Study on Influence Evaluation and Control Measures of Open-cut Construction of Ramp Tunnel Adjacent to Bridge Piers

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Abstract: Improper control of tunnel structure adjacent to bridge piers in soft soil area will lead to structural deformation and traffic unsafety. In view of the engineering difficulties in the construction of the near-bridge-pier interchange ramp between Shenzhen-Zhongshan Bridge and Guangzhou-Shenzhen Expressway along Yangtze River, numerical simulations are carried out based on analyses of the position relationship and geological conditions. During ramp tunnel construction, the maximum horizontal displacement of the diaphragm wall structure is 19 mm, and the maximum horizontal displacement of the bridge pier, located in the middle of the foundation pit, is 7.4 mm. The vertical uplift displacement at the bottom of the foundation pit and that at the top of the open-cut tunnel structure is large, about 5.3 mm. In view of the analysis results, control measures such as soil reinforcement treatment and timely lateral support are introduced to ensure construction safety and provide reference for similar projects.

1. Introduction

In the construction process of underground ramp near bridge piles, foundation pit excavation will cause stratum displacement and bridge pile foundation deformation. Without proper control, they will affect the safety and comfort of vehicles on the bridge [1]. Therefore, it is of great significance to analyze the influence of underground ramp excavation and construction on pile foundation deformation of existing bridges and to propose control measures to ensure the safety of existing structures during ramp construction [2-3].

Scholars at home and abroad have carried out much research on influence analyses and control measures of underground construction. For example, based on an actual project and results of Abaqus simulation, Xu Guisheng proposed a control measure of enlarging parameters of high pressure jet grouting pile reinforcement. He pointed out that the reinforcement width of 2.5 m and the reinforcement depth of 25 m could control pile foundation deformation [4]. Jiang Wei analyzed the construction process of a regional tunnel under interchange. He put forward that as the distance from the excavation surface to the bridge pile reached to L=7D, the bridge pile started to be affected. It would be influenced most when L=3D. In addition, he proposed the bridge deformation control standard by analytic hierarchy process [5].

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However, research on ramp tunnels under bridge pile foundations is rare. Besides, due to the particularity of stratum conditions and environmental conditions, it is necessary to conduct a targeted study on the F ramp tunnel connecting Shenzhen-Zhongshan Bridge and Shenzhen Bao’an International Airport Expressway [6]. Combined with the design scheme and numerical simulation by FLAC3D, the paper analyzes the deformation of bridge pile foundation in the construction process, and puts forward control measures to ensure construction safety and normal operation of the expressway [7-10].

2. Project Profile

2.1 Positions
The tunnel connecting Bao’an Airport is located in East Artificial Island of Shenzhen-Zhongshan Bridge. It adjoins Fuyong Ferry Terminal in the north, faces Guangzhou-Shenzhen Expressway along Yangtze River in the east, and boarders the island wall of East Artificial Island in the west. As Fig.1 shows, the tunnel designed to realize interconnection between Shenzhen-Zhongshan Bridge and Guangzhou-Shenzhen Expressway along Yangtze River contains four directional underground ramps. The F ramp, a cut-and-cover tunnel, is close to the existing bridge foundation of Guangzhou-Shenzhen Expressway along Yangtze River. It starts at FK0+830.0 and ends at FK0+975.0 with a distance of 145 m.

The F ramp is under the 49# and 50# bridge piles of Guangzhou-Shenzhen Expressway. The depth of the foundation pit is 11.384 to 13.019 m. The horizontal distance between the two pile caps is 20.83 m, and the minimum distance between the outer edge of the tunnel and the pile cap is only 1.99 m. Fig.2 shows the structure of the ramp under the bridge piles. The vertical height between the artificial island surface and the bridge structure bottom is 15.41 m. Cast-in-situ bored piles with a diameter of 1.6 m are adopted. The bottom elevation of the piles which insert over-two-meter deep into the weathered rock layer is -32.7 m.

2.2 Geological Conditions
The F ramp is located in the East Artificial Island with water depth of about 0.00 to 4.500 m. The seabed is quaternary holocene marine silt with the thickness of 6.2 to 13.4 m. Its bearing capacity is about 40 to 45 kpa. The medium sand layer is slightly and medium dense with thickness of 1.2 m. The residual silty clay shows plasticity and hard plasticity with thickness of 1.4 to 4.4 m. The bedrock is completely and strongly weathered mixed granite layer with thickness of 10.0 m. Its bearing capacity is 300 to 800kpa. The elevation of the medium and slightly weathered granite is -26.87 to -37.37 m with the bearing capacity of more than 3000kpa. The East Artificial Island adopts rubble-mound dike.

Fig.1 Plan View of the Ramps Connecting Bao’an Airport
Numerical Simulation Analysis

3.1 Calculation Model
FLAC3D is used for numerical simulation. To facilitate calculation, two layers of silt are simplified into one layer, fully weathered granites are simplified into one layer, and the pile foundation of the retaining structure is converted into diaphragm wall by equivalent stiffness method. The mohr-column model is used to simulate the soil mass; the elastic model is used to simulate the pile and the cap; the grid element parameters are changed to simulate the construction process of the diaphragm wall; and null element simulation is used to simulate the excavation process of foundation pit. During tunnel excavation, horizontal support is applied. After tunnel excavation, shell element simulation is adopted for tunnel structure. The calculation model is shown in Fig.3.
3.2 Parameter Selection
The suggestive geotechnical calculation parameters are listed in Table 1. The parameters are chosen in consideration of laboratory test results, in-situ test results, relevant codes, regional experience and comprehensive analyses.

3.3 Construction Process
In order to be consistent with the construction sequence of foundation pit excavation and support, the following control sequence is adopted during calculation. First, construct bridge structure, apply structure load, and obtain original ground stress field. Second, level ground. Third, construct supporting structure. Forth, excavate the foundation pit in four steps, and apply concrete support and steel support. Fifth, construct the main structure and backfill soil above roof.

3.4 Result Analysis
The distribution of abutment displacement after tunnel construction is shown in Fig.4. Abutments move towards the tunnel excavation area, and the maximum displacement is in the middle and upper part of the pile on the excavation side. The maximum lateral displacement is about 7.4mm, yet the vertical displacement shows a small uplift close to the excavation side of the foundation pit and a subsidence far from the excavation side. However, the values of both uplift and subsidence are so small that they would not cause insecurity and instability.

The distribution of diaphragm wall displacement after tunnel construction is shown in Fig.5. A large lateral displacement takes place in the middle part of the diaphragm wall with the maximum displacement of about 19 mm. Affected by the extrusion of the soil layer at the bottom of the foundation pit, vertical displacement of uplift appears. The uplift value at the top of the foundation pit is small while that at the bottom is large with the maximum value of 5.5 mm.

| Rock Mass/Structure          | Bulk Density $\gamma$ (kN/m$^3$) | Cohesion $c$ (kPa) | Frictional Angle $\phi$ (°) | Poisson's Ratio $\nu$ | Elastic Modulus (MPa) |
|-----------------------------|---------------------------------|-------------------|-----------------------------|-----------------------|-----------------------|
| Backfilling Medium-coarse Sand | 20.0                            | 2                 | 32                          | 0.30                  | 30                    |
| Silt Layer                  | 15.0                            | 6.4               | 7.1                         | 0.40                  | 2.8                   |
| Sandy Cohesive Soil         | 18.6                            | 17.1              | 27.1                        | 0.35                  | 12                    |
| Fully Weathered Granite     | 19                              | 20.5              | 29.4                        | 0.29                  | 32                    |
| Sandy Granite               | 19.8                            | 30.5              | 30.6                        | 0.27                  | 35                    |
| Medium-weathered Granite    | 25.0                            | 3000              | 41                          | 0.15                  | 3000                  |
Fig. 4 Displacement of Bridge Piers and Pile Caps

Fig. 6 shows the distribution of tunnel structure displacement after the tunnel structure construction. It can be seen from the figures that the horizontal displacement of the tunnel structure is small with the maximum value of less than 1 mm. The vertical displacement is relatively larger with a maximum displacement of about 5 mm at the top and 2 mm at the bottom.

As the soil between the two bridge piles is excavated first, the horizontal constraint between the piles decreases, and it will cause bridge abutment structure moving towards the tunnel excavation area. The maximum horizontal displacement of 7.4 mm occurs in the middle and upper part of the pile foundation, which corresponds to the excavation position of the foundation pit. Affected by horizontal displacement of the pile foundation, the diaphragm wall structure has lateral displacement. The maximum lateral displacement of 19 mm is located in the middle of the diaphragm wall. Affected by the excavation of the soil above the tunnel structure, the vertical and horizontal constraint of the foundation pit reduces, which result in extrusion of the soil layer at the bottom of the pit. The maximum uplift value is at the bottom of the pit.

Fig. 5 Displacement of Supporting Structure
4. Control Measures

In order to control bridge pile deformation and protect structure safety, the high pressure rotary jet pile grouting is used to reinforce the ④I layer and its above layer (see Fig.2). During construction process, the deformation monitoring and measurement of foundation pit structure and bridge structure should be strengthened to prevent foundation pit instability and bridge tilting. During foundation pit excavation, horizontal steel support should be applied in time to balance the horizontal force on both sides of the foundation pit and prevent collapse caused by excessive horizontal deformation. In addition, the bottom of the foundation pit should be reinforced, and the soil above the tunnel should be backfilled in time after the completion of tunnel construction.

5. Conclusion

The following conclusions are drawn in consideration of the survey data and design scheme of the F ramp tunnel as well as the checking calculation of tunnel under the expressway bridge pile foundation by stratum structure method.

(1) Lateral displacement of bridge pile foundation and diaphragm wall appears after finishing the tunnel structure construction. They are caused by decreasing lateral restraint, the result of soil disturbance. Therefore, the soil near the pile foundation should be reinforced. Meanwhile, timely steel support should be made to prevent soil collapsing.

(2) Construction quality should be controlled and monitoring should be made to prevent large deformation of the existing bridge pile and cap structure, and to ensure normal operation of the expressway during construction.

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