Study on Underpinning Scheme of Viaduct Pile Foundation Crossed by Shield Tunnel

Zhang Liangliang\textsuperscript{1,2}

\textsuperscript{1}China Railway Siyuan Survey and Design Group Co., Ltd., Wuhan, Hubei 430063, China
\textsuperscript{2}National- Local Joint Engineering Research Center of Underwater Tunnelling Technology, Wuhan, Hubei 430063, China

Abstract. Rapid developments in domestic metro construction could inevitably result in cross-engineering conflicts between metro lines and existing bridge pile foundations. Pile underpinning technology has been successfully applied to such projects to ensure the operating safety of viaducts and synchronous construction of metro lines. One section tunnel of Jinan Metro Line R2 is selected as the research object in this study. First, the processes of pile underpinning and tunnel crossing construction are numerically simulated using finite element software. Next, the deformation law of underpinning structures is studied and the engineering risk points are determined. Finally, the design scheme of pile underpinning is proven to be correct and reasonable. The results are as follows: (1) The underpinning structure presents a trend of overall settlement. The horizontal displacement of the pile body occurs in the form of a bow. Maximum deformation occurs at the underpinning beam and top of the pile. (2) The influence area of the soil surface is approximately 4 m outside the underpinning beam, and the deformation values of the underpinning system meet construction requirements. (3) The following construction steps are recommended. Step 1: Pre-jacking constructing. Step 2: Pile cutting. Step 3: Jack removal and underpinning beam and pile cap construction. Step 4: Road surface backfilling and repair. The shield machine should then be allowed to pass. (4) This paper provides targeted risk management measures. For example, isolation piles should be set on both sides of the tunnel.

Keywords: underpinning of pile foundation; metro tunnel; bridge pile; deformation of pile foundation; numerical calculation

1. Introduction
Given the continuous construction of urban infrastructure, cross-engineering conflicts between metro tunnels and viaduct foundations are inevitable. Developing means to control tunnel construction tasks without compromising the operating safety of viaducts is an important endeavor. At present, underpinning technology of pile foundation emerges as the times require, which is used to replace the original pile to bear the upper load [1-2]. The deformation control of viaducts is very strict. However, tunnel excavation could inevitably disturb the surrounding rock and affect the bearing capacity of pile foundations [3-4]. Understanding the deformation characteristics of the underpinning process is vital,
and reasonable engineering measures should be implemented to ensure the construction safety of shield tunnels and viaducts.

This project involves two construction technologies: pile underpinning and shield passing. The existing research often neglects the influence of superstructures and underpinning technology, and the results are established only on the basis of underpinning completion [5-7]. This work takes Jinan Metro Line R2 as the background to predict the sensitive environment accurately, and the two design processes are refined and continuously simulated. The deformation of the process is then predicted, and the schemes of pile breaking and underpinning are studied. Finally, the engineering risks of pile underpinning are listed.

2. Engineering summary
The tunnel section between the Shengchan Road and Lihuang Road stations of Jinan Rail Transit Line 2 is located in a municipal road along the southern side of the Beiyuan viaduct. This tunnel crosses ramps H and G of Beiyuan Interchange and ramps C and D of the southeastern quadrant ramp ridge and ends at Lihuang Road Station crossing Dongluohe Bridge.

There are 5 crossing engineering between ramp piers and tunnels. Shengchan Road ramp, which features a large size difference between the original and underpinning piles, is selected as the research object in this paper. The Shengchan Road ramp bridge is a four-hole one-link concrete continuous box girder measuring approximately 6 m high. Two bridge piles should be underpinned because the tunnel passes through the pier. Under the bridge cap are two cast-in-place piles with a diameter of 1.5 m and length of 28.5 m. The angle between the central line of the pile foundation and the shield tunnel is 64°. The relative relationship between the section tunnel and the ramp bridge is shown in Figs. 1 and 2.

![Figure 1](image1.png) **Figure 1.** Location of the tunnel and bridge.  
![Figure 2](image2.png) **Figure 2.** Section diagram of the tunnel and bridge.

3. Design scheme of pile underpinning construction

3.1. Comparison and selection of a design scheme
The Shengchan Road ramp structure comprises a concrete continuous box girder that experiences complex forces and is sensitive to deformation. Uneven settlement of the pile foundation could redistribute the stress of the main girder. Excessive stress changes will affect the bearing capacity of the main girder and the safety of the superstructure. However, adjusting the face pressure and controlling the driving posture during shield tunneling in such complex strata is difficult. The ramp adopts active
underpinning to control for pile settlement and reduce the traffic impact of underpinning construction. Before the original bridge pile is unloaded, a load is applied to the underpinning system by a jacking device.

3.1.1 Pile breaking scheme
The manual piling scheme is adopted in this project. The pile foundation in the shield tunneling range is chipped away by excavating the artificial shaft vertically at the top of the tunnel. This design scheme has the advantages of low risk, controllable cost, and no influence on shield construction. The construction sequence is as follows. Step 1: A high-pressure jet grouting pile or sleeve valve pipe is used to reinforce the surrounding strata prior to shaft excavation according to the surrounding geological conditions. Step 2: Lock ring beams and grill wall protection are set up. Step 3: The cross passage at the top of the shield tunnel is excavated and reinforced by grouting and arching double rows of small conduits. Step 4: The artificial shaft at the top of the shield tunnel is vertically excavated. Step 5: The pile foundation is chiseled using an air pick and gas cutter. And the C15 concrete is backfilled in shaft while chiseling pile. A diagram is shown in Fig. 3.

![Diagram](image)

**Figure 3.** Schematic of manual piling.

Using the shield machine to cut piles directly presents great risk to the construction period and cost. In addition, the cutter and screw conveyor must be transformed, which could cause sudden phenomena, such as steel bar winding and cutter damage. However, shield opening and pile breaking by pre-reinforcement of the soil layer to ensure operation in an anhydrous environment are difficult to carry out. Moreover, the risk of long-term shutdown of the shield machine, which could affect the duration of the project, is fairly high.

3.1.2 Construction procedures
The following procedures are proposed for the project. Step 1: Pre-jacking constructing. Step 2: Pile cutting. Step 3: Jack removal and underpinning beam and pile cap construction. Step 4: Road surface backfilling and repairing. The shield machine should then be allowed to pass. One alternative to this process is as follows: Step 1: Pile cutting. Step 2: Shield machine passage. Step 3: Underpinning beam and pile cap construction. Step 4: Pavement backfilling and repair. However, this alternative has high construction safety and procedural requirements. Moreover, it could lead to massive traffic interference. A second alternative involves the removal of jacks and fixed joints prior to the cutting of the piles. This alternative is a safer scheme compared with the first one when the calculation of the pre-jacking force is
accurate. However, over-jacking or insufficient jacking force may occur on account of the influence of the original pile on the jacking force. The underpinning beam is also subject to an eccentric load, which often shows a large difference between the actual and theoretical values. The proposed scheme takes into account the advantages of the two schemes. The bridge deck deformation could be optimized by adjusting the jacking force when an error occurs to ensure the safety of the existing bridges.

3.2. Design of the pile foundation underpinning scheme
The influence of tunnel excavation on the pile foundation is considered, and the control mean of the underpinning beam span is used. The reserved net distance between the tunnel and underpinning pile foundation is 1 m, and the underpinning pile is made up of two cast-in-place piles with a diameter of 1.8 m and length of 40 m. The rock-socketed pile is then designed. The underpinning beam of this pile has a simple supported structure with a thickness of 3 m, length of 15 m, and width of 4 m. The vertical and downward directions of the beam are then determined. Pre-stressing is applied to the original pile and cap to increase the torsional, longitudinal, and transverse thrust stiffness. The plane and elevation of the underpinning structure are shown in Figs. 4 and 5, respectively.

![Figure 4. Planar layout of the underpinning structure.](image)

![Figure 5. Diagram of the underpinning structure elevation.](image)

4. Numerical analysis

4.1. Modeling description
The three-dimensional geotechnical finite element analysis software MIDAS GTS/NX is used for numerical analysis and calculation. When the ratio of the calculation model of the soil to the planar size of the actual structure exceeds 3–5, the boundary effect has little influence on the static and dynamic responses of the structure. Therefore, the calculation ranges of the model along the X, Y, and Z directions are 50, 45, and 40 m, respectively. The boundaries on both sides and bottom of the model restrict horizontal displacement. Otherwise, the surface is free from other constraints. The surrounding rock and soil layers are assumed to be homogeneous and horizontally stratified. The physical and mechanical parameters of the surrounding rock, soil layers, and materials are detailed in Table 1 (Note: “#” indicates an empirical value). The calculation model is detailed in Fig. 6.
Soil model

Model of the underpinning structure

**Figure 6.** Models determined by numerical computation.

| Material name                  | Thickness/m | Natural gravity $k_0/(N-m^{-1})$ | Compressive modulus $k_s/(MPa)$ | Cohesion/K Pa | Internal friction angle/° | Poisson ratio | Element attribute | Constitutive model       |
|-------------------------------|-------------|----------------------------------|---------------------------------|---------------|--------------------------|--------------|--------------------|-------------------------|
| Miscellaneou us fill          | 3.05        | 19                               | -                               | 5#            | 15#                      | -            | Solid element      | Mohr–Coulomb model     |
| Clay                          | 20.1        | 18.4                             | 3.4                             | 25.0          | 10                       | 0.35         | Solid element      | Mohr–Coulomb model     |
| Completely weathered diorite  | 2.1         | 17.9                             | 4.3                             | 15            | 20                       | 0.3          | Solid element      | Mohr–Coulomb model     |
| Strongly weathered diorite    | 2.5         | 21#                              | -                               | 35#           | 35#                      | 0.3          | Solid element      | Mohr–Coulomb model     |
| Moderately weathered diorite  | 10.1        | 23#                              | -                               | 35#           | 40#                      | 0.3          | Solid element      | Mohr–Coulomb model     |
| Segment                       | 0.35        | 25                               | 27500                           | -             | -                        | 0.2          | Plate element      | Elastic constitutive model |

4.2. **Simulated working conditions**

Before the foundation of underpinning structure, the initial in situ stress and pier load are simulated. The stress state produced by the normal operation of the bridge is retained by using the displacement clearing function, and the initial deformation of the surrounding rock is eliminated. Subsequently, the underpinning structure is established, including the original pile and the tunnel was excavated. The specific construction stages are shown in Table 2.
4.3. Deformation analysis of the bridge pile

According to the principle of energy conservation, the existence of the pile foundation interrupts the deformation of the stratum as the metro tunnel passes through the existing bridges. The pile foundation absorbs the elastic energy released by the excavation of some tunnels, which indicates that the deformation of the pile foundation is the control core of the construction of adjacent existing bridges near the metro [9-10].

4.3.1 Vertical deformation of the bridge pile

Part of the bridge load is transferred to the underlying soil layer by the underpinning beam. The soil compression deformation increases, and the underpinning beam sinks accordingly. The underpinning pile is subjected to an eccentric load, and the pile body is subsequently subjected to compression deformation. The pile top is highly affected by this deformation because it is connected to the underpinning beam. The friction resistance of the soil to the side of the pile increases with the depth, and the vertical displacement of the pile body decreases gradually from the top of the pile. The pile is rock-socketed, and the deformation of the pile bottom is approximately 33% that of the top. Figure 7 shows the vertical deformation nephogram of the bridge piles under different working conditions.

Figure 8 illustrates that the settlement of the pile foundation is less than 1 mm because of its large self-weight. The third condition is the main stage of vertical deformation of the underpinning structure, the settlement of which is approximately 3.5 mm. After pile cutting, the stress of the original pile is released and an obvious stress concentration is observed at the cutting site. The original pile moves approximately 3 mm toward this location after drilling.

| Construction stage | Content |
|--------------------|---------|
| Step 1 (working condition 1) | Activation of the load of the soil, bridge, and pier and clearing of the displacement |
| Step 2 (working condition 2) | Activation of the underpinning structure |
| Step 3 (working condition 3) | Removal of part of the original pile and application of a pre-jacking force for passivation |
| Step 4 (working condition 4) | Passivation of the tunnel soil and activation of the shield shell |

**Figure 7.** Cloud map of the vertical deformation of bridge piles
4.3.2 Horizontal deformation of the bridge pile

The flexural deformation of the underpinning beam appears under the bridge pier load, and the top of the underpinning pile is curved inward. The horizontal displacement of the middle part of the pile body deviates from the central load, and its deformation trend decreases with increasing depth. The distant bridge pile structure is displaced toward the underpinning center. When the original pile is removed, the lower support of the underpinning beam decreases but the deflection increases. Both ends of the beam and the top of the pile are curved inward and the underpinning pile is displaced outward because of the stress release from the original pile. Figure 9 shows the horizontal deformation cloud of bridge piles under different working conditions.

Figure 10 shows that the overall displacement is oriented toward the center, with constructing of underpinning structure. The maximum deformation, which is approximately 0.4 mm, is observed in the inner side of the top of the pile. Piling results in the maximum horizontal deformation of the lower structure of the bridge, which has a great impact on the surrounding supporting system. Both ends of the underpinning beam have an inward displacement of approximately 1.1 mm. The underpinning piles at the chiseling site all move 0.6 mm outward, and the displacement of the pile body occurs in the form of a bow.

---

**Figure 8.** Vertical deformation of the pile foundation under different working conditions during pile underpinning construction.

**Figure 9.** Cloud map of the horizontal deformation of the bridge pile.
Figure 10. Horizontal deformation of the pile foundation under different working conditions during pile underpinning construction.

4.4. Influence area of the surface settlement
During underpinning construction and shield tunneling, the soil is disturbed, which leads to stress redistribution and subsequent surface subsidence. The normal operation of viaducts is also influenced by these activities. Figures 11 and 12 reveal that the surface settlement basically conforms to the U-curve of the settlement trough. The maximum settlement is found near the existing cap and approximately 4.8 mm. The influence range is 4 m outside the underpinning beam, and the settlement outside the scope is less than 0.5 mm.

Figure 11. Cloud map of surface settlement and deformation.  

Figure 12. Deformation map of surface settlement under different conditions.

4.5. Deformation effect of the underpinning pile foundation crossed by a shield tunnel
In this project, the underpinning pile is located near the inflection point of the settlement curve above the arched top of the tunnel. The pile body is susceptible to the influence of tunnel excavation. Figures 13 and 15 respectively illustrate the vertical and horizontal deformation nephograms of the bridge piles after tunnel excavation.

Figure 14 shows that tunnel excavation exerts little influence on the vertical deformation of the bridge piles. During tunnel excavation, the stress of the soil is redistributed and the soil at the lower part of the tunnel rebounds. The underpinning piles are displaced upward by approximately 0.2 mm and settle by approximately 4.1 mm.

Figure 16 reveals that the horizontal deformation of the bridge piles remains basically the same after tunnel excavation. Most of the piles are displaced toward the tunnel side by approximately 0.2 mm.
because of the large stress release of the soil near the tunnel side and the imbalance of soil pressure on both sides of the pile body. Under the effect of the upper soil weight and lower soil rebounding, the soil on both sides of the tunnel is compressed. The pile at the horizontal axis of the tunnel further deviates from the tunnel with an outward displacement of approximately 0.5 mm. According to relevant domestic regulations [11-12], the deformation of each part should not exceed 5 mm. Thus, the deformation control of the project meets this requirement.

Figure 13. Vertical deformation cloud of the pile foundation after tunnel excavation.

Figure 14. Nephogram of the horizontal deformation of the pile foundation after tunnel excavation.

Figure 15. Vertical deformation map of the pile foundation after tunnel excavation.

Figure 16. Horizontal deformation map of the pile foundation after tunnel excavation.

5. Risk management measures
The results of numerical analysis indicate that the pile foundation migrates toward the tunnel under soil pressure during piling and tunnel excavation. The isolation piles may be installed on both sides of the tunnel to bear the earth pressure sufficiently and protect the underpinning piles. Ground settlement peaks at the underpinning site, especially between segments and the surrounding rock. It is suggested to reserve grouting holes in tunnel segments and to grout in peripheral strata.

A number of risk points, such as pile–beam connection treatment, pre-lifting, and pile-drilling, are identified in the simulation.
### Table 3. Statistical table of risk management measures

| Project                                 | Risk                                                                 | Suggestion                                                                 |
|-----------------------------------------|----------------------------------------------------------------------|-----------------------------------------------------------------------------|
| Underpinning girder construction        | Difficulty in underpinning the formwork of the girder                | Optimize the underpinning cap to the longitudinal and transverse beam frame design |
|                                        | Arrangement of pre-stressing tendons in the underpinning girders    | Pre-stress the force design according to jacking up 1 mm                    |
|                                        | Reinforcement planting at fixed joints of the pile–beam              | Reinforcement of 200 mm for underpinned piles and glue material with good durability |
|                                        | Digging groove in the pile–beam joint                               | Design for underpinned pile grooves                                          |
|                                        | Temperature control during pile–beam fixing construction             | Necessary temperature control measures                                       |
| Pre-jacking                             | Top load distribution of underpinning piles                          | Combine the design calculation with the bearing capacity of the original pile to determine the size of the jacking force |
|                                        | Synchronized loading measures for jacks of underpinning piles       | Connect jacks in series and load them synchronously                          |
|                                        | Overloading and overloading control                                 | Double control monitoring indicators of design jacking force and pier 1 mm |
|                                        | Jack of load holding                                                | Implement safety measures, such as mechanical self-locking jacks, steel columns, and safety cushions |
| Pile chiseling                          | Cutting time of the pile foundation                                 | Cut underpinned piles in the cave and control jack lifting according to dynamic monitoring |
|                                        | Pile cutting scheme for artificial shafts                           | Strengthen stratum reinforcement, backup well dewatering, grid support, and construction cross tunnels prior to excavation to provide support; peel off and cut the concrete symmetrically during pile cutting with air picks |
|                                        | Underpinning pile protection                                        | Isolation pile (micro-pile with 350mm@600mm) and ground grouting reinforcement |
| Shield tunneling construction           | Selection of driving parameters in the underpinning system          | Optimize the design of the horizontal and vertical sections according to the detailed survey to reduce the construction risk of shield tunneling under the earth and rock |
|                                        | Construction of the overlapping tunnel                              | Construct the upper structure first, followed by the lower structure; carry out temporary support, cave grouting, and ground pre-grouting |
6. Conclusion
The mechanical behavior and deformation characteristics of viaduct pile underpinning under metro tunnel cross-construction are studied, and the construction procedures of pile underpinning and shield tunneling are simulated. The stability of underpinning structures is then analyzed to verify the feasibility of the scheme. Finally, risk management measures are proposed.

- During pile foundation underpinning, the underpinning structure is deformed because of the subsidence of the surrounding soil. After the underpinning structure is established, the displacement of the pile body occurs in the form of a bow and both ends of the underpinning beam are displaced toward the pier. Thus, the horizontal displacement of both ends of the underpinning beam and the top of the pile should be closely monitored during construction. The vertical displacement of each structure, the value of which is approximately 3 mm, increases obviously during piling. Settlement monitoring should be strengthened at the top of the pile and the center of the underpinning beam.

- The underpinning structure basically retains the same shape during shield tunnel excavation. The horizontal displacement of the pile foundation at the tunnel axis, which increases by approximately 30% compared with the initial state, is greatly affected by tunnel excavation.

- The surface subsidence curve is U-shaped, and the main influence area is 4 m outside the underpinning beam. The maximum subsidence, which is approximately 4.8 mm, occurs above the tunnel.

- The feasibility of manual piling is verified by numerical analysis. The following construction procedures are recommended: (1) Pre-jacking constructing, (2) pile cutting, (3) jack removal and underpinning beam and pile cap construction, and (4) road surface backfilling and repair. The shield machine should then be allowed to pass. Considering the high risk of pile underpinning construction, risk management measures are given in combination with numerical analysis.

References
[1] Niu Bin J 2020 Pile Foundation Underpinning of Special Shaped Bridges in Shield Section Urban Rapid Rail Transit vol 33.1 pp 84-90

[2] Xu Qianwei and Zhu Hehua and Ma Xianfeng J 2012 Pile underpinning and removing technology of shield tunnels crossing through group pile foundations of road bridges[J]. Chinese journal of geotechnical engineering vol 34 pp 1217-1226

[3] Che Zaqun and Lang Bo and Lu Da and YANG Ya J 2019 Research on Pile Foundation Underpinning Technology for the Shield Tunnel Passing through Bridge Pile Foundation Group Moden Tunnelling Technology vol 56 pp 133-141

[4] MA Wenjie and WANG Xu and WANG Binglong and WANG Bolin and WANG Xuelei J 2020 Application of Passive Pile Foundation Underpinning Technology on Lanzhou Rail Transit Line 1 Urban Mass Transit vol 7 pp 51-55

[5] Li Huiliang and Liu Baoxu and Feng Haibao J 2019 Study on Construction Risk of Existing Viaduct near Subway Tunnel Highway vol 1 pp 284-289
[6] Liu Xiandong J 2020 Solutions to Several Key Design Problems of Shield Tunnel in Soft Soil Area Urban Rapid Rail Transit, vol 33 pp 87-97

[7] Tu Qiang J 2008 Analysis of the Displacement Controlling Value of Large Pile Foundation Substitution Works Journal of Railway Engineering Society, vol 113 pp 26-30

[8] Jiang Huachun. Surrounding Rock Boundary Range Study on Tunnel Numerical Simulation[J]. Highway Engineering, 2013, 38(3):132–136.

[9] Wu Wenliang and Wang Jianjun and Sun Fanhao J 2018 Application of Secondary Underpinning Technology for Pile Foundation to Ziyang Station Wuliting Station Section on Fuzhou Metro Tunnel Construction, vol 38 pp 1220-1227

[10] YANG Zhenghua J 2018 Design of pile foundation underpinning for metro tunnels under-passing irregular continuous beam Railway standard design, vol 62 pp 104-109

[11] Ministry of housing and urban rural development of the people's Republic of China S 2014 Code for monitoring measurement of urban rail transit engineering (Beijing:China Construction Industry Press)p 57

[12] China Railway Siyuan Survey and Design Group Co., Ltd. R 2017 Preliminary design of section tunnel of Jinan rail transit line R2(Jinan:Jinan Rail Transit Group Co.,LTD.) pp 1-15

Acknowledgments
The author would like to thank the Scientific Research Project of Jiluo Road Yellow Tunnel organized by Jinan Urban Construction Group Co., Ltd., for supporting this work.