Study on Influence of Shield Side-piercing Construction on Pile Foundation of Nearby High-speed Railway Bridge

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Abstract—Taking the pile foundation of Suzhou Metro Line 3 passing through viaduct as the engineering background, the driving process of shield tunnel is simulated by finite element software. Through the analysis of surface settlement, bridge pier deformation and bridge pile foundation deformation in shield construction, the following conclusions are drawn: The foundation reinforcement “scheme of root pile + sleeve valve pipe grouting” has an obvious effect on reducing the ground settlement, the deformation of bridge piers and the deformation of pile foundation structure. The deformation and stress of the pile foundation of the bridge and the horizontal displacement of the pier above it are related to its distance from the tunnel, and the nearer it is, the greater its influence is. Whether the foundation is strengthened or not has little influence on the change law of axial force of bridge pile foundation, and the maximum axial force appears at the inflection point of horizontal displacement. Due to the excavation of shield tunnel, the bending moment of pile foundation changes in three sections along the depth direction, and the change of bending moment in the middle section is opposite to that on both sides.

1. INTRODUCTION

With the rapid development of urban rail transit and the influence of urban geographical environment, there are more and more subway tunnels under the existing lines. Especially in miscellaneous fill and sand-pebble stratum, the disturbance caused by shield construction will cause the settlement of the...
surface and buildings, and even the cracks of buildings and the collapse of road surface. Especially when the tunnel passes through the high-speed railway bridge, higher requirements are put forward for the control of the tunneling parameters of the shield and the reinforcement measures of the building, and the reinforcement measures are related to whether the project can be carried out smoothly[1]. Taking Zhengzhou Metro Line 3 as the background, Chen Hui analyzes the influence of shield construction on adjacent bridge piles and puts forward a scheme to set up isolation piles to protect bridge piles[4]. Guo Yibin et studied the influence of shield tunneling at different depths on the bearing behavior, deformation and internal force of super-long pile through numerical simulation of the process of shield tunneling through super-long pile foundation[5]. Peng Kun et al analyzed the deformation law of surface and pile body under two different pile foundation reinforcement schemes[6]. Wang Li et analyzed the stress and deformation law of pile foundation in the process of shield advance[7].

Based on the background of Suzhou New District Station to Development Road Station of Suzhou Rail Transit Line 3, this paper selects the cross-section of pile under shield as a typical section, and adopts the method of numerical simulation to analyze the settlement and deformation of strata and buildings before and after foundation reinforcement, so as to provide reference for the construction of similar projects in the future.

2. ENGINEERING SITUATION

The interval line from Development Road Station to Suzhou New area Station runs eastward along Shanghai-Nanjing Railway to Datong Road and south through Shanghai-Nanjing Intercity Railway and Shanghai-Nanjing Railway to access Development Road Station near Development Road. The distance between the center lines of the left and right lines is 12mcm and 27.9m. The interval is constructed by shield method. The foundation soil revealed within 60m of this site is alluvial facies of Quaternary Upper Pleistocene to Lower Pleistocene, clay deposited between sea and land, silty clay, silty sand, silt, etc. According to the revealed stratum depth, characteristics, physical and mechanical properties, the revealed stratum along this line is divided into 8 layers and each soil layer is mainly distributed in layers. Most of the intercalations with local distribution are lenticular or banded.

The Huanghuajing Bridge of Shanghai-Nanjing intercity high-speed railway is driven by shield. The bridge is a simply supported box girder system constructed by prefabricated method. The intersection angle between the section line and the railway is 58°~ 61°. The height of the pier of the ballastless double-track bridge is 2.35m~2.85m, the length of the box girder is 32.6 m, and the slope of the line is 4.5‰. There are 8φ1000mm bored piles under each pier and abutment, the length of which is 45.5m (No.65), 46m (No.66) and 47m (No.67), and the clearance under the bridge is about 3m. Under the construction of the shield tunnel, and the buried depth at the top of the tunnel is about 16.8m, and the minimum horizontal net distance between the outside of the tunnel and the pile foundation is 6.5m. The foundation reinforcement treatment of the lower crossing section: in order to reduce the influence of grouting on the pile foundation of the high-speed railway bridge, the sleeve valve pipe grouting is carried out between the bridge piles, and the main reinforcement area is about 20m along the tunnel direction. Under the high-speed railway bridge, there are three rows of root piles and two rows of other sections. Add a row of φ850@600mm triaxial mixing piles on the outside of the secondary reinforcement area, as shown in figure 1.
3. Numerical Calculation

3.1. Model parameters
According to the selected typical section, it is extended to the axis of the tunnel for a certain distance, and the soil constitutive model is based on Mohr-Coulomb model[8]. In the whole model, the tunnel is 48m longitudinally, 120m wide and 68m high. The boundary constraint conditions are imposed on the soil, the vertical displacement is limited at the bottom of the model, and the horizontal displacement is limited at the side of the model. The soil, segment and equivalent layer are simulated by solid element, and the bridge pile is simulated by pile element. The model is shown in figure 2.In this paper, for the purpose of comparative analysis, the foundation is also calculated before reinforcement, and the specific working conditions can be seen in the description of working conditions. The stratigraphic division and soil mechanical parameters refer to the Geotechnical Engineering investigation report of Suzhou Rail Transit Line 3 (detailed investigation stage), and the physical and mechanical parameters of each soil layer are shown in Table 1.

| Soil layer | Compression modulus/MPa | ρ/(Kg/m³) | C/kPa | φ/(°) |
|------------|-------------------------|-----------|-------|-------|
| Plain fil  | 6.18                    | 1910      | 6     | 8     |
| Silt sand  | 11.71                   | 1990      | 6     | 30.3  |
| Silt sand  | 8.39                    | 2010      | 44.8  | 14.4  |
6-2 silty clay  7.06  1960  33.4  14.9
7-3 silty clay  5.57  1880  23.3  15.8

| Materials                  | E/MPa | ρ/(KN/m³) | μ  |
|----------------------------|-------|-----------|----|
| Root pile                  | 2e3   | 22        | 0.22 |
| Piles and caps             | 3.5e4 | 26.2      | 0.24 |
| Segment                    | 2.85e4| 25        | 0.2  |
| Equivalent layer           | 40    | 20        | 0.24 |
| Grouting reinforcement area| 300   | 24.5      | 0.28 |

3.2. Layout of monitoring points and description of calculation conditions
This numerical simulation calculation mainly analyzes the pier displacement, surface settlement, and pile structure displacement and stress; the surface settlement monitoring takes about 2D distance from the boundary; because of the large number of bridge piles, only the middle pile inside each pier is selected for analysis; four corners at the top of the pier are analyzed, and the specific monitoring points are arranged as shown in figure 4.

The numerical simulation calculation is divided into two cases: reinforced and unreinforced, each is divided into left-line excavation (single-line) and double-line excavation, a total of four working conditions. Here the working conditions are numbered, a-unreinforced left-line excavation, b-unreinforced double-line excavation, c-reinforced left-line excavation, d-reinforced double-line excavation.

3.3. Analysis of calculation results
3.3.1. Analysis of surface subsidence
Under different working conditions, after shield tunnel excavation, the surface settlement curve is shown in figure 5. As can be seen from figure 5, during the single-line excavation of the tunnel, the surface settlement appears directly above the shield tunnel. The farther away from the middle line of...
the tunnel, the smaller the surface settlement. The surface settlement curve shows the shape of large middle and small grooves at both ends, which is consistent with the Peck settlement curve. After the double-line excavation of the tunnel, the surface subsidence curve shows two troughs, namely W-type, from \( C = L / (H + R) = 2.1 > 0.5 \), which accords with the law of Chen Chunlai that the limit of C value of land subsidence curve from V-type to W-type is 0.5[9].

When unreinforced single-line excavation, the maximum surface settlement is 11.78mm; When unreinforced double-line excavation, the maximum surface settlement is 13.39mm, which is 14% higher than that of single-line excavation. After single-line excavation after reinforcement, the maximum surface settlement is 2.56mm, and that of double-line excavation after reinforcement is 2.81mm, which is 9.7% higher than that of single-line excavation. After reinforcement, the maximum surface settlement of double-line tunnel excavation is relatively reduced by 79%, which shows that the effect of the reinforcement measures is obvious.

3.3.2. **Displacement Analysis of Bridge Piers**

After the completion of tunnel excavation, the displacement of bridge piers under various working conditions is shown in Table 3 below.

During shield construction, the soil above the tunnel moves downward due to excavation disturbance and shield tail clearance, which causes the surface structure to shift to the center of the tunnel. As can be seen from Table 3 above, when the pier is not reinforced, the maximum horizontal displacement of the pier is 16.41mm, and the final maximum horizontal displacement is 8.14mm, all of which appear near the side of the tunnel after the left line tunnel is excavated. The maximum vertical displacement of the pier is -16.06mm, and the pier between the two tunnels appears after the two-way excavation is completed. After reinforcement, the maximum horizontal displacement of the pier is 1.98mm, and the maximum horizontal displacement after double-line excavation is 1.8mm, and the maximum vertical displacement is 3.37mm, which is much lower than that without reinforcement.

| Pier number | No.67 | No.66 | No.65 |
|-------------|-------|-------|-------|
| step 3      | 3     | 4     | 5     |
| a           | 7.24  | 7.02  | 16.41 |
| b           | 8.14  | 7.84  | 7.84  |
| c           | 1.96  | 1.98  | 1.98  |
| d           | 1.80  | 1.80  | 1.80  |
| Horizontal displacement/mm | 7.24 | -6.15 | -6.01 |
|             | 8.14  | -0.25 | -0.18 |
|             | 1.96  | -1.73 | -1.74 |
|             | 1.80  | 0.08  | 0.08  |
|             | -5.69 | -5.92 | -8.18 |
|             | -8.88 | -8.82 | -6.87 |
|             | -6.93 | -0.15 | -0.11 |
|             | -0.07 | -0.00 | -0.11 |
| Vertical displacement/mm | -5.95 | -8.57 | -8.31 |
|             | -15.85 | -16.06 | -16.00 |
|             | -15.79 | -5.81 | -5.76 |
|             | -3.97 | -4.02 | -3.97 |
|             | -1.37 | -1.46 | -2.15 |
|             | -2.07 | -2.18 | -2.20 |
|             | -1.57 | -1.55 | -0.07 |
|             | -0.04 | -0.08 | -0.11 |
|             | -0.92 | -1.03 | -1.67 |
|             | -1.56 | -3.33 | -3.37 |
|             | -3.39 | -3.36 | -1.08 |
|             | -1.04 | -0.51 | -0.55 |

According to the change of the pier displacement after the shield tunnel excavation, it can be seen that the displacement near the side of the tunnel is larger than that far away from the pier. Due to the
influence of the left and right double-line tunnel excavation, the change of the final horizontal
displacement is small, and the settlement is the largest due to the influence of repeated disturbances in
tunnel excavation.

3.3.3. Analysis of horizontal deformation of pile body
After tunnel excavation, the horizontal displacement curve of pile foundation under various working
conditions is shown in figure 6 ~ figure 8.

The excavation of the shield tunnel will cause the stratum to converge to the tunnel, and the bridge
pile will also have tilt and flexure deformation; as can be seen from figure 6 to figure 8, under
different working conditions, the horizontal displacement of the pile foundation shows an obvious
shape of 'groove' in the influence area of the tunnel, the horizontal displacement of the top of the pile
foundation changes the most, and the horizontal displacement of the pile foundation below 25m does
not change much[10]. In the case of reinforcement and un reinforcement, the variation law of
horizontal displacement of pile foundation is basically the same, and the maximum value of horizontal
displacement of most pile foundation after reinforcement is smaller. The horizontal displacement
direction of the pile foundation is related to the position of the pile foundation, and the horizontal
displacement direction of the pile foundation near the tunnel side is opposite to that far away from the
tunnel side pile foundation. The closer the pile foundation is to the tunnel, the greater the horizontal
displacement changes, which shows that the horizontal displacement of the pile foundation is sensitive
to the distance between the pile foundation and the tunnel.

3.3.4. Analysis on the influence of internal force of pile body
After tunnel excavation, the axial force and bending moment of pile foundation under various working
conditions are shown in Fig. 9 ~ Fig. 14.
Figure 9. No.67 Axial Force of Pier pile Foundation

Figure 10. No.66 Axial Force of Pier pile Foundation

Figure 11. No.65 Axial Force of Pier pile Foundation

Figure 12. No.67 bending moment of pier pile foundation

Figure 13. No.66 bending moment of pier pile foundation

Figure 14. No.65 bending moment of pier pile foundation
As can be seen from figure 9 to figure 11, the axial force of the pile foundation first increases and then decreases due to the shield tunnel excavation, that is, the shape of the small 'groove' at the two ends in the middle of the pile body, which is mainly because the pile foundation is a friction pile. The position of the maximum axial force is consistent with the inflection point of the horizontal displacement of the pile foundation, which also shows that the foundation reinforcement has little influence on the change law of the axial force of the pile foundation.

It can be seen from Fig. 12 to Fig. 14 that the bending moment of the pile foundation basically presents a positive or negative moment in a certain range from the top of the pile and above the bottom of the pile, and the moment opposite to the top and bottom of the pile in the middle of the pile. The bending moment of the pile foundation near the tunnel is larger than that of the pile foundation far away from the tunnel. It can also be seen from the diagram that the maximum bending moment basically appears about 17m below the top of the pile, that is, the position of the tunnel vault; compared with the unreinforced foundation, the bending moment value decreases after the foundation is strengthened.

4. CONCLUSION
In this paper, the numerical simulation method is used to analyze the surface settlement, the pier and the deformation of the pile foundation before and after the foundation reinforcement, which provides the basis for ensuring the safe passage of the shield. Through the analysis, the following conclusions are drawn: The foundation reinforcement scheme of root pile + sleeve valve pipe grouting can reduce the surface settlement, the deformation of bridge pier and the deformation force of pile foundation structure to a certain extent. The deformation and stress of the bridge pile foundation and the horizontal displacement of the pier on it are related to the distance from the tunnel, the nearer the influence is, the greater the influence is. Whether the foundation is strengthened or not has little influence on the change law of axial force of bridge pile foundation, and the maximum axial force appears at the inflection point of horizontal displacement. The excavation of the shield tunnel makes the bending moment of the pile foundation appear three changing sections along the depth direction, the middle bending moment changing section is opposite to that on both sides, and the maximum bending moment appears in the tunnel vault position.

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