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Study on Underpinning Scheme of Shield Tunnel Crossing Pile Foundation of Viaduct

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Abstract. With the increasingly dense distribution of urban metro network, it will inevitably lead to the problem of intersection between metro line and existing Viaduct Pile foundation. In order to ensure the normal operation of viaduct and complete the construction task of Metro at the same time, pile underpinning technology has been successfully applied to such projects. On the basis of theoretical analysis and relying on the ramp of Jinan Metro Line R2 production station to Lihuang station, this paper carries out numerical simulation of underpinning construction and tunnel underpass through finite element software, studies the deformation law of underpinning structure, determines the engineering risk points, and verifies the underpinning scheme to be adopted. The results show that the overall settlement of underpinning structure and the horizontal deformation of pile body presents "bow" shape. The structural deformation is mainly affected by underpinning construction, and the deformation of underpinning beam and the top of pile is the largest. The influence area of the surface is 4 m outside the underpinning beam. The above deformations meet the requirements of the code, that is, the scheme of manual piling. And the process of pre jacking up→chisel pile→construction of underpinning beam and pile cap→passage of shield machine are safe and feasible.

1. Introduction

With the continuous construction of urban infrastructure, the cross conflict between subway tunnel and viaduct foundation is inevitable. How to complete the subway construction task under the condition of ensuring the normal operation of viaduct has become the focus problem. At present, pile foundation underpinning technology emerges as the times require, that is, the underpinning structure is used instead of the original pile to bear the upper load.^[1] Because the deformation control of viaduct is extremely strict, and tunnel excavation is bound to cause surrounding rock disturbance, affecting the bearing capacity of pile foundation. It is of great significance to master the deformation characteristics of underpinning process and take reasonable engineering measures to ensure the safety of shield tunnel construction and the safe operation of viaduct^[2].

For engineering difficulties of underpinning pile foundation of viaduct under tunnel experts and scholars have carried out a lot of research work. Xu Qianwei^[3] studied the stress conversion mechanism of pile-raft system and the influence of shield cutting pile on superstructure. The results show that after the upper load is completely transferred to the underpinning structure, the removal of part of pile



foundation has little effect on the safety of bridge structure. Zhang Yiran^[4] through the comparative analysis of the monitoring data and the simulation results of tunnel underpinning construction, it is concluded that the influence of tunnel excavation on pile foundation settlement is about 3 times that of underpinning construction. However, the project involves two construction techniques, and the existing studies often ignore the influence of superstructure and underpinning technology, the results are only based on the completion of underpinning. In order to obtain the accurate numerical prediction of the sensitive environment, this paper takes the R2 line of Jinan subway as the background, refines and simulates the two processes continuously, and carries out the deformation prediction of the whole process. It also makes a targeted study on the pile breaking scheme, the selection of underpinning procedure and the engineering risk.

2. Engineering summary

The first phase of Jinan Rail Transit Line R2 project (Production road station to Lihuang road station section) passes through the ramp of Production road and is laid underground along the south side of the Beiyuan viaduct. Cross the Beiyuan Interconnection H, G ramp, Southeast Quadrant ramp Bridge (C, D ramp), cross Dongluo River Bridge to Lihuang Road There are five ramp piers in the interval conflict with the tunnel. This paper intends to select the production ramp with great difference in size between the original pile and the underpinning pile and the existence of short-distance pile foundation. The production ramp bridge is a 4-hole 1-joint concrete continuous box girder with a height of about 6 meters. The right line shield passes through a pier and needs to be replaced with two bridge piles. Below the cap is a cast-in-place pile foundation with a diameter of 1.5 m and a pile length of 28.5 m. The angle between the center line of pile foundation and shield tunnel is 64° . The relative relationship between interval tunnel and ramp bridge is shown in Fig. 1 and 2.

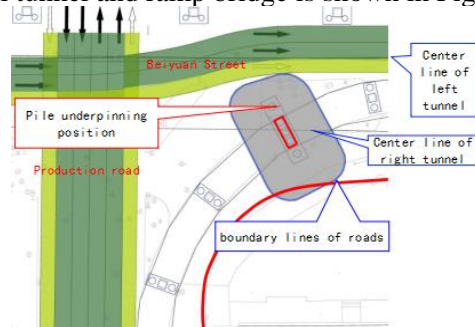


Fig.1. Location diagram of tunnel and bridge



Fig.2. Present situation of bridge piers

3. Design of the scheme of pile foundation underpinning

Considering the influence of tunnel excavation on pile foundation and the control of underpinning beam span, it is determined that the reserved net distance between tunnel and underpinning pile foundation is 1 meter. The underpinning pile is two cast-in-place piles with a diameter of 1.8 meters, and the length of the pile is 40 meters, which is designed according to the rock-socketed pile; The underpinning girder is a simply supported beam structure with a thickness of 3 meters, a length of 15 meters and a width of 4 meters. The longitudinal and upper and lower parts of the beam are prestressed and connected with the original pile and the original cap in order to increase the torsional stiffness and the longitudinal and transverse stiffness. The plan view and elevation view of the underpinning structure are shown in Fig. 3 and 4.

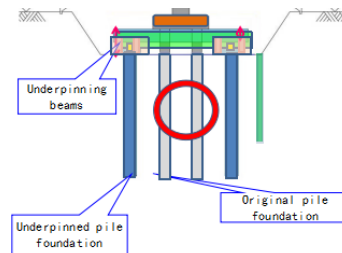
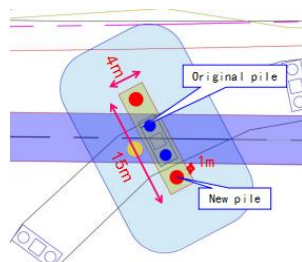


Fig.3. Plane layout of underpinning structure Fig.4. Elevation diagram of underpinning structure

4. Numerical analysis of the whole process of pile foundation underpinning and shield tunnel crossing

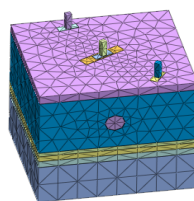
4.1. Model establishment

In this paper, numerical analysis and calculation are carried out by using three-dimensional geotechnical finite element analysis software MIDAS GTS/NX. According to the relevant literature, when the ratio of the soil calculation model to the plane size of the actual structure is more than 3 to 5 times, the boundary effect has little effect on the static and dynamic response of the structure, which can be ignored. Therefore, the calculation range of the model along the X, Y and Z directions is taken : 50m×45m×40m. Calculate boundary: The horizontal displacement is limited by the boundary on both sides of the model; The bottom limits the vertical displacement; the surface is a free surface. In this calculation, the surrounding rock and soil layers with similar mechanical properties are combined, and it is assumed that each rock and soil layer is homogeneous and horizontal layered distribution. The physical and mechanical parameters of surrounding rock and soil layers and materials are detailed in Table 1. The calculation model is detailed in Fig.5.

Table.1 Material mechanics parameter list

Item	Bulk density γ (kN/m ³)	Internal friction angle ϕ (°)	Cohesive force c (kPa)	Compression modulus E_s (MPa)	Thickness (m)	Poisson ratio ν	Constitutive model
Miscellaneous fill	19	15°	5	4.1	3	0.35	Mohr-Coulomb
Clay	18.4	10	25.0	3.4	7.5	0.3	Mohr-Coulomb
Totally weathered diorite	17.9	20	15	4.3	1.5	0.3	Mohr-Coulomb
Strongly weathered diorite	21	35	35	/	11.6	0.3	Mohr-Coulomb
Moderately weathered diorite	23	40	35	/	43.0	0.2	Mohr-Coulomb
Segment	25	/	/	27500	/	0.20	Elastic Constitutive Model

(Notice: “#” Indicates that the value takes empirical value.)



a. Graph of soil model

b. Model diagram of underpinning structure

Fig.5. Figure of numerical calculation model

4.2. Simulated working condition

Before the establishment of the underpinning structure, the initial ground stress and pier load are simulated. By using the zero clearing function of displacement, not only the stress state caused by the normal operation of the bridge is retained, but also the surrounding rock deformation caused by it is removed. Then the establishment of the underpinning structure, the chiseling of the original pile and the excavation of the tunnel are carried out. The specific construction phase is shown in the table 2.

Table.2. Step sequence of simulated construction in the whole process of underpinning construction and tunnel crossing

Construction stage	Specific content
The first step	Activate the load of soil, bridge and pier, and remove the displacement from zero.
The second step	Activate underpinning structure
The third step	Passivation needs to chisel part of the original pile and apply pre-top force
The fourth step	Passivating tunnel soil, activating shield shell

4.3. Analysis of deformation control of bridge pile

Based on the principle of energy conservation, in the process of passing through the existing bridge under the subway tunnel, the existence of the pile foundation blocks the ground deformation, and the deformation energy of the pile foundation absorbs the elastic performance released by the excavation of the tunnel. The results show that the deformation of pile foundation is the control core of the construction of existing bridges near the subway. ^[6]

4.3.1. Analysis of Vertical deformation Control of Bridge pile

Under the action of pier load, the underpinning beam transfers part of the load to the underlying soil layer, the soil compression deformation is large, and the underpinning beam sinks; the supporting pile is subjected to eccentric load, the pile body is compressed, and the compression deformation occurs. When the pile top is connected with the supporting beam, the deformation of the trusted beam has the greatest influence. On the other hand, with the increase of the friction resistance of soil to the side of the pile, the vertical displacement of the pile decreases gradually from the top of the pile, and the pile is a rock-socketed pile, and the deformation at the bottom of the pile is about 33% of that of the top of the pile Fig.6 shows the vertical deformation cloud image of bridge pile under different working conditions.

From Fig. 7, it can be seen that after the underpinning beam is established, the settlement of the pile foundation is smaller than that of 1mm because of its large self-weight. Working condition 3, that is, the chiseling process of the original pile. It is the main stage of vertical deformation of the underpinning structure, and the settlement of about 3.5mm occurs. After the pile cutting, the stress of the original pile is released, and there is an obvious stress concentration at the place where the pile is cut off. After chiseling, the original piles are moved about 3mm towards this place.

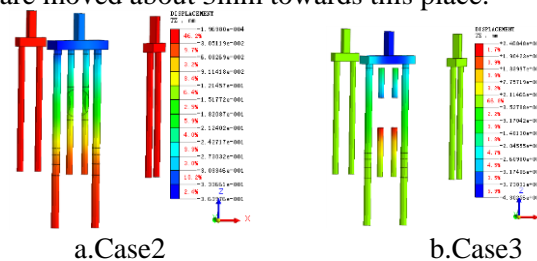


Fig.6. Vertical Deformation Cloud of Bridge Pile

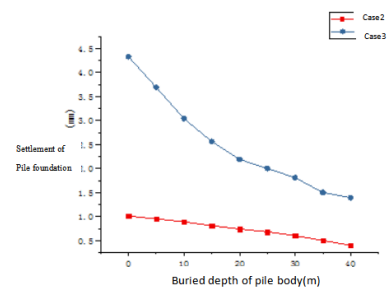


Fig.7. Vertical deformation diagram of pile foundation under different working conditions in pile foundation underpinning

4.3.2. Control analysis of horizontal deformation of bridge pile

The underpinning beam deforms under the load of the pier, and the top of the underpinning pile bends inward. Horizontal displacements deviated from the central load occur in the middle of the pile, and the trend of deformation decreases with the depth. The distant bridge piles are also affected by it, and the structures are all displaced to the center of underpinning. After the original pile is chiseled out, the lower support of underpinning beam decreases. The deflection increases and both ends of the beam and the top of the pile bend inward. Because of the stress release of the original pile, the underpinned pile body displaces outward. Figure 8 shows the horizontal deformation cloud of bridge piles under different working conditions.

Fig. 9 shows that the construction of underpinning structure tends to displace toward the center. The maximum deformation occurs in the inner part of the pile top, and the inward displacement is about 0.4 mm. The process of removing piles is the stage of maximum horizontal deformation of the lower structure of the bridge, which also has a great influence on the surrounding supporting system. Both ends of the underpinned beam displace inward about 1.1 mm, while the underpinned piles at the chiseling site displace outward about 0.6 mm, and the pile body presents a "bow" shape change.

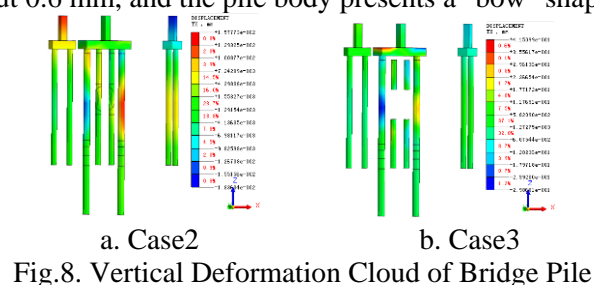


Fig.8. Vertical Deformation Cloud of Bridge Pile

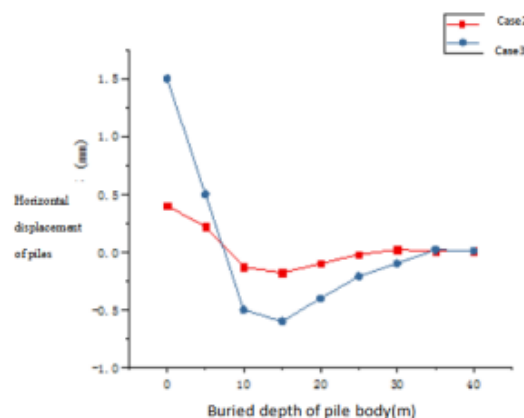


Fig.9. Horizontal deformation diagram of pile foundation under different working conditions in pile foundation underpinning

4.4. Regional analysis of the influence of surface subsidence

During construction of underpinning and shield tunneling, the stress redistribution of soil is caused by construction disturbance. The subsidence of the ground surface occurs, which affects the normal operation of viaducts. From figs. 10 and 11, it can be seen that the settlement of the surface basically conforms to the "U" curve, and the maximum value appears near the existing cap, that is, above the tunnel at the underpinning, which is about 4.8mm in settlement. The influence is 4 m outside the underpinning beam, and the settlement outside the scope is less than 0.5 mm.

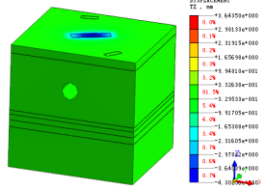


Fig.10. Deformation Map of Surface Settlement

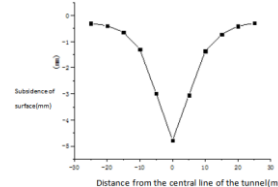


Fig.11 Deformation map of surface settlement under different conditions

4.5. Effect of shield tunnel construction on deformation of underpinned pile foundation

In this project, the underpinned piles are located near the inflection point of settlement curve above the arch top of the tunnel, and the pile body is susceptible to the influence of tunnel excavation. Fig.12 and 13 are the vertical and horizontal deformation nephograms of bridge piles after tunnel excavation, respectively.

Fig. 14 shows that the excavation of tunnel has little influence on the vertical deformation of bridge piles. However, during the excavation process, the stress redistribution of the soil and the rebound of the soil at the lower part of the tunnel will push the underpinning pile upward. Compared with the previous working condition, the upward displacement of pile top is about 0.2 mm, and the settlement is about 4.1 mm.

From Fig. 15, it can be seen that the horizontal deformation of bridge piles after tunnel excavation is basically the same. Because the stress release of soil near the tunnel side is large, the soil pressure on both sides of the pile is unbalanced, and most of the pile displacement to the tunnel side is about 0.2 mm. Under the double action of the self-weight of the upper soil and the rebound of the lower soil, the soil on both sides of the tunnel is compressed. The pile body at the horizontal axis of the tunnel further deviates from the tunnel and displaces about 0.5mm outward. According to the requirement of the design document, "the deformation of each part is not more than 5 mm", the control of the deformation of the project meets the requirement.

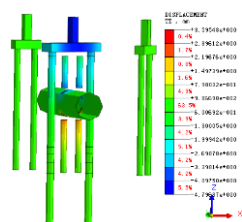


Fig.12. Vertical Deformation Cloud of Pile Foundation after Tunnel Excavation

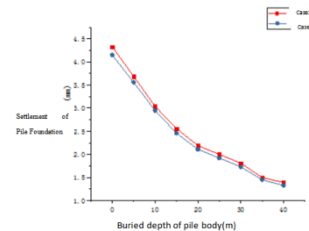


Fig.13. Vertical Deformation Map of Pile Foundation after Tunnel Excavation

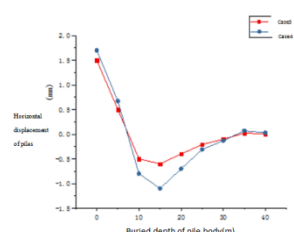
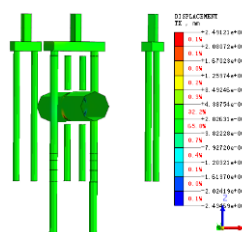


Fig.14. Horizontal Deformation Cloud of Pile Foundation after Tunnel Excavation

Fig.15. Horizontal Deformation Map of Pile Foundation after Tunnel Excavation

5. Conclusion

In view of the study of tunnel underpass the underpinning of pile foundation of viaduct, the underpinning of pile foundation and shield tunneling are simulated continuously, and the stability of underpinning structure in the whole process is analyzed. Then the feasibility of the scheme is verified and the risk management measures are put forward.

(1) During the underpinning process of pile foundation, the soil settles under pressure and the underpinning structure deforms. After the foundation of underpinning structure, the change of underpinning piles presents a "bow" shape. Both ends of underpinning beams displace toward piers. The horizontal displacement of the two ends of the underpinning beam and the top of the pile should be paid close attention in the construction process. In the process of removing the pile foundation, the vertical displacement of each structure increases obviously, and the deformation is about 3mm. The settlement monitoring should be strengthened at the center of the underpinning beam and the pile top.

(2) During the excavation of shield tunnel, the shape of underpinning structure is basically consistent. The horizontal displacement of the pile foundation at the axis of the tunnel is greatly affected by it, which increases by about 30%.

(3) The curve of surface subsidence is basically U-shaped, and the main influence area is 4 m outside the underpinning beam. The maximum value is above the tunnel, and the settlement is about 4.8 mm.

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