Comparison and Selection of Reinforcement Schemes for Shield Tunnelling Close Crossing High-speed Railway Viaduct Group

Bo Wu, Ziyi Zhang, Wei Huang

1College of Civil Engineering and Architecture, Guangxi University, 100 University Road, Nanning, Guangxi, 530004, China
2Key Laboratory of Disaster Prevention and Structural Safety of Ministry of Education, Guangxi University, 100 University Road, Nanning, Guangxi, 530004, China
3Key Laboratory of Disaster Prevention and Engineering Safety of Guangxi, Nanning, 530004, China
*Corresponding author’s e-mail: wwdn92@126.com

Abstract. Numerical simulation is carried out of the group pile foundation project of the shield tunnel on Nanjing metro airport line which crossing Beijing-Shanghai high-speed railway. The paper analysed the characteristics of the horizontal displacement along bridge of the pile foundation during the whole crossing process. On this basis, the reinforcement effects of grouting reinforcement, longitudinal beam and cross bracing reinforcement, bored cast-in-place pile reinforcement are comparative analysed with the horizontal displacement alone bridge of pile as the evaluation index. Also, the feasible program of the shelter pile reinforcement could be determined by combing with the construction process and conditions.

1. Introduction

In view of the small urban space, dense buildings and a large number of urban subway engineering, the adjacent construction of underground projects has been concerned and urgently needed to be solved. At present, China has not formed a complete and mature theoretical and practical system in the adjacent construction of underground engineering, but a lot of theoretical and practical explorations have been carried out by relevant scientific research institutions, design and the construction organization. According to the construction accidents happened in the engineering field, the core problems of the underground adjacent construction can be summarized as follows: reducing the influence on the existing buildings, ensuring the regular service and safety of new construction and existing structures[1].

As the needs of urban development and the improvement of the tunnel construction technology, compared with the early projects, the adjacent projects, the current underground projects are facing the acid test of smaller adjacent gap, higher requirement of displacement change, larger project scale and longer crossing time, especially the urban subway shield passing through existing buildings and bridge pile foundation engineering. At present the relevant research specialist and construction technique staff have studied shield through existing pile foundations and obtained a large amount of valuable research production. Hu X.Y used ANSYS finite element software to numerically simulate the shield tunneling near-distance through the pile foundation of urban overpass, and compared and analyzed the two
reinforcement schemes of flower tube grouting and stratum reinforcement \[^2\]. Zhang Z.Q not only studied the influence of new shield tunneling on the pile foundation of existing buildings, but also studied the stress and deformation characteristics of the new tunnel \[^1\]. Fang Y used ANSYA software to numerically simulate the shield. In the dynamic excavation process, the influence of two shield construction parameters, jacking force and grouting pressure, on the inclination ratio of pile foundation and horizontal displacement of pile top is analyzed \[^3\]. Li Y.C uses GTS software to simulate the shield tunnel crossing the pile foundation of urban overpass, and discusses in detail the construction process and matters needing attention of four protective measures, i.e. isolation pile, the sleeve valve pipe grouting, auxiliary jacking and optimizing shield tunneling parameters \[^4\]. Zhang H used FLAC3D software to simulate the pile foundation group engineering of double-line Shield Tunnel Crossing the Expressway overpass, and studied the stress and deformation law and the development process of pile foundation when left-right tunnel passed pile foundation successively \[^5\]. By means of numerical simulation, Hu D.H studied the influence law of different shield tunneling postures on the nearby pile foundation \[^6\]; Zhao H.H used Plaxis 3D Tunnel software to study the changing law of lateral deformation and settlement of pile foundation and the distribution along the pile body during the whole crossing process, and analyzed the influence of pile length on the deformation of pile foundation \[^7\]. By using finite element software ABAQUS, Li B preliminarily studied the influence of Shield Crossing on deformation and internal force of pile group foundation of high-speed railway bridge, and analyzed the reinforcing effect of isolation protection pile \[^8\]; Zhang Z.Y summarized the main research results of shield construction on ground deformation and adjacent structures, and proposed the direction of further research \[^9\]; Zhu F.B used Plaxis 3D Tunnel finite element software to study the influence of shield tunneling on nearby single pile and pile groups in heterogeneous soil \[^10\].

Nanjing Metro Airport Line passes through six railway bridges successively, with a distance of 210m and a duration of 2 months. The scale and difficulty of the project are very great. This paper uses the finite element software ANSYS to carry out numerical simulation. Taking the pile foundation of shield tunneling through Beijing-Shanghai high-speed railway bridge as the research object, the change characteristics of the horizontal displacement along the bridge in the course of shield tunneling are thoroughly analyzed. Three reinforcement schemes, grouting reinforcement, longitudinal beam and cross bracing reinforcement and isolation reinforcement of bored piles, are compared and selected.

2. Project overview

The Nanjing Metro Airport Line is a double-track shield tunnel with a net distance of 26.2m, a segment diameter of 6.2m and an inner diameter of 5.5m. It passes through the Beijing-Shanghai high-speed railway bridge section with a subway buried depth of 23m. The direction of the subway tunnel is basically orthogonal to the high-speed railway bridge. The viaduct is a continuous girder bridge. The pile foundation is composed of 14 bored pile groups with a diameter of 1.25m and a pile length of 28.5m. The position relationship between the subway and the viaduct is shown in Fig. 1.

The stratum distribution of pile foundation (38#pier) of Beijing-Shanghai high-speed railway viaduct is from top to bottom: plain filling soil, about 1.6-2.1m; silty clay, about 12.4-12.9m; strongly weathered siltstone, about 2.9-3.6m; medium weathered siltstone, about 10.6-12.3m. Metro tunnels are all located in medium weathered siltstone strata. The geological conditions of this section are shown in Fig. 2.
3. Numerical simulation

3.1 Finite element model

In order to reduce the influence of model boundary conditions on calculation accuracy, the distance between the left and right boundary of the model and the outer edge of the pier caps on both sides is 5 times the width of the cap, the distance between the front and back boundary of the model and the outer edge of the pier caps is 1 times the length of the cap, the distance between the lower boundary of the model and the bottom of the tunnel is 3 times the height of the tunnel, and the distance between the upper boundary of the model and the top of the tunnel is the depth of the tunnel. The geometric parameters of the whole model are shown in Fig. 3; the geometric relationship between bridge pile foundation and tunnel is shown in Fig. 1; and the geometric parameters of bridge cap and pile foundation are shown in Fig. 4, in which the length of cap is 22m and the width is 5.6m.
3.2 Material parameters and constitutive properties
The physical and mechanical parameters of materials are recommended in the detailed investigation report of geotechnical engineering at the Detailed Geotechnical Engineering Survey Report on the Two Ends of Nanjing South Railway Station of Nanjing-Gaochun Intercity Rapid Track (4#~7#).

The Mohr-Coulomb elastic-plastic constitutive model is adopted for surrounding rock, and the element type is Solid45 solid element; the segment is elastic model, and the element type is Shell63 shell element; the cap and pile foundation are elastic model, and the element type is Solid45 solid element.

3.3 Pier Cap Load
The pier gravity and the vertical live load of railway train are applied to the pier cap by the surface load.

According to the plane elevation of the bridge at the high speed of Beijing-Shanghai high-speed railway across the airport, the pier length is 19.8m, the height is 9.3m, the width is 2m, and the concrete density of the pier is 2500kg/m³. The surface load of the pier gravity on the pile cap can be obtained:

\[ p_1 = \frac{19.8 \times 9.3 \times 2 \times 2500 \times 9.8}{5.6 \times 22.1 \times 1000} = 73\text{kPa} \]

The pier span of viaduct is 34m. The ZK load in the Basic Code for Design of Railway Bridges and Culverts is adopted for vertical live load of railway trains. The diagram is shown. The vertical live load of the railway train on the surface load of the cap can be obtained:

\[ p_2 = \frac{(34/1.6+1) \times 250}{5.6 \times 22.1} = 44.4\text{kPa} \]

![ZK Standard Live Load Diagram](image)

Figure 5. ZK standard live load schematic diagram

From this, the load on the cap surface can be obtained:

\[ p = p_1 + p_2 = 73 + 44.4 = 117.4\text{kPa} \]

4. Analysis of Pile Deformation along Bridge Direction
In order to show the deformation characteristics of pier cap and pile foundation more intuitively, the deformation of pile foundation under three conditions, that is, Left-Line excavation to the pier, Right-Line excavation to the pier and left-right line passing through the pier, is given. Detailed deformations are shown in Figs. 6, 7 and 8.

From Fig. 6, it can be seen that when the left tunnel is excavated to the pier, the base of pier No.38 in the middle is bent (far from the tunnel), and the bending deformation is very uneven along the length of the pile foundation, and the bending of the left pile foundation near the tunnel side is larger than that of the right pile foundation far from the tunnel; the pile foundation of pier No.37 in the left side is also bent, but the bending deformation distributes evenly along the length of the pile foundation; The pier cap No.39 and pile foundation basically are hardly deform.

From Fig. 7, it can be seen that when the right tunnel is excavated to the pier, the base of pier No.39 is bent (far from the tunnel), and the bending deformation along the length of the pile foundation is extremely uneven, and the bending of the left pile foundation near the tunnel side is larger than that of the right pile foundation far from the tunnel; the pile foundation of pier No.38 is slightly bent, due to the offset of the deformation occurring during the excavation of the left line, the
right pile foundation of pier No.38 no more obvious bending occurs, and the cap and pile foundation of pier No.37 basically do not continue to deform.

From Fig. 8, it can be seen that the middle pier cap No.38 only has a large settlement after the left and right tunnel is completed, and the inclination angles along and across the bridge are small; the pier cap No.37 has a certain inclination angle along the bridge and settlement, and basically does not have a transverse inclination angle; the pier cap No.39 has a certain inclination angle along the bridge and settlement, and basically does not have a transverse inclination angle.

In the course of shield tunneling, there are great differences in the deformation of pile foundation at different locations, among which the pile foundation of pier No.38 and pier No.39 are the most obvious and unevenly distributed along the pile body.

Figure 6. Diagram of Pile Foundation Deformation during Left Line Tunnel Driving to Bridge

Figure 7. Diagram of Pile Foundation Deformation in the Right Line Tunnel Driving to Bridge

Figure 8. Pile Foundation Deformation Diagram after Tunnel Crossing Bridge 25m
5. Comparison and Selection of Reinforcement Schemes
Due to the special nature and high displacement requirement of the underpass railway, the construction unit has organized expert demonstrations and put forward a number of reinforcement suggestions, including grouting reinforcement, longitudinal beam cross bracing reinforcement and bored cast-in-place pile isolation reinforcement. In order to find the best scheme, the safety factor is further improved, and the reinforcement scheme is compared and studied.

5.1 Grouting reinforcement
Grouting reinforcement is one of the commonly used reinforcement measures when tunnel passes through Viaduct Pile Foundation in a certain range near bridge pile foundation. The concrete grouting reinforcement plane layout of this project is shown in Figs. 9 and 10. The depth of grouting reinforcement is from the surface down to the top of strongly weathered argillaceous sandstone. Grouting reinforcement is carried out along the bridge direction within 3 meters from both sides of the cap. The transverse direction of the bridge is 3 meters beyond the two sides of the pier. The shaded part shown in the figure.

The effect of reinforcement is analyzed by taking the nearest 1# pile and 2# pile from tunnel. Fig. 11 shows the horizontal displacement of pile No.1 and No.2 after tunnel excavation without grouting reinforcement and grouting reinforcement. It can be seen from the figure that after grouting reinforcement, the horizontal displacement of pile body decreases in the range of about 20 meters below the pile top, the horizontal displacement of pile body below 20 meters basically remains unchanged, and the horizontal displacement of pile top No.1 and No.2 decreases by 39% and 42% respectively. The maximum reduction is reached at 4m below the top of the pile, 50% and 55% respectively, which shows that grouting reinforcement can effectively reduce the horizontal displacement of the pile body.

Figure 9. Schematic diagram of grouting reinforcement effect on elevation

Figure 10. Plane effect diagram of grouting reinforcement
5.2 Reinforcement of Longitudinal Beam and Transverse Brace

In order to control the influence of shield tunnel construction on Beijing-Shanghai high-speed railway, longitudinal beams and cross-braces were strengthened on 37#, 38# and 39# caps of Beijing-Shanghai high-speed railway, which mainly limited the occurrence of horizontal displacement. The section size of 1# longitudinal beam is 2×2m, the section size of 2# and 3# longitudinal beam is 2×3m, the section of 4# longitudinal beam is 2×3m, all close to each pier cap, the cross-section length of the bridge is the same with each cap, 1# cross-section size is 1.0×1.0m, 2# cross-section size is 1.0×2.2m, three cross-braces are set up, the transverse spacing is 6.0m, the specific size is shown in Figs. 12 and 13.

Figure 12. Diagram of elevation strengthened by longitudinal beam and transverse brace
From Fig. 14, it can be seen that the horizontal displacement of the pile below the pile top decreases slightly, and the horizontal displacement of the pile below 20m basically remains unchanged. The horizontal displacement of the top of pile 1 and 2 decreases by 36% and 29% respectively, and the maximum reduction is achieved at 4m below the pile top, 46% and 42% respectively. It can be seen that the horizontal displacement of the pile can also be effectively reduced by the lateral bracing reinforcement.

5.3 Reinforcement of isolation pile

Four rows of isolation piles are protected between the two sides of the left-right tunnel and the pile foundation of the Beijing-Shanghai high-speed railway viaduct. Each row has 28 isolation piles, with a diameter of 1m, a spacing of 1.5m, a protective length of 41m and a protective length exceeding 6m of the pier pile foundation; five of the four rows of isolation piles are long piles at both ends of each row, 28m long, 18 of them are short piles and 20m long (embedded in rock layer 2 m); the left-line tunnel has a net distance of 1m from the tunnel on the left side of the right tunnel and 0.5m, the left protective piles of the right tunnel are 3m and the right protective piles of the right tunnel are 1m. The distribution of reinforced piles is shown in Figs. 15 and 16.

Fig. 17 shows that the horizontal displacement of the whole pile body decreases after the isolation pile is strengthened. The horizontal displacement of the top of piles No.1 and No.2 decreases by 46.6% and 37.5%, respectively. The maximum reduction is achieved at 4m below the top of the pile, 46% and 42% respectively. It can be seen that the control of the horizontal displacement of the pile body by the
isolation pile reinforcement is very significant.

Figure 15. Plane diagram of isolation pile reinforcement

Figure 16. Diagram of elevation strengthened by isolation piles

Figure 17. Diagram of Horizontal Displacement of Pile Body Reinforced by Isolated Pile

5.4 Comparison and Selection of Reinforcement Schemes
This paper mainly compares and analyses three kinds of reinforcement schemes from two aspects of site construction feasibility and reinforcement effect, so as to determine the most advantageous reinforcement scheme for this project.

The piers crossing the high-speed railway bridge group are low, the construction clearance is limited, and the deformation requirements of the bridge are strict. The construction conditions on site cause great difficulties to the construction of the reinforcement scheme. Longitudinal beam and transverse brace reinforcement scheme directly acts on the elevated bridge cap, although it is not limited by construction clearance, but the construction is difficult and dangerous, which is not conducive to the control of bridge deformation in reinforcement construction; deep grouting reinforcement and isolation pile reinforcement construction have less impact on bridge deformation,
and can break through the restriction of construction clearance through the transformation of construction equipment. Therefore, grouting reinforcement and isolation pile reinforcement are preferred.

According to the horizontal displacement diagrams of the three reinforcement schemes (Fig. 11, Fig. 14 and Fig. 17), the reinforcement effect of isolation pile is the most obvious, which can effectively reduce the horizontal displacement of the whole pile body. Therefore, the isolation pile reinforcement scheme is preferred.

Considering the feasibility of site construction and the effect of reinforcement, isolation pile reinforcement is preferred as the reinforcement scheme of this project.

6. Conclusion
The findings are summarized as follows:

(1) For a single pile foundation, the pile body near the tunnel bends away from the tunnel, and the pile body bends towards the tunnel at other locations. The closer the tunnel is to the pile foundation, the more obvious the uneven deformation of the pile foundation is.

(2) In the course of crossing, the pile foundation deformation between the left and right tunnels changes frequently, and the settlement deformation is the main one, while the horizontal displacement is small.

(3) Grouting reinforcement and longitudinal beam cross-bracing reinforcement can only reinforce the horizontal displacement of the upper half of the pile foundation, while isolation pile reinforcement can reinforce the whole pile foundation, and the horizontal displacement of the pile foundation is significantly smaller than that of grouting reinforcement and longitudinal beam cross-bracing reinforcement.

Acknowledgement
The authors acknowledge the financial support of the National Science of China (51478118, 51678164). The authors would like to express the appreciation and thanks to the managers and China Tiesiju Civil Group Co., LTD.

Reference
[1] Zhang, ZQ., He C. (2003) Research on mechanics behaviour of a shield tunnel construction in metro adjacent to existing pile foundation. JOURNAL OF THE CHINA RAILWAY SOCIETY, 25(1): 92-95.
[2] Hu, XY. (2013) Study on the influence of shield construction on bridge pile foundation under different reinforcement methods. Railway Engineering, (3): 75-77.
[3] Fang, Y., He C. (2008) Study on the influence of metro shield tunnelling on close-by pile foundation. MODERN TUNNELLING TECHNOLOGY, 45(1): 42-47.
[4] Li, YC. (2013) Protection of Viaduct Piles Close to Subway Shield Tunnel. Railway Construction Technology, (1):11-16.
[5] Zhang, H., Chen, SG., Deng, XF. (2011) Analysis on Influence of Shield Tunnelling on Ground and Bridge Pile. Chinese Journal of Underground Space and Engineering, 07(3): 552-557.
[6] Hu, DH., Duan, JC. (2015) Study on Characteristics of Deformation of Adjacent Pipe Foundations Caused by Shield Boring. Tunnel Construction, (5): 413-418.
[7] Zhao, HH., Chen, GX., Ye, B. (2010) Research on the Deformation of Single Pipe Induced by Adjacent Shield Driving. CHINESE JOURNAL OF UNDERGROUND AND ENGINEERING, 06(4): 794-802.
[8] Li, B. (2014) Analysis of influence of shield-driven tunnel on bridge pile foundation of high speed railway and study on its countermeasures. Railway Engineering, (5): 75-78.
[9] Zhang, ZY. (2002) Environment impact of shield tunnelling. MODERN TUNNELLING TECHNOLOGY, 39(2): 7-11.
[10] Zhu, FB., Yang, P., Lin, SX. (2010) Study of influence of shield tunnelling on neighbouring loaded piles. ROCK AND SOIL MECHANICS, 31(12): 3894-3900.

[11] Zhang, ZQ., He, C. (2003) Study on the mechanical behaviour of a metro tunnel construction adjacent to existing pile foundations in Shenzhen. CHINESE JOURNAL OF GEOTECHNICAL ENGINEERING, 25(2): 204-207.