Environmental Engineering Deformation Control of High-speed Railway Shield Tunnel Under Crossing Bridge Piles

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Abstract: With the continuous acceleration of my country's high-speed rail construction, it is inevitable to cross the existing engineering structure during the construction process. During the construction of high-speed railway, the control of the influence and deformation of the existing structure is a subject that needs to be studied in environmental engineering. Hangzhou metro line 1 is designed to cross under the Hu-Hang high-speed railway. According to the design, the shield tunnel is very close (minimum distance 5.19m) to the bridge piles of the Hu-Hang high-speed railway. Therefore, how to control the deformation of the bridge piles is a big problem in the shield tunnel excavation. Before construction, the method of the bored piles coupled with the jet grouting piles was proposed. The 3D numerical model was built to study the deformation of the bridge piles with the cases of the shield tunnel excavation without soil consolidation, the construction of the bored piles coupled with the jet grouting piles and the shield tunnel excavation with soil consolidation. The results show that the method of the bored piles coupled with the jet grouting piles can control the deformation of the bridge piles in the shield tunnel excavation effectively. Then, the deformation monitoring of the bridge piles was performed in the process of construction. The monitored data were close to the calculated results, which implies that the method of the bored piles coupled with the jet grouting piles is effective.

1. Introduction

As we all know, high-speed rail is developing rapidly in China. Although the stations of the high-speed railways, which are usually located on the bridge, are always built far away from the city centers, the new designed metro lines sometimes have to cross under them. The soils around the bridge piles will be disturbed by the tunnel construction [1-2]. The bearing capability of the soils will be reduced, which will make the train operation unsafe [3].

There are many papers about the piles of the building foundation affected by the tunnel construction [4-6]. However, the deformation research of the bridge piles of the high-speed railway in the shield tunnel excavation is rare. Xu [7, 8] proposed the pile underpinning technology to guarantee the normal traffic function and the safety of bridge structure during the Shanghai metro line 10 excavation. Yuan [9] analyzed the horizontal deformation of the piles of a viaduct during the process of the Hefei metro line 1 passing by based on the mechanical principle of coupled springs for bridge-pile structures and the finite difference method. Wang [10] employed the least squares principle and the finite
difference method to study the pile foundation of a viaduct when the construction of the Xicun station of the Guangzhou metro. Lee [11] built the 3D elastoplastic numerical model to study the effects of tunneling in weak weathered rock on the behavior of a preexisting single pile and pile groups in weathered residual soil above a tunnel. Wu [12] built a simplified 3D model to research the viaduct piles when the Nanjing metro line 3 passing by. Guo [13] analyzed the deformation of the bridge piles by the numerical method. Boonyarak [14] observed pile group responses due to tunneling in Bangkok stiff clay.

This paper is organized as follows. Section 2 introduces the engineering backgrounds. In section 3, the difficulties of this project is proposed and the solutions are presented. The numerical model is calculated in section 4. In order to verify the results of the numerical analysis, the monitoring is performed in section 5. Conclusions are in section 6.

2. Engineering backgrounds

The high-speed railway bridge is a three-span continuous girder bridge, which is constructed for the Yu-Hang South Station in Hu-Hang high-speed railway. Hangzhou metro line 1, comprised of two shield tunnels, is planned to cross under the middle span of this bridge, see Figure 1.

![Figure 1 The high-speed railway bridge](image)

An earth pressure balance shield was employed for the Hangzhou metro line 1. The excavation direction of the shield tunnels is shown in Figure 2. The left shield tunnel was excavated firstly. Then, the right shield tunnel was excavated. The distance between the axes of these two shield tunnels is about 15 m. Both of covering depths of the shield tunnels are 11.7 m. The designed outer diameter of the shield tunnel is 6.2 m. The thickness of the shield segment is 0.35 m.

![Figure 2 Demonstration of the shield tunnels and the bridge (unit: m)](image)
There are two main lines, two station tracks and two platforms on the high-speed railway bridge. The size of the pile cap under the main lines is about 10.38m × 9.3m × 3.5m. The size of the pile cap under the station tracks is about 14.3m × 9.3m × 3.5m. There are 8 bored piles, 69.5m in length, under one pile cap for the main lines. There are 12 piles, 71.5m in length, under one pile cap for the station tracks. The diameter of all bored piles is 1.5m.

This engineering project is located in Hangzhou northeast coastal plain. According to the soil investigation, soil layers of this area were obtained, shown in Figure 3. ① is the miscellaneous fill. ② and ⑥ are the silty clay. ③⑤ are the sandy silt. ③② and ③⑧ is the silty sand. ⑦ is the clay. Table 1 is the physical parameters of the soils. Generally, the distance between the groundwater line and the ground surface is about 0.6~1.7m. This distance can reach 0.5~1.0m when the groundwater line climbs.

| Layer number | Soil layer  | Water content in percent of dry weight | Total unit weight (γ) | Degree of saturation (Sr) | Void ratio (e) | Coefficient of permeability (Kv) × 10^-6 | Coefficient of permeability (Kh) × 10^-6 |
|--------------|-------------|---------------------------------------|-----------------------|---------------------------|---------------|-----------------------------------------|----------------------------------------|
| ②①          | Silty clay  | 29.3                                   | 18.8                  | 94                        | 0.846         | 25                                      | 35                                     |
| ③①          | Sandy silt  | 27.1                                   | 19.1                  | 95                        | 0.771         | 150                                     | 200                                    |
| ③②          | Silty sand  | 25.5                                   | 19.2                  | 92                        | 0.743         | 300                                     | 400                                    |
| ③⑤          | Sandy silt  | 26.5                                   | 19                    | 93                        | 0.771         | 150                                     | 250                                    |
| ③⑧          | Silty sand  | 25                                     | 19.2                  | 92                        | 0.731         | 400                                     | 600                                    |
| ⑥①          | Silty clay  | 33.8                                   | 18.2                  | 95                        | 0.977         | 2.5                                     | 4                                      |
| ⑦①          | Clay        | 28.1                                   | 18.8                  | 92                        | 0.836         | 1                                       | 1.5                                    |

3. Engineering difficulties and technology

3.1. Engineering difficulties

According to the operation plan of the Hu-Hang high-speed railway, the designed top speed of the train is about 350km/h. In order to avoid train derailment and keep operation stability, the track geometry must be maintained strictly.
As described in section 2, we find that:

1) The designed shield tunnels are very close to the bridge piles, see Figure 2. The minimum distance between the bridge pile and the left shield tunnel is 6.16m. The minimum distance is 5.19m for the right shield tunnel. Therefore, the soils around the bridge piles will be disturbed easily in the process of shield excavation, which may reduce the bearing capability of the foundation. (2) The soils crossed by the shield tunnel are (3) the silty sand and (5) the sandy silt. From Table 1, we know that they have great permeability. Under rich water condition, the soils are easier to liquefy, which will lose the bearing capability of the foundation.

The above two factors will make the bridge piles deform easily. Then, the operation unsafety is up. Consequently, deformation controlling of the bridge piles in the excavating process of the shield machine is a big engineering problem.

3.2. Technology of deformation control
In order to control the deformation of the bridge piles in the excavation of the shield machine, the method of the bored piles coupled with the jet grouting piles was employed. The bored piles and the jet grouting piles have a large number of applications in civil engineering. The construction method of the bored piles is to drill a hole with special drilling tools. Then, the reinforced bar will be put into the bored hole and concrete will be poured into it. The soils will be consolidated when the poured concrete hardens. Furthermore, the jet grouting technique is to inject some liquid concrete by means of a drill in the subsoil. It forms a sort of column that consolidates the surrounding soil after the liquid concrete hardens.

![Figure 4](image)

Figure 4 Relative positions of the jet grouting piles and the bored piles (unit: m)
There are one row of bored piles and two rows of jet grouting piles on each side of the tunnels, as shown in Figure 4. The bored piles and the jet grouting piles at the left side are from the reinforced area to the site extending 3.8m from the platform. The bored piles and the jet grouting piles at the right side are also from the reinforced area. They are extended 3.3m from the platform.

The diameter of the bored pile is 0.8m. The central distance between the adjacent bored piles is 0.9m. The diameter of the jet grouting pile is 0.6m. The jet grouting piles lap over each other 0.2m. The distance between the jet grouting piles and the tunnel wall is about 1m. The length of the bored pile is 17.9m. The jet grouting pile is 2m shorter than the bored pile in length. There is a top beam on the bored piles. Figure 5 demonstrates the relationships among the bored piles, the jet grouting piles, the shield tunnels and the top beams.
4. Deformation analysis by numerical models

4.1. Model building
The commercial FEM software ANSYS was adopted to build the 3D model. Considering the boundary effect in the computing process, the model size was set as 150m (length) \(\times\) 100m (width) \(\times\) 100m (height), shown in Figure 6. The pile caps, the bridge piles, the bored piles, the jet grouting piles and the shield tunnels were built as the sizes described in section 2 and section 4.2.

![Figure 6 The 3D FEM model built in ANSYS](image)

Although the distance between the pile #2 and the right shield tunnel is smaller than the distance between the pile #1 and the left shield tunnel, the soils around the pile #2 have been consolidated, shown in Figure 4. Therefore, the bridge pile #1 will be the most dangerous pile, i.e. the pile #1 will be easiest to deform. Then, the horizontal deformation and the vertical deformation of the pile #1 were analyzed in this paper.

4.2. Tunnel construction without soil consolidation
Figure 7 is the horizontal deformation of the bridge pile #1 in the shield excavation without soil consolidation.
consolidation. The horizontal displacement of the pile #1 increases in the process of the shield tunnel excavation. The maximum horizontal displacement is about 2.7mm at the elevation -10m after the construction of the right shield tunnel. Figure 8 is the vertical displacement of the bridge pile #1 in the shield tunnel excavation without soil consolidation. Figure 8 shows the vertical displacement is similar to the horizontal displacement. The maximum vertical deformation of the pile #1 is -0.32mm at the top of the pile #1 when the construction of the shield tunnel is finished.

4.3. Construction of the bored piles and the jet grouting piles

Figure 9 is the horizontal displacement of the pile #1 in the construction process of the bored piles. The maximum horizontal displacement of the pile #1 is 0.043mm at the top of the pile #1. The bottom of the pile #1 almost has no horizontal displacement. In general, the maximum horizontal displacement increases with the construction of the bored piles. Similarly, the vertical displacement of the pile #1 increases with the construction of the bored piles as shown in Figure 10. The maximum vertical displacement of the pile #1 is 0.08mm, which takes place at the top of the pile #1 as well.

Figure 11 is the horizontal displacement of the pile #1 with construction of the jet grouting piles. There is almost no horizontal displacement under the elevation -20m for the pile #1. Furthermore, the horizontal displacement of the pile #1 increases with the construction of the jet grouting piles. The maximum horizontal displacement of the pile #1 is 0.217mm at the top of the pile #1. Figure 12 shows
the vertical displacement of the pile #1 with the construction of the jet grouting piles. It's similar to Figure 10. The vertical displacement of the pile #1 increases with the construction of the jet grouting piles. The maximum vertical displacement of the pile #1 is 0.05mm at the top of the pile #1.

Figure 11 Horizontal displacement of the bridge pile #1 under construction of the jet grouting piles

Figure 12 Vertical displacement of the bridge pile #1 under construction of the jet grouting piles

4.4. Tunnel construction with soil consolidation

Figure 13 shows the horizontal displacement of the pile #1 in the tunnel excavation after soil consolidation by the bored piles coupled with jet grouting piles. The maximum horizontal displacement of the pile #1 is 0.34mm at the top of the pile #1. Figure 14 is the vertical displacement of the pile #1. The maximum vertical displacement of the pile #1 is 0.29mm, which is at the top of the pile as well. Compared with the calculated results shown in Figure 7 and Figure 8, the method of the bored piles coupled with jet grouting piles consolidates the soil around the piles effectively. It enhances the bearing capability of the foundation, which makes the deformation of the pile #1 smaller, especially in the horizontal direction. It means that the above proposed method can control the deformation of the bridge piles when the shield tunnels crossed.

Figure 13 Horizontal displacement of the bridge pile #1 in the shield tunnel excavation process after construction of the bored piles and the jet grouting piles

Figure 14 Vertical displacement of the bridge pile #1 in the shield tunnel excavation process after construction of the bored piles and the jet grouting piles
5. Deformation monitoring
The deformation monitoring of the bridge piles was performed in construction. In order to compare with the results of the numerical simulation above, the deformation of the pile #1 should be monitored. However, the pile #1 was buried. Therefore, the monitoring point was shifted to the pier #1, shown in Figure 4. Here, we assumed that the deformation of the pier #1 is equal to the deformation of the pile #1. Figure 15 is the monitoring point on the pier #1 in the horizontal direction and the vertical direction.

![Monitoring point in the horizontal direction](image)

![Monitoring point in the vertical direction](image)

Figure 15 The monitoring point on the pier #1

After the right shield tunnel excavation, the maximum horizontal displacement of the pier #1 is 0.25mm and the maximum vertical displacement of the pier #1 is 0.31mm. These results are very close to the numerical results. Therefore, the method of the bored piles coupled with the jet grouting piles is available to control the deformation of the bridge.

6. Conclusions
The Hu-Hang high-speed railway is one of the highest level for the train operation in China. Hangzhou metro line 1 is designed to cross under the Yu-Hang South Station, which is one of the stations on the Hu-Hang high-speed railway. In order to control the deformation of the piles and guarantee the operation safety, the method of the bored piles coupled with the jet grouting piles was proposed in this paper.

The 3D numerical model was built using the commercial software ANSYS. Then, the shield tunnel excavation without soil consolidation, the construction of the bored piles coupled with the jet grouting piles, and the shield tunnel excavation with soil consolidation were simulated. The results show that the consolidation method can control the deformation of the bridge piles in the shield tunnel excavation effectively. In order to verify the numerical model, the in-site monitoring was performed. The monitored deformation of the bridge piles is close to the simulated deformation. Consequently, we think the proposed method was effective.

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