broere and Brinkgreve, 2002) and lining contraction method (Möller and Vermeer, 2008). The tunnel linings

were activated first and then the elements inside the tunnel were deactivated (Ge, 2002). Before the next calculation step, the displacements of soils and structures are reset to zero. Then, the excavation is simulated using a step-by-step approach. The function of waterproof curtain is modeled by activating interface element along the excavation peripheries. As shown in Table 2, the dissipation of excess pore water pressure is simulated during the consolidation step in the time interval that exists between every two successive construction stages. The above simulation, broadly in line with the field conditions, is referred to as case 1. Furthermore, in order to investigate the excavation-soil-tunnel interaction mechanism, a simulation, called case 2, is conducted for the case that the twin tunnels do not exist.

In addition, the effects of divided excavation on the left tunnel are also evaluated in case 3. In this case, three divided excavation schemes are simulated. To be specific, as shown in Figs. 4 (a) and (b), the soils which would be excavated during the original 2nd and 3rd excavation steps are divided by 12 pieces of which widths are about 20 m and excavated from the longitudinal periphery to the central section of the excavation in case 3-1. The previous last two excavation steps are divided along the transversal direction in case 3-2. Compared with the above two cases, and as shown in Fig. 4 (c), the original last two excavation steps are conducted initially in the transversal direction and then the longitudinal direction in case 3-3.

The effects of soil improvement using a soil-cement mixing method adopted along the southeast excavation periphery are investigated in case 4, as shown in Fig. 5 (a). As depicted in Fig. 5 (b), the soil-cement mixture zone extends vertically 16.5 m

from -2.9 m to -19.4 m and horizontally 10 m from the retaining piles to the excavation zone. The effective Young's modulus of the improved soil is 120 MPa, and the corresponding effective cohesion and friction angle are 500 kPa and 30 °, respectively. The soil improvement is conducted prior to the general excavation procedure.

Finally, in case 5, as shown in Fig. 5, the effects of a cut-off wall installed prior to the excavation procedure are also investigated. The cut-off wall, located between the retaining piles and left tunnel, is composed of bored piles. The scale of the cut-off wall in plan view is about 0.5 times the length of the southeast excavation periphery. The diameter of bored piles with axial spacing of 1 m is 800 mm. The total length of bored piles is 30 m. The above analysis cases are listed in Table 3.

4.2. Material model and parameters

In the FE models, the soil layers are modeled using a 10-nodes wedge element. For the behavior of resistance to bending, the reinforced concrete struts are simulated by a 3-nodes beam element. The 6-nodes plate element is used to simulate the behavior of retaining piles, tunnel linings and isolation piles on the basis of equal stiffness. The behavior of the above structures is assumed to be linear elastic. To simulate the interaction between structures and soil layers, a 12-nodes interface element is used which allows the interface condition to be analyzed. A strength factor R_{inter} is introduced to define the strength parameters of the interface relative to those of the original material. For instance, the mesh of the FE model of case 1 is shown in

Fig. 6 which consists of about 160,000 10-node wedge elements.

The effective stress indices are used to represent the strength characteristics of all the soil layers of which the behavior is assumed to be elastoplastic. The Hardening soil (HS) model and Mohr-Coulomb model are employed to simulate the behavior of soft soils and other stiffer soils, respectively. The HS model is an elastoplastic, double-hardening, effective stress soil model of which failure is defined by the Mohr-Coulomb failure criterion (Schanz et al., 1999). The soil parameters used for analysis in this study were obtained from a series of laboratory tests, including triaxial isotropically consolidated undrained tests, drained tests and oedometer tests (Li, 2015). The input soil parameters for numerical modeling are presented in Table 4.

Considering the influence of joints between every two intersecting segments, the effective rigidity ratios of the lining for longitudinal and circumferential directions are set to be 0.17 and 0.7 (Huang et al., 2013). Meanwhile, the stiffness of retaining piles, isolation piles and struts is reduced by 20% (Lim et al., 2011) from the nominal value considering that the stiffness of the concrete retaining piles reduces when cracks occur in the concrete. The above reductions of stiffness are only for the Young's modulus, which will not change the boundary condition. To simplify the model, the effects of steel lattice columns on the vertical constraint of struts are simulated by setting the prescribed vertical displacement of intersections to zero. The mechanical property parameters of plate elements involved in the models are presented in Table 5.

5 Results and discussions

5.1. Sensitivity analysis and numerical model verification

To evaluate the reliability of the above simulations, the horizontal and vertical displacements of the left tunnel at the invert level during the 3rd excavation stage are obtained from both measurements and calculation. Considering the lack of the measured displacement, sensitivity analysis with 10 sets of stiffness and strength parameters of all soils involved in the numerical model, i.e. 0.8, 0.9, 1.0, 1.1 and 1.2 times the effective Young's modulus E' , effective cohesion c' and tangent friction angle φ' listed in Table 4, is conducted. As shown in Fig. 7 (a), the calculated horizontal displacement using the soil parameters listed in Table 4, which is referred to as 1.0 Stiffness, is close to the corresponding measured value. And the horizontal displacement of left tunnel within the excavation area increases with the decreasing of soil stiffness parameters. Despite the lack of measured vertical displacement which can roughly depict the vertical displacement pattern, as presented in Fig. 7 (b), the calculated vertical displacement of left tunnel is highly sensitive to the soil stiffness parameters, of which obtained from the original soil stiffness parameters, i.e. 1.0 stiffness, reflects a pretty good consistency with the measured value.

Fig. 8 (a) illustrates that the calculated horizontal displacement of left tunnel obtained from different soil strength parameters is also roughly close to the measured value. And the horizontal displacement is less sensitive to the soil strength parameters. Fig. 8 (b) depicts that the vertical displacement is more sensitive to the soil strength

parameters compared with the horizontal displacement and the calculation using 1.0 strength parameters achieve the most suitable results compared with the measured value.

Overall, it is found that the calculated vertical displacement is highly sensitive to the adopted both soil stiffness and strength parameters. And the original soil parameters listed in Table 4, i.e. 1.0 stiffness and 1.0 strength, achieve the most suitable results compared with the measured value. Hence, it is appropriate to conclude that the above simulations are reliable. In addition, for both horizontal and vertical displacements, it is evident that displacement of the left tunnel increases significantly when approaching the central section of the nearby excavation.

5.2. Development of bending moment and displacement of left tunnel

As discussed above, the excavation was conducted step-by-step. Hence, the nearby left tunnel is influenced to varying degrees during different construction stages. Fig. 9 plots the displacement increments of the left tunnel during different construction stages of the adjacent excavation. The horizontal displacement increments during the 1st and 2nd excavation steps are almost the same and significantly greater than those during the 3rd excavation step. The maximum horizontal displacement increments during the above three excavation steps are 41.0 mm, 39.5 mm and 27.6 mm, respectively. For the vertical displacement increments, the situation is distinctively different in that the increments are about the same during the 2nd and 3rd excavation steps and considerably greater than those during the 1st

excavation step. To be specific, the maximum vertical displacement increments during the above three excavation steps reach -10.5 mm, -27.6 mm and -26.2 mm. Increments are also obtained of both horizontal and vertical displacements during strutting steps. There is a clear resilience of the vertical displacement during the 1st strutting step of which the maximum value reaches 4.3 mm. The maximum horizontal displacement increment during the 1st strutting step reaches 5.2 mm while the value is only 0.7 mm during the 2nd strutting step. Consequently, it is indicated that non-ignorable displacement increments are caused during strutting steps compared with those during excavation steps. Essentially, the time effect is distinct for the large excavation in soft soils.

As shown in Fig. 10 (a), the bending moment of Ring 175 changes stage by stage along with the construction procedure of the excavation. After the 3rd excavation step, the maximum positive and negative bending moments reach 247 kN·m/m and -192 kN·m/m. In addition, it is easy to find that larger bending moments are caused around the left springline zone compared with those around the right springline zone. Fig. 10 (b) plots the radial displacement increments of Ring 175 during different construction stages and the final radial displacements after the 3rd excavation step. It can be seen that considerable radial displacement increments are caused during strutting steps with the maximum value of nearly -6.9 mm. During excavation steps, radial displacement increments towards the tunnel center are caused in the zone between the right springline and crown of the whole ring while it is just the opposite in the zone between the invert and left springline. As a result, the

accumulated radial displacement induced by excavation is significant with the maximum value of 136 mm at an angle of 205.7 °.

Considering the relative position between excavation and Ring 175, the above displacement pattern and bending moment distribution are strongly related to the performance of the surrounding soils. The excavation-induced soil unloading effects around the zone between the invert and left springline cause the tunnel linings in the zone to deform radially away from the tunnel center. However, radial displacement towards the tunnel center is induced by the ground movement towards the excavation in the zone between the right springline and crown. And the relatively larger bending moments around the left springline zone can also be attributed to the unloading effects and displacements of surrounding soils induced by the nearby excavation. The above results of bending moment and radial displacement can be verified by the appearance of observed cracks and leakages in these zones.

5.3. Excavation-soil-tunnel interaction mechanism

It is easy to appreciate that the adjacent excavation, surrounding soils and existing tunnel are interactive in practice. This study also attempts to reveal the excavation-soil-tunnel interaction mechanism. Hence, as presented in Fig. 11, the vertical displacement of the ground surface along *B-B* line, which is perpendicular to the southeast excavation periphery at *A* as shown in Fig. 1 in case 1 and case 2 is obtained. It is found that the existing twin tunnels significantly decrease the vertical displacement from the maximum value of -168 mm to -148 mm. It can also be seen

that the vertical displacement is greatly decreased around the zone just above the twin tunnels.

The lateral displacement of soils at the positions with different distances to the southeast excavation periphery along *B-B* line in case 1 and case 2 is presented in Fig. 12. As can be seen, at the position between the left tunnel and the excavation ($d=0.5H$), the existing twin tunnels slightly increase the lateral displacement of soils in the shallow zone while those in the deep zone are decreased. As to the position just away from the right tunnel ($d=4H$) and between the left tunnel and right tunnel ($d=2H$), the lateral displacement is just the opposite. For the position relatively far away from the right tunnel ($d=6H$ and $d=8H$), the existing twin tunnels slightly increase the lateral displacement of soils along the entire depth.

The lateral displacement of retaining piles at *A* is shown in Fig. 13. It is found that the existing twin tunnels slightly increase the lateral displacement of the retaining pile in the shallow zone while those in deep zone are significantly decreased. The above changes of performance of surrounding soils and retaining piles induced by the twin tunnels will inevitably in turn cause exert additional effects on the twin tunnels themselves as discussed in *Section 5.2*.

5.4. Effectiveness of protective measures

Finally, the effectiveness of divided excavation, soil improvement excavation and a cut-off wall on alleviating the influence of the nearby excavation on the left tunnel is also discussed. Before evaluating their effectiveness, the impact of these

measures on vertical displacement of ground surface and lateral displacement of soils is investigated.

Fig. 14 illustrates the vertical displacement of the ground surface along the *B-B* line obtained in cases where the twin tunnels are not simulated, i.e. case 2. Compared with case 1 that no additional protective measures were adopted, it can be seen that soil improvement and longitudinal divided excavation effectively restrain the vertical displacement of the ground surface along *B-B* line. As to the effects of the cut-off wall, the vertical displacement of ground surface is initially decreased and then increased. For the cases in which the excavation is divided in transversal and bi-directional directions, the vertical displacement of ground surface is slightly decreased.

As shown in Fig. 15, the lateral displacement of soils towards excavation at the position where the distance to the excavation periphery is 0.5 times the excavation depth ($d=0.5H$) is also presented. It is clear that all protective measures achieve evident effects on decreasing the soil lateral displacement in the shallow zone especially soil improvement. While, in the relatively deep zone, namely approximately beneath the elevation of the left tunnel crown, the longitudinal divided excavation significantly decreases the soil lateral displacement. It is worth noting that the most significant soil lateral displacement around the elevation of the left tunnel is obtained in case 5 in which the cut-off wall is considered. The above effects of protective measures on surrounding soils displacement will then exert influence on the existing twin-tunnels.

Then, as shown in Fig. 16 (a), the effects of protective measures on the

horizontal displacement of the left tunnel are investigated. It is found that longitudinal divided excavation achieved the most significant effect in decreasing the horizontal displacement of the left tunnel compared with other measures. Compared with case 1 in which no additional protective measures are adopted, longitudinal divided excavation decreases the maximum horizontal displacement of left tunnel from 112 mm to 65.8 mm. However, unexpectedly, the cut-off wall significantly increases the horizontal displacement such that the maximum value is increased to 139.8 mm. For the vertical displacement of the left tunnel illustrated in Fig. 16 (b), similarly, it can be seen that longitudinal divided excavation achieved the most significant effect. And, compared with case 1, the maximum horizontal displacement is decreased from -60.8 mm to -27.3 mm. Compared with the situation of horizontal displacement, the cut-off wall achieves a distinct effect on decreasing vertical displacement of the left tunnel within the scope of the cut-off wall.

As illustrated in Fig. 17, we also examine the radial displacement and bending moment of Ring 175 induced by excavation. Compared with other cases, the transversal divided excavation significantly increases the bending moment of Ring 175 such that the maximum positive and negative values reach 232 kN·m/m and -205 kN·m/m, respectively. For radial displacement, as presented in Fig. 17 (b), the cut-off wall achieves an adverse effect on alleviating the radial displacement of Ring 175. This result can be attributed to the relatively larger lateral displacement of soils between the left tunnel and the excavation within the elevation scope of the left tunnel, i.e., from GL-11.9 m to GL-18.1 m, as discussed above. The radial displacements

obtained in case 3-2, case 3-3 and case 4 are similar. However, for both bending moment and radial displacement, compared with case 1, the longitudinal divided excavation achieves the most significant effect on alleviating the influence of excavation on the left tunnel. The maximum above values are decreased from 247 kN·m/m to 175 kN·m/m and 136 mm to 80.5 mm, respectively.

In order to investigate the reason for the different effectiveness of a cut-off wall on alleviating horizontal and vertical displacement, the lateral displacements of the cut-off wall (in case 5) and soils (in case 1) at *C*, as shown in Fig. 5, are illustrated in Fig. 18. This shows that there is overall lateral displacement of the cut-off wall. Compared with soil lateral displacement in case 1, the lateral displacement of the cut-off wall is larger at an elevation of -14.6 m to -24.3 m which may increase the lateral displacement of the left tunnel compared with that of case 1. Furthermore, the inflection of the cut-off wall would restrict the development of the vertical displacement of soils in front of it. Thus, as shown in Fig. 16 (b), the development of the vertical displacement of the left tunnel is restricted indirectly in case 5.

6 Conclusions

In this paper, the influence of a nearby large excavation on existing twin tunnels in soft soils is studied by 3D FEM and verified by field monitoring. The development of bending moment and displacement of the left tunnel, the excavation-soil-tunnel interaction mechanism and effectiveness of several protective measures are investigated. The conclusions of this study can be generalized as follows:

1. From field monitoring, the maximum horizontal displacement and convergence of the left tunnel caused during the 3rd excavation step of the adjacent excavation reaches 33.5 mm and 25.3 mm, respectively. As a result, longitudinal cracks and leakages were observed in many places of the left tunnel. On this occasion, the safety of the left tunnel was severely threatened.

2. Compared with the horizontal displacement, the calculated vertical displacement is more sensitive to the adopted both soil stiffness and strength parameters. And the original soil parameters achieve the most suitable results compared with the measured value and other soil stiffness and strength parameters.

3. For both horizontal and vertical displacement of the left tunnel, it is evident that displacement of the left tunnel increases significantly when approaching the central section of the adjacent excavation. The left tunnel would be influenced to varying degrees during different construction stages of the excavation. Compared with other construction stages, the major horizontal displacement increments are caused during the 1st and 2nd excavation steps while for vertical displacement increments during it is the 2nd and 3rd excavation steps. Bending moment and radial displacement of Ring 175 also develop stage by stage. The distribution of the radial displacement of Ring 175 may be attributed to the unloading effects and displacement of surrounding soils.

4. The nearby excavation, surrounding soils and existing twin tunnels are interactive. Nearby excavation causes the additional displacement and bending moment of the twin tunnels. In turn, the existing twin tunnels change the displacement

of retaining piles and surrounding soils compared with the case in which the twin tunnels do not exist.

5. The effectiveness of divided excavation, soil improvement excavation and cut-off wall on alleviating the influence of excavation on left tunnel are distinctively different. Compared with other protective measures, the relatively ideal effects are achieved when longitudinal divided excavation is conducted. Due to significant overall lateral displacement and inflection of the cut-off wall, compared with case 1 in which no protective measures are considered, unexpectedly, it is worth noting that greater horizontal displacement and smaller vertical displacement occur in the left tunnel.

From the above findings, for this particularly large excavation in soft soils, it is appropriate to conclude that the proper improvement of excavation sequence, namely longitudinal divided excavation, would be the most effective way to alleviate the influence of excavation on a nearby tunnel rather than other strengthening measures like soil improvement or a cut-off wall. The above discoveries should be instructive to similar projects.

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Fig. 1. Plan view of the shape and relative position of the excavation and twin tunnels.

Fig. 2. Profile of subsurface soil layers, excavation sequence and relative position between the excavation and twin tunnels.

(a)

(b)

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(a)

(b)

(c)

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Table 1

Soil basic physical property index.

Soil layer	Void ratio e_0	Volumetric weight γ (kN/m ³)	Water content w (%)	At-rest earth pressure coefficient K_0
① ₁ Fill	0.95	18.5	34.0	0.5
① ₂ Clay	0.966	18.4	34.3	0.48
① ₃ Silty clay	1.344	17.1	48.3	0.62
② ₁ Mud	1.558	16.5	55.6	0.66
② ₂ Muddy clay	1.381	16.8	49.0	0.6
③ ₁ Silty sand	0.730	19.1	25.5	0.35
③ ₂ Silty clay	0.871	18.7	30.0	0.44
④ ₁ Silty clay	1.12	18.3	31.5	0.6
④ ₂ Clay	1.27	17.6	39.2	0.6
⑤ ₁ Clay	0.781	19.2	27.3	0.3

Table 2

Time intervals simulated in consolidation steps.

Simulated steps	Time interval between two steps (days)
Left tunnel construction	180
Right tunnel construction	30
Retaining structure activated	60
1st excavation	60
2nd excavation	
3rd excavation	60

Table 3

Analysis cases.

Case	Twin tunnels	Divided excavation	Soil improvement	Cut-off wall
1	Simulated	—	—	—
2	—	—	—	—
3-1	Simulated	Longitudinal	—	—
3-2	Simulated	Transversal	—	—
3-3	Simulated	Bi-directional	—	—
4	Simulated	—	Simulated	—
5	Simulated	—	—	Simulated

Table 4

Soil parameters for Hardening Soil model and Mohr-Coulomb model.

Parameter type(units)	① ₁	① ₂	① ₃	② ₁	② ₂	③ ₁	③ ₂	④ ₁	④ ₂	⑤ ₁
Constitutive model	MC/D	MC/U	MC/U	HS/U	HS/U	MC/D	HS/U	HS/U	HS/U	MC/U
E_{50}^{ref} (kPa)	—	—	—	1370	2045	—	6180	4579	2091	—
$E_{\text{ur}}^{\text{ref}}$ (kPa)	—	—	—	4110	6135	—	18540	13737	6273	—
$E_{\text{od}}^{\text{ref}}$ (kPa)	—	—	—	1370	2045	—	6180	4579	2091	—
E' (kPa)	12000	11037	6264	—	—	40200	—	—	—	12258
m	—	—	—	1.0	1.0	—	0.9	1.0	1.0	—
c' (kPa)	5	9.3	6.6	6.6	2	0	0	0	8	41.6
φ' (°)	30	26.1	25.1	21.1	23.7	31.1	33.9	23.6	27	24.1
ν_{ur}	—	—	—	0.2	0.2	—	0.2	0.2	0.2	—
ν	0.3	0.3	0.3	—	—	0.3	—	—	—	0.3
R_{inter}	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65

Note: D =Drained; U =Undrained; E_{50}^{ref} =reference secant stiffness of trial axial compression stress paths; $E_{\text{ur}}^{\text{ref}}$ =reference stiffness for unloading/reloading stiffness; $E_{\text{od}}^{\text{ref}}$ =reference stiffness from one-dimensional compression tests; E' =effective Young's modulus; m =power that controls the stress dependency of stiffness; c' =effective cohesion of soil; φ' =effective friction angle of soil; ν_{ur} =Poisson's ratio of unloading/reloading; ν =Poisson's ratio for MC model; and R_{inter} =soil strength reduction in interface element.

Table 5

Parameters for retaining pile, tunnel lining and isolation pile.

Parameter type (units)	Retaining pile	Lining	Isolation pile
d (m)	0.82	0.35	0.69
γ (kN/m ³)	4.75	7.0	4.40
E_1 (kN/m ²)	1.89E+7	5.87E+6	1.75E+7
E_2 (kN/m ²)	—	2.42E+7	—
ν	0.21	0.15	0.21

Note: d =thickness of plate element; γ =additional unit weight of plate; E_1 =Young's modulus in longitudinal direction for lining; E_2 =Young's modulus in circumferential direction for lining; and ν =Poisson's ratio of concrete.