Influence of a nearby large excavation on existing metro in soft soils

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1 INTRODUCTION

For the past few years, metros have entered into a rapid development period in many populous cities. As a life line structure, much attention should be paid to its safety and serviceability. However, metro tunnels inevitably suffer various impacts by changes of surrounding environment in urban cities. Typically, adjacent excavation is a major fact which has a great impact on existing metro. The unloading effects induced by excavation cause changes of the stress state and displacements of surrounding soils which will naturally affect the adjacent tunnel.

To get a better understanding of the influence of excavation on adjacent tunnel, theoretical analysis, field monitoring and numerical analysis have been conducted by several researchers (Jiang et al., 2007; Shi et al., 2008; Chen et al., 2011; Wei, 2013). By analytical and semi-analytical method, the interaction between excavation-soil-tunnel was studied and existing tunnel was assumed as an elastic beam (Zhang et al., 2013; Zhang et al., 2013). Numerical analysis was conducted to evaluate the deformation response of existing tunnel induced by adjacent excavation (Sharma et al., 2001; Dolezalova, 2001; Huang et al., 2013; Hu et al., 2013). However, the above researches mainly focused on the cases in which the existing tunnel was just underneath the above excavation and assumed that the interaction between excavation and adjacent tunnel plane-strain which could not reveal the discipline of effect of excavation on adjacent tunnel exactly. In addition, the studied excavations adjacent existing tunnels were substantially all small-sized which could not cause evident space effect when excavated.

In this study, three dimensional numerical analyses on the impacts of excavation of a large excavation on the nearby existing twin tunnels in soft soils are conducted. Combining with field monitoring and numerical analyses, this study reveals the development of displacements and internal forces of existing twin tunnels and the relationship between displacement of surrounding soils and existing twin tunnels. Furthermore, the effects of divided excavation during the 3rd excavation step on alleviating the displacements and internal forces of left tunnel are also discussed.
2 PROJECT INTRODUCTION

The studied twin tunnel section is a part of Ningbo Metro Line 1 in Ningbo city in east part of China. This twin tunnels were driven by two earth pressure balanced shield machines (EPBS). The inner and outer diameters of linings are 5.5 m and 6.2 m, respectively. Horizontal distances between centerlines of the twin tunnels ranged from 12 m to 15 m. The cover depth above the tunnel crown varied from 9 m to 15 m, and was 11.9 m on average. The Young’s modulus of lining concrete is 34.5 GPa. Each ring of linings consists of six prefabricated reinforced concrete segments. These segments are joined together by crooked bolts in longitudinal and circumferential directions.

Nearby excavation, namely C1-6/7, was retained by bored piles combining with two levels of reinforced concrete struts. 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 10.2 m to 12 m. The diameter, length and spacing of bored piles were 950 mm, 22.8 m and 1100 mm, respectively. The struts were supported in vertical direction at intersections by steel lattice columns. The Young’s modulus of bored piles and struts were all 30 GPa. The horizontal distance between the excavation and centerline of left tunnel ranged from 10.3 m to 16.1 m. The soil excavation was conducted vertically in three steps: excavated to levels of -3.4 m, -7.9 m and -11.4 m. Consequently, two levels of reinforced concrete struts were installed at the levels of -2.9 m and -7.4 m, respectively. The shape and relative position of the excavation and twin tunnels in plan view are shown in Fig. 1. Furthermore, profile of subsurface soil layers, excavation sequence and relative position between the excavation and twin tunnels is shown in Fig. 2.

3 GEOLOGICAL CONDITIONS

The twin tunnels and excavation were constructed in typical soft soil stratum. The groundwater level was at a depth of 1.0 m below the ground surface (GL-1.0 m). The typical profile of subsurface soil layers is presented in Fig. 2. Thick marine sedimentary soft soils characterized by high water content, high compressibility, high sensitivity and low strength were widely distributed in the construction site. The soil layers that shield machine tunneling mainly went through included mud (layer ②1), silty 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 reached 1.558 and 55.6%, respectively. The mechanical properties of the above soils would be weakened severely after being disturbed by nearby construction. In this project, the excavation inevitably caused disturbance on the surrounding soils and thus impacts on the nearby twin tunnels. Furthermore, soil layer ③1 was a confined aquifer characterized by high water content and high water level. In this case, severe leakages would occur in penetrating cracks in tunnel linings.

Fig. 1. Plan view of excavation and twin tunnels.
4 OBSERVATION AND FIELD MONITORING

Cracks and leakages at invert region of left tunnel were observed by workers on March 13th 2012. Afterwards, longitudinal cracks and leakages at invert and springline region of left tunnel were observed on March 19th 2012. Ring 40 to Ring 414 of left tunnel were damaged by varying degrees, including ring joints stretched, dislocated and segments damaged.

Meanwhile, field monitoring also indicated that left tunnel suffered considerable deformation. The maximum increment of horizontal displacements of left tunnel during the 3rd excavation step as shown in Fig. 2 in which the soils from level of -7.9 m to -11.4 m were excavated reached 33.5 mm at Ring 163. Moreover, increments of horizontal convergence, vertical convergence and settlement of Ring 221 during the 3rd excavation step were 21.9 mm, 16 mm and 25.3 mm, respectively. From the completion of left tunnel to the completion of the excavation, the maximum increments of horizontal convergence and vertical convergence all occurred at Ring 241 and reached 28 mm and 23 mm, respectively. The maximum increment of settlement during the period reached 33.6 mm at Ring 160.

5 DETAILS OF NUMERICAL ANALYSIS

For eliminating the effects of model scope on calculation results, horizontal and vertical boundaries are extended to more than 4 times the final excavation depth (Lim et al., 2010). Thus, the domain of the model is $360 \times 260 \times 40$ m. Lateral boundaries are fixed in horizontal direction and the bottom boundary in both vertical and horizontal directions.

In the FE model, the soil layers are modeled using 10-nodes wedge element. Considering the behavior of resistance to bending, the reinforced concrete struts are simulated by 3-nodes beam element. The 6-nodes plate element is used to simulate the behavior of linings and retaining piles. The behavior of structures involved in the model is assumed to be linear elastic. To simulate the interaction between structures and soil layers, 12-nodes interface element is used which allow the interface condition to be analyzed.

The effective stress indices are used to represent the strength characteristics of all the soil layers. The behavior of soil layers is assumed to be elastoplastic. Hardening soil model and Mohr-Coulomb model are used for soft soils and other stiffer soils in the model, respectively. The HS model is an elastoplastic, double-hardening, effective stress soil model of which failure is defined by Mohr-Coulomb failure criterion (Schanz et al. 1999). Parameters for HS model and MC model were obtained by an extensive laboratory tests involving characterization tests, permeability tests, oedometer tests, triaxial tests, etc.

Considering the influence of joints between every
two intersecting segments, the effective rigidity ratios of the lining in longitudinal and circumferential direction are set to be 0.17 and 0.7 in this study (Huang et al., 2013), respectively. Meanwhile, the effective rigidity ratios of retaining piles and struts are set to be 0.84 and 0.93 respectively considering the construction deficiency. To simplify the model, the effects of pillars on vertical constraint of struts at intersections are simulated by setting the prescribed vertical displacement of intersection points to zero.

To precisely consider the field construction procedure, the metro line construction prior to the excavation is also simulated using lining reduction method (Möller and Vermeer, 2008). Then, the excavation is simulated using a step-step approach. The function of waterproof curtain is modeled by activating the presupposed interface element at the periphery of excavation. The dissipation of excess pore water pressures is simulated in consolidation step in the case that time interval exists between every two successive construction steps. As shown in Fig. 3, the above simulation which is broadly in line with field condition is referred to as case 1. Furthermore, in order to evaluate the influence of existing twin tunnels on displacement of surrounding soils, numerical model in the case that the twin tunnels do not exist in the full simulation process of excavation, namely case 2, is also included and discussed.

In addition, effects of divided excavation on alleviating the deformations and internal forces of left tunnel during the 3rd excavation step are also simulated in case 3. In this case, as shown in Fig. 1, the 3rd excavation step is divided by 6 steps from the periphery to the central section of the excavation. The soils which would be excavated during the 3rd excavation step in case 1 are divided by 12 pieces of which widths are all about 20 m. The above three analysis cases are presented in Table 1.

| Case | Simulation procedure |
|------|----------------------|
| 1    | Broadly in line with field condition |
| 2    | The twin tunnels were not simulated |
| 3    | The original 3rd excavation step was divided by 6 steps from the periphery to central section of the excavation |

6 RESULTS AND DISCUSSIONS

6.1 Horizontal displacement

Numerical analyses results reveal that left tunnel and surrounding soils suffer considerable horizontal displacement caused by the nearby excavation. Firstly, Fig. 3 presents horizontal displacement of left tunnel during the 3rd excavation step obtained from field monitoring and numerical analysis. The maximum calculated horizontal displacement is 44 mm at Ring 175. Horizontal displacement of left tunnel obtained from field monitoring and numerical analysis all increase greatly when approaching the centre section of the excavation.

As shown in Fig. 4, numerical analysis also obtains horizontal displacement of left tunnel caused by nearby excavation in case 1 and case 3. Apparently, calculation results indicate that divided excavation in the 3rd excavation step decreases the horizontal displacement of left tunnel compared with case 1 in which the 3rd excavation step is not divided. The maximum horizontal displacement of left tunnel is decreased from 168 mm to 104 mm.

As shown in Fig. 5, the horizontal displacement of soils at the cross section of centre length of the excavation during the whole excavation stage in case 1 and case 2 are calculated as well. Compared with case 2 in which the twin tunnels do not exist, the existing twin tunnels decrease the horizontal displacement of soils in the immediate vicinity of the excavation base near the right excavation periphery and enlarge the area of soils being disturbed.
6.2 Settlement

As presented in Fig. 6, settlement of left tunnel induced by the nearby excavation in case 1 and case 3 is also obtained to investigate the effects of divided excavation on alleviating the settlement of existing left tunnel. The maximum settlements obtained in case 1 and case 3 are 78.7 mm and 34.5 mm respectively which all occur in the centre length of excavation. Obviously, the divided excavation in the 3rd excavation step decreases the settlement of left tunnel significantly.

Similarly, as shown in Fig. 7, numerical analysis also obtains increment of settlement of surrounding soils at the cross section of centre length of the excavation during the whole excavation stage in case 1 and case 2. In case 1, the existing twin tunnels obviously increase the settlement of the soils between left tunnel and nearby retaining piles compared with other areas. Moreover, compared with case 2, the existing twin tunnels greatly decrease the settlement of the above soils. As a result, the constraint the left tunnel exerts on the surrounding soils will inevitably in turn result in the additional settlement of left tunnel.

6.3 Internal forces

The circumferential and longitudinal bending moments of left tunnel are also calculated to evaluate the effects of divided excavation in the 3rd excavation step on alleviating the internal forces of left tunnel. As shown in Fig. 8, it is evident that circumferential bending moment of left tunnel are significantly larger than longitudinal bending moment which could account for the appearance of longitudinal cracks and leakages of left tunnel. Divided excavation during the 3rd excavation step decreases the maximum circumferential and longitudinal bending moments occurring at the stringline level of left tunnel from 458 kN·m/m to 397 kN·m/m and 67.1 kN·m/m to 60.4 kN·m/m,
respectively. As a whole, divided excavation during the 3rd excavation step decreases not only the circumferential bending moment but also the longitudinal bending moment of left tunnel within the scope of the nearby excavation.

![Graphs showing variation of bending moment of left line](image)

**Fig. 8. Variation of bending moment of left line with Y-coordinate: (a) Circumferential bending moment; (b) Longitudinal bending moment.**

### 7 CONCLUSIONS

In this paper, the influence of a large excavation on nearby existing twin tunnels is studied by 3D FEM and field monitoring. The conclusions of this study are generalized as follows:

1. According to the numerical analysis results, the maximum horizontal displacement and settlement of left tunnel induced by the nearby excavation reach 168 mm and 78.7 mm, respectively. Meanwhile, considerable internal forces are obtained, including circumferential and longitudinal bending moments. The maximum circumferential bending moment occurring at the ringline level of left tunnel reaches 458 kN·m/m. In the construction site, visible longitudinal cracks and leakages were observed in many places of left tunnel. The safety of existing twin tunnels was severely threatened.

2. The nearby excavation and existing twin tunnels are interactive. Divided excavation during the 3rd excavation step decreases the maximum horizontal displacement and settlement of left tunnel from 168 mm to 104 mm and 78.7 mm to 34.5 mm, respectively. Similarly, circumferential and longitudinal bending moments of left tunnel also decrease significantly.

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