Analysis on construction of the subway shield underpassing the underground pedestrian passage at close range

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Abstract. Numerical simulation analysis was conducted on the shield tunneling construction of the right line between Tangdong station and Huangcun station of Guangzhou rail transit line 21, the right line subway shield underpassing the underground pedestrian passage at close range. The numerical simulation vertical settlement of the ground and floor outside the foundation pit was compared with the field monitoring. The results show that the numerical analysis of the trend of land subsidence is consistent with the field monitoring, the thickness of the tunnel roof overburden has a great influence on the ground settlement. The ground settlement is mainly subsidence with thick overburden, while the thin overburden, the ground settlement is mainly uplift; the Equivalent Circular Zone formed by simultaneous grouting and secondary grouting has a great influence on the ground settlement. During the site construction, the tunneling parameters should be adjusted according to the site monitoring, and parameters such as soil and water pressure on the tunneling surface, overburden thickness, synchronous grouting pressure and secondary grouting pressure should be taken into comprehensive consideration to control the tunneling of shield underpassing the existing structures at close range.

1. Introduction

With the large-scale construction of urban subway project, the underground rail transportation network became increasingly dense, which brought about the problem of cross transfer of each line, and the engineering problem of intersections tunnel crossing each other. For example, in the 2050 urban rail transit planning map of Beijing, there were as many as 118 crossing sections of node stations and subway sections[1], which posed more severe challenges to the design and construction of the subway. Urban subway tunnels had small crossing spacing and large interaction, the construction of new subway tunnel would inevitably cause the disturbance of surrounding soil, change the stress state of soil, cause the subsidence of surrounding ground, cause additional internal force and deformation of adjacent existing line structures, and may even cause damage to existing tunnel structures.

For example, the tunnel between Guomao station and Shuangjing station on line 10 of Beijing metro passed through the tunnel between Guomao station and Dawang Road station on line 1, with a distance of only 1.079 m[2]. The tunnel at the eastern end of Chongwenmen station of the newly built Chongwenmen station on Beijing metro line 5 was only 1.98m away from the existing subway tunnel. Shanghai Mingzhu line second-phase Pudian Road ~ Zhangyang Road interval tunnel underpassed line 2, and the distance between the projected intersection between the two tunnels was 1.719m. The
importance of existing lines was high, and the requirement of additional deformation war strict, which made the crossing project difficult and risky[3]. In the crossing project of urban subway tunnel, if the understanding of potential risk factors was insufficient and the construction control was improper, it may caused serious consequences[4]. For example, during the construction of Beijing metro line 5, the existing infrastructure of line 2 and the track line of line 2 had a large settlement due to the construction, forcing line 2 to adopt strict speed limit measures at Dongdan station and Chongwenmen station, which greatly affected the service quality and operation capacity of the subway.

This paper mainly relied on the right line between Tangdong station and Huangcun station of Guangzhou rail transit line 21, which started from Huangcun station and went through the newly built transfer channel (changing with the existing line 4). The minimum net distance from the structure floor was only about 734 mm, which was a super-close distance shield tunneling through the building. The simulation analysis and the construction parameter research of shield tunneling underpass building were carried out to guide the field construction.

2. Project overview

The line between Tangdong station and Huangcun station mainly ran under roads and existing houses. It was a flat alluvial plain in the pearl river delta. The super-close underpass of the shield in this section mainly consists of fine sand, medium coarse sand, silty clay, strongly weathered argillaceous siltstone and moderately weathered argillaceous siltstone. There were 3-6m thick water-rich sand layers. The geological conditions were complex, and the construction risks were high.

Shield tunneling was carried out under the condition that the existing interface of line 4 was not completed and the roof was not backfilled. The retaining structure was 800mm thick underground diaphragm wall, 16 fiberglass subterranean diaphragm walls in the range of shield break, and 14Φ1200 mm rock-socketed piles were set, embedded in the aeolian rock layer were not less than 1.5m. The reinforcement at the end of Huangcun station had been completed. The reinforcement range of the right line foundation at the end of Huangcun station was 10 m in length, 3 m in the west and 3.3 m in the east of the tunnel structure (total width: 12.3 m), and there was transfer channel above the right line tunnel. The reinforcement depth was 1.14 m to the top of the tunnel.

The transfer channel range was right YDK5+609.8 ~ 5+694.7. The depth of the tunnel in this range was 10.4 m ~ 11.7 m. The distribution of strata from top to bottom was: 1.5 m thick artificial fill, 1.5 m thick silty clay, 2.9 m thick medium coarse sand, 4.8 m thick silty clay, 0.8 m thick medium coarse sand, 2.7 m thick silty sand, 2.2 m thick silty clay layer, 1.1 m fully weathered silty siltstone. The hole body mainly passed through the fine sand layer. Shield tunneling transfer section diagram, construction site diagram see figure 1, 2.

3. Numerical model

3.1. Selection of unit types

Figure 1. The cross-section diagram of shield goes down the transfer channel. (mm)

Figure 2. Transfer channel construction site diagram.
Based on the construction site of shield tunneling, the settlement of the transfer channel under shield tunneling was simulated by using the finite element software Midas GTS NX, and the surrounding rocks were assumed to be continuous. The strata were composed of multiple layers. In order to simplify the calculation process, the deformation of the soil above and the foundation pit of transfer channel during shield tunneling is mainly studied. The strata above the tunnel are divided in detail. The surface element is used in the shield shell of the tube lining and shield, which was simulated by linear elastic material. The concept of "The Equivalent Circular Zone" was adopted to simulate the formation loss caused by shield construction[5].

3.2. Plastic yield criterion

The drucker-prager yield criterion was applied, and the yield was based on the maximum shear stress. The yield function was shown in formula 1, and the yield failure surface was shown in figure 3.

\[
F(\sigma) = \frac{2 \sin \phi}{\sqrt{3(3-\sin \phi)}} I_1 + \sqrt{J_2} - \frac{6c \sin \phi}{\sqrt{3(3-\sin \phi)}} = 0
\]  

(1)

In the formula, \( I_1 = \sigma_x + \sigma_y + \sigma_z \) is the first invariant of the stress tensor, \( J_2 = \frac{1}{6} \left[ (\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 \right] + \tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2 \) is the second invariant of the stress tensor, \( \phi \) is the internal friction Angle.

3.3. Model

The material parameters were shown in table 1. The shield segment was precast concrete segment, concrete strength C50, steel reinforcement S12, elastic modulus was 34.5 GPa. Since the length of the pipe segment was only 1.2 m, the joint had a certain influence on the stiffness, and the stiffness reduction coefficient was 15%.

| Material           | Thickness (m) | Density (Kg/m^3) | Poisson's ratio | Modulus of elasticity (GPa) | Cohesion (Kpa) | Angle of internal friction (°) |
|--------------------|---------------|------------------|----------------|----------------------------|----------------|-------------------------------|
| Silty clay 1       | 3.49          | 1940             | 0.28           | 1.0                        | 0              | 26                            |
| Coarse sand        | 2.9           | 2000             | 0.3            | 2.8                        | 3              | 27                            |
| Silty clay 2       | 4.8           | 1940             | 0.28           | 1.0                        | 0              | 26                            |
| Silty sand         | 2.7           | 1840             | 0.3            | 2.0                        | 26.2           | 30                            |
| Argillaceous siltstone | 4.6          | 2200             | 0.25           | 3.0                        | 40             | 24                            |
| Equivalent Circular Zone | 2000       | 0.3              | 0.2            |                            |                |                               |

The size of the model was determined according to the value of the monitoring range in "tang-huang interval monitoring scheme" of guangzhou metro line 21. X axis is the width of the model, according to the regulations of metro construction monitoring the relevant specification: Generally,
1.5~ 2.0 h on both sides of the foundation pit or tunnel (H is the depth of the foundation pit or the buried depth of the tunnel) was selected for the monitoring scope of the building settlement and tilt monitoring project., the stress concentration principle about 1.5 times the aperture range[6], the horizontal width of the vertical tunnel in this project was 49.70 m; the longitudinal length of the tunnel is 50.4 m (42 rings) for simulation analysis. Considering the height of the model, the buried depth of shield tunnel-excavated tunnel was 11.29~11.66 m, the outer diameter of shield tunnel-excavated tunnel was 6.0 m, and the soil under the shield was 11.80 and 29.20 m, with a total of 16,713 units. See figure 4 for the tunnel model.

4. Numerical analysis

4.1. Shield construction process simulation
During shield construction, the working face was excavated with cutter head, the tail tube segment was assembled and grouting was carried out simultaneously. Finally, secondary grouting was carried out for the shield segment. Due to diminishing of the diameter of the contour outline of knife, the knife dish, shield and the segment, after the assembled segment was separated from the tail of the shield, a gap was formed between the segment lining and the excavation contour of the soil, if synchronous grouting quantity did not meet the requirements, the soil mass on the soil contour of the tunnel will move towards the clearance along the radial direction, at the same time, after the shield passes through, the soil around the tunnel is consolidated by the original disturbance, resulting in the soil deformation around the tunnel. The calculation steps were as follows: 1. Zero the displacement according to the initial stress state of the soil under the dead weight stress; 2. Passivated shield tunneling machine propulsion direction ring 1 (1.2 m) and activated the concrete grid corresponding to the ring number of the shield tunneling pipe and The Equivalent Circular Zone grouting grid; 3. Activate the earth chamber pressure to be applied to the soil on the working face of shield tunneling machine; 4. Activate to apply a radial pressure (value is grouting pressure) on the concrete pipe piece; 5. Loop steps 2 to 4.

4.2. Results analysis
Deformation analysis. The model was analyzed by using nonlinear construction stages, which were divided into 43 construction stages, with 1.2 m footage for each stage. During shield construction, the surrounding strata of the shield area would be lost and the stress would be redistributed, resulting in uneven settlement of the upper ground and uneven uplift of the soil beneath the pipe segment. According to the numerical model established above, after 32 excavation steps, the displacement cloud diagram of the final deformation is shown in figure 5. Through statistical analysis of the surface settlement value in the process of shield crossing, the settlement curve of the surface directly above the tunneling direction 9.6 m away from the initial excavation surface was obtained, as shown in figure 6. In the process of excavation with the tunnel digging up the progress of the surface subsidence value increases gradually, in advance to the ring 8 (9.6 m), subsidence value maximum - 0.22 mm, with shield continue to push forward, it reduced weight of soil mass in vertical unloading, made the bottom of the tunnel uplift, by segment vertical deformation, surface appeared a small amount of rebound, uplift 0.09 mm, finally appeared with the development of shield post-construction settlement.
4.2.1. Foundation pit bottom deformation. Two monitoring sections were arranged on the model to monitor the bottom plate of the southern end of the transfer channel and the settlement law of the bottom plate of the transfer channel[7]. The locations directly above the tunnel at the bottom of the pit, 16 m and 36 m from the initial excavation face, were selected as the monitoring sections, and the monitoring points were arranged as shown in figure 7. The monitoring data and the results of numerical simulation were compared and analyzed.

With the tunneling of shield tunneling machine, the foundation pit gradually rises as shown in figure 8, 9, and the accumulated uplift value presents a monotonically increasing trend, which tends to be stable with the advance of shield tunneling. When the shield tunneling machine is tunneling in the area at the bottom of the foundation pit, the pressure value in the warehouse is adjusted to balance according to the thickness of the soil layer, but the soil layer above the tunnel is thin, making the soil heave when the shield tunneling machine passes through the area at the bottom of the foundation pit.
4.2.2. Effect of grouting on deformation. In the process of shield construction, synchronous grouting played a very important role in controlling settlement. In order to study it quantitatively, physical parameters of reinforced surrounding rocks were adopted in the numerical analysis model to simulate advanced grouting reinforcement and secondary grouting reinforcement, so as to control the surface heave caused by shield construction. In the process of shield tunneling, the effects of grouting were simulated by adjusting the parameter properties of The Equivalent Circular Zone and compared with the simulation results without the zone, as shown in figure 10.

By comparing the above model calculation with the monitoring data, and combining the analysis results of the actual construction situation, it could be known that the cumulative maximum vertical settlement trend of the monitoring point was highly consistent with the results of the finite element simulation, and the finite element analysis results could better guide the field construction. Before the shield passed through the monitoring surface, the settlement rate of the monitoring point is slow. As the tunneling surface approaching, the settlement rate increased, and the tunneling surface left the monitoring surface, the settlement tends to be stable; in the transfer channel model of shield tunneling, the bottom plate settlement value after adding equal generation layer to simulate grouting effect was significantly lower than that without adding The Equivalent Circular Zone. indicating that during the process of shield tunneling through existing tunnels, parameters such as synchronous grouting amount and grouting pressure of shield tunneling construction had a certain influence on the vertical settlement of existing tunnel structures.

5. conclusion
Through the shield tunnel between tangdong station and huangcun station of the newly built line 21 underground excavation transfer channel foundation pit numerical simulation. The following conclusions are obtained:

(1) The numerical simulation results are in good agreement with the maximum deformation value of the measured data, and the change trend of the numerical simulation values is basically consistent with the actual monitoring data, indicating that the finite element simulation results can reflect the construction process in a macro sense, and the simulation results can guide the actual engineering construction.

(2) The ground subsidence is closely related to the thickness of the overburden of the tunnel. The overburden is thick, the ground is mainly subsidence, the overburden is shallow, and the vertical deformation of the ground is mainly uplift. During construction, the tunneling parameters should be adjusted according to the field monitoring, and the tunneling of the shield tunneling through the existing structures should be carried out by taking into comprehensive consideration the soil and water pressure on the tunneling surface, the thickness of overburden, the synchronous grouting pressure and the secondary grouting pressure.

(3) The finite element simulation, according to the geological exploration data, construction experience, set the initial value in advance for the total thrust of shield tunneling machine, soil
warehouse pressure, synchronous grouting pressure, etc., then adjust the parameters in real time according to the surface settlement, and finally control the settlement value in a reasonable range, so it can guide the construction by the simulation results, reduce the frequency of adjusting the tunneling parameters during the construction of shield tunneling and improve the tunneling efficiency.

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