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Influence of Shield Tunnel and Train Load on Existing Bridge Piles

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Abstract. With the rapid development of urban rail transit, the shield tunneling method used to construct new subways across existing high-speed railway bridges often occurs. In this paper, under the combined action of the double-track construction of a shield tunnel in a certain project and the train load, railway pile foundation from the deformation of the bridge pier and the settlement of the pile foundation. The vertical displacement distribution law analyzes the impact of shield construction and train load on the pile foundation of the existing bridge, and at the same time evaluates the safety of the bridge accordingly. The results show that the deformation of the existing bridge caused by the shield tunneling construction and the train load mainly affects the initial excavation stage. With the excavation, the settlement value gradually stabilizes, and the settlement of the bridge decreases slightly when the left line tunneling is completed. The shield tunneling of the right line has a certain compensation effect on the left line, and the overall settlement value of the bridge pile foundation is in a stable state.

Keywords. Double shield, Train load, Railway bridge pile, Pile deformation, numerical analysis

1. Introduction

In recent years, with the rapid development of urban rail transit projects, the subway has also developed rapidly due to its high speed, large capacity, low pollution, low energy consumption, and low land occupation. A large number of existing transportation facilities such as expressways and railways have appeared. Construction case happen from time to time. Due to strict construction control requirements for underpassing railways and expressways, shield construction is used for tunnels in subway sections that are difficult and risky.The construction technology of shield tunnels has matured and is constantly developing.[1] Shield tunnels passing through the pile foundations of existing railway or highway viaducts will cause loss of stratum soil, which will lead to redistribution of the soil stress field near the tunnel. The normal stress around the adjacent pile foundation will be released to varying degrees, making the pile foundation Reduction in carrying capacity[2].

When the shield passes under the existing high-speed railway bridge, the risk analysis and assessment of the impact of the shield construction on the high-speed railway bridge is carried out in advance to ensure the safety and comfort of the

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high-speed railway operation. Reduce unnecessary economic losses and negative social impacts. The existing calculation methods for the corresponding deformation caused by shield construction mainly include the peck method [3]. The constitutive models of soil mainly include Drucker-Prager model[4], M-C elastoplastic model[5], Cambridge model[6] Yang Liming [7] and others combined the shield tunneling under the existing line project, using finite element software to model the shield tunneling structure, and analyze the settlement characteristics of the pier and abutment caused by the construction. Meng Wei [8] took the actual project as an example, based on the analysis of the influencing factors of the ground settlement, discussed the construction control measures of the shield tunnel under the Longhai Railway, and discussed the effective control of the overall settlement and difference of the railway subgrade and bridge piles. In addition to the shield itself, the settlement factors are also related to the characteristics of the stratum soil, the groundwater, and the superposition of the tunnel interaction. Research by Dr. Tiago Gerheim Souza Dias1 and Adam Bezuijen[9] through tunnel construction shows that most structures are not affected, but under certain conditions active intervention is necessary. C.W.W. Ng, H. Lu [10] analyzed the three-dimensional centrifugal simulation of the double tunnel effect of existing piles and analyzed that excavation activities inevitably cause soil stress changes and ground surface deformation, thereby affecting existing pile foundations nearby.

The above documents have studied the related factors and laws of the displacement and deformation of the existing bridge caused by the shield construction, but they did not consider the influence of the shield construction and the train load on the deformation of the existing bridge. This paper intends to study the deformation law of the existing high-speed rail bridge by numerical simulation under the train load, and the subway shield is successively underpassed.

2. Project Overview

This project is the southern section of the between Dongxin Station and Hongcheng Market Station. The ground elevation along this section has small fluctuations, and the section passes under the bridge piles of the Changfu and Shanghai-Kunming railway bridges. The underpass sections of the railway bridge are all simply supported beam bridges with a span of 32m. The pile foundation of Ganjiang Bridge on Changfu Railway is bored piles with a diameter of 1.25m, and the pile length is about 23m; the piles of Ganjiang Bridge on Shanghai-Kunming High-speed Railway are bored piles with a diameter of 1.0m, and the pile length is about 30m.

The section is excavated successively in the left and right double lines. The hybrid earth pressure balance shield method is adopted for construction. The inner diameter of the segment is 5.4m, the outer diameter is 6.0m, the thickness is 300mm, and the ring width is 1200mm. The underpass section of the interval mainly crosses the gravel sand layer, and the angle between the subway line and the railway is 88 degrees. The elevation and plane positions of shield tunnels and existing bridges are shown in Figures 1 and 2 below.

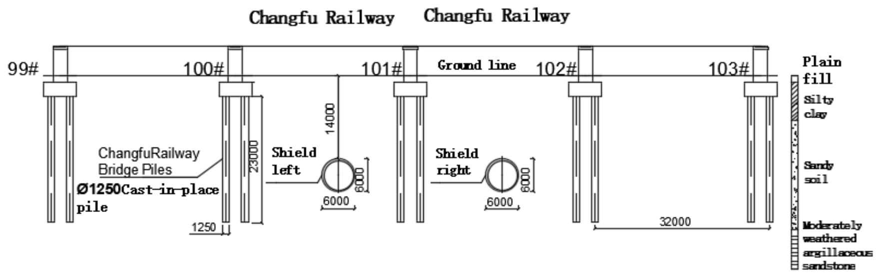


Figure 1. Elevation of shield tunnel and existing bridge

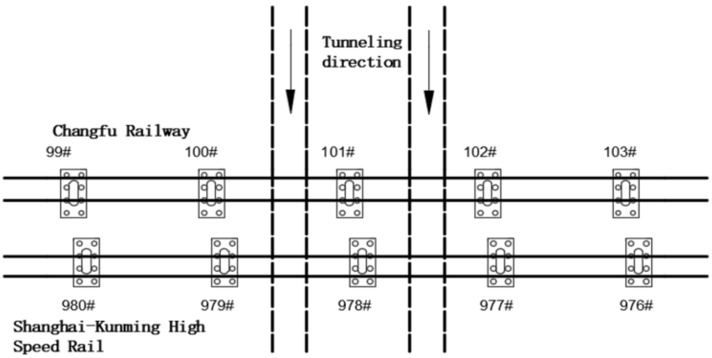


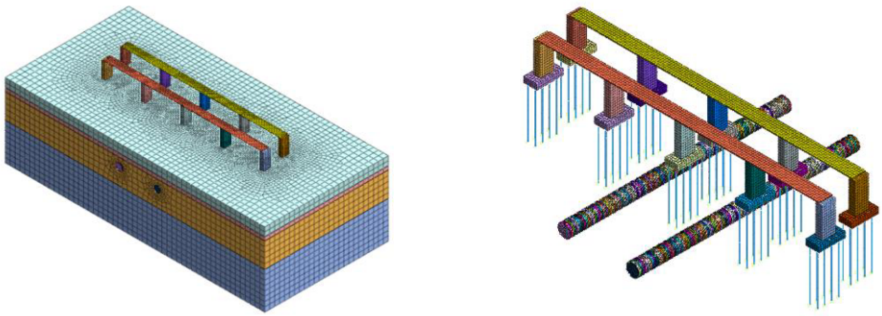
Figure 2. Plane position of shield tunnel and existing bridge

3. Establishment of Three-dimensional Analysis Model

The length from the left line to the right line is 200m. According to the construction plan, the tunneling process is divided into 64 construction stages. Shield tunneling is excavated every 4m, and the two lines are constructed successively. According to the impact of shield tunneling on the ground and combined with the geological conditions of the construction site, the size of the model is 200m in length, 100m in width and 60m in height.

The model uses the shield tunneling direction as the Y axis and the vertical direction of the strata as the Z axis. Except for the ground, the model is subjected to X-direction displacement constraints on the left and right, and Y-direction displacement constraints are imposed on the front and rear directions of the shield tunneling. The lower part of the model is restricted by X Displacement in the, Y, and Z directions, the pile beam element is set as rotation constraint.

The model type of the soil material is the Mohr-Coulomb constitutive model. According to the site survey, the layer distribution is shown in Figure 2 above. For structural materials such as segments, shield shells, grouting, etc., select an elastic model that does not consider material nonlinearity, use plate elements to simulate shield shells and grouting, and use solid elements for modeling of segments and rock soil. The meshing is shown in Figure 3 below. During shield tunneling and excavation, it is assumed that HP (heading pressure) and J (jack thrust) will have an effect on the tunneling surface of the shield. The selection of various material parameters in the model is shown in Table 1 below.



(a) Overall meshing (b) Shield tunnel grid division

Figure 3. 3D model meshing diagram

Table 1. Material parameters

Number	Soil layer	Elastic Modulus MPa	Poisson's ratio（v）	Bulk density（r）	K cm/s	Cohesion kPa	Friction angle（φ）°	thickness m
1	Plain fill	3.00E+03	0.20	18	-0.5	0	19	7.0
2	Silty clay	5.00E+04	0.30	18	-0.5	18.4	20	3.0
3	sand	2.50E+04	0.20	17	-0.5	0	30	20.0
4	Moderately weathered argillaceoussiltstone	1.20E+06	0.24	26	-0.5	15	25	30.0
5	Abutment	2.10E+07	0.18	25	-	-	-	-
6	pile	2.10E+08	0.30	74	-	-	-	-
7	Tube piece	2.10E+07	0.30	24	-	-	-	-
8	Shield shell	2.50E+08	0.20	78	-	-	-	-
9	Grouting	1.00E+07	0.30	22.5	-	-	-	-

4. Shield Tunneling Process Simulation

4.1 Numerical Simulation

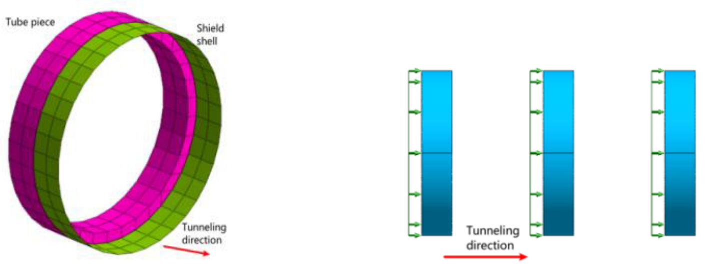
There are many influencing factors in the process of shield tunneling, and it is difficult to perform detailed simulation in simulation analysis. The construction process is simplified, mainly as follows:

(1)Excavation of soil in front of shield tunneling

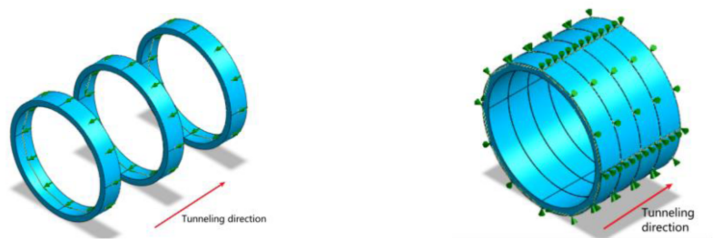
During the shield construction process, tunneling pressure will be generated on the excavation surface. Excavation is carried out every 4 meters, and the tunneling pressure acts on the excavation face. According to the related literature of shield tunneling [11], the tunneling pressure is 200. (The tunneling pressure is shown in Figure 4(b)), and the thrust of the jack during excavation is selected to be 4500 (as shown in Figure 4(c)).

(2) The external pressure of the shield shell and the external pressure of the segments during the tunneling process

During shield tunneling, the excavation back shield shell bears the pressure on the periphery of the excavation surface, according to relevant literature and construction data, the external pressure of the shield shell is 50 (as shown in Figure 4(d)). After excavation, the segment is applied, and the pressure on the outer surface of the segment is simulated by uniformly distributed load as shown in Figure 4(d) , The segment is simulated by the plate unit.



(a) Tube and shield shell (b) Shield tunneling pressure



(c) Jack thrust (d) External pressure of shield shell

Figure 4. Model components and Model force

4.2 Shield Tunneling Construction Simulation

4.2.1 Initial Stress Field Simulation

According to the actual construction process of the shield tunnel, the calculation simulation process is as follows:

Boundary conditions and initial conditions: the surrounding and bottom of the model are normal constraints, and the surrounding rock strata firstly reach the initial stress balance state.

The pile foundations, caps and piers of existing railway bridges are calculated to a balanced state. The model displacement is cleared.

The left-line shield tunnel is excavated and pushed closer along its axis. After each section is excavated, shield segments are then applied in sections.

Consistent with the left line excavation, the right line tunnel was excavated and shield segments were applied.

4.2.2 Simulation of the Tunneling Process

Shield tunneling construction is divided into 64 construction stages. The excavation is divided into sections, each section is 4m. When the i section is excavated, the soil in the excavation area is first passivated, and the shield shell in the excavation area is activated. The excavation face exerts a driving thrust and the shield shell exerts external pressure. The next step is to passivate the i+1, i+2, and i+3 sections of the soil in turn while applying the excavation force and the external pressure of the shield shell. At the i+3 section, the i segment is activated and the surrounding segments Apply external pressure on the segment and jack thrust.

Follow this step to cycle from section 1-n

5. Analysis of Numerical Results

5.1 Analysis of Working Conditions and Measurement Point Layout

The simulation calculation of this frequency value is mainly to analyze the effect of the successive construction of the double-track shield tunnel and the train load on the existing bridge piles. Five pier center points are selected from the two existing high-speed rail bridges under the line. And the pile foundation to measure its settlement changes.

(1)This three-dimensional numerical calculation is divided into two kinds of working condition simulations:

Working condition 1 (no train load added): the shield tunnel directly crosses the bridge.

Working condition 2 (additional train load) shield tunnel directly crosses the bridge

Description of typical construction steps

(2)In the calculation, to analyze the impact of shield tunnel excavation on the pile foundation structure of the upper crossing railway bridge, it is divided into two working conditions of adding train load and no load for analysis and research. In the process of tunnel excavation, type 8 construction is selected The steps are shown in Table 2 and Figure 5.

Table 2. Typical construction step

	Typical construction steps
1	the left to the near edge of the cap under the bridge
2	the left line to 1/2 of the cap under the bridge
3	left line to 1/2 of the cap above the 2 beams of the bridge
4	Construction of the left line is completed
5	the right line to the near edge of the cap under the bridge
6	the right line to 1/2 of the cap under the bridge
7	the right line to 1/2 of the cap above the bridge
8	Right line construction completed

(a) Construction steps 1-4

(b) Construction steps 5-8

Figure 5. Typical construction steps

(3) Layout of Measuring Points

Generally, the deformation of the bridge pier can be mainly considered as the rigid body displacement under the influence of the settlement of the cap top. The above simulation method is used to analyze the joint influence of the shield tunnel penetration and the train load. This time it is important to analyze the center point displacement of the pier top during construction.The additional deformation calculation of the pier top is shown in Figure 6.

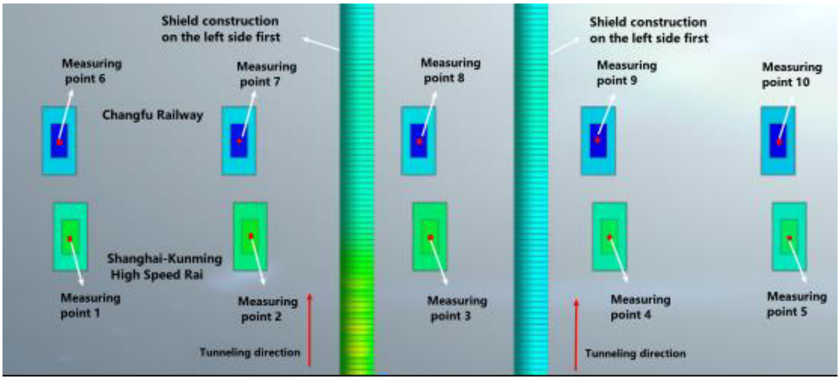


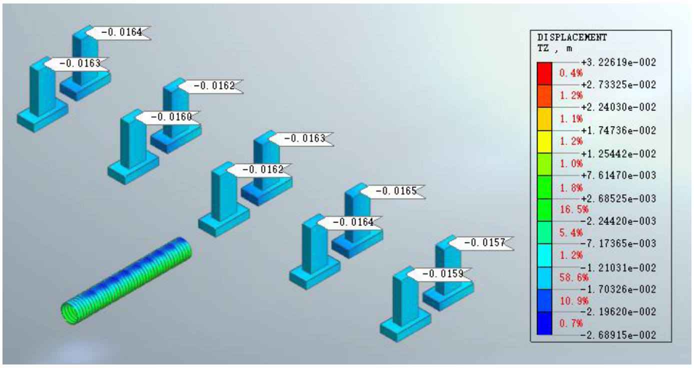
Figure 6. Layout of measuring points

Measurement points 1, 2, 6, and 7 are located on the left side of the shield tunnel, measurement points 3 and 8 are located between the two shield tunnels, and measurement points 4, 5, 9, and 10 are located on the right side of the shield tunnel.

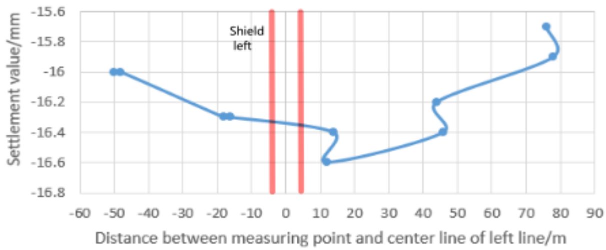
5.2 Displacement Cloud Diagram and Deformation of the Center Point of the Pier Top

During the shield tunnel excavation process, the settlement displacement cloud diagram of the center point of the railway bridge pier and abutment at 2, 3, 4, 8, and 4 typical construction steps and the vertical settlement along the x-direction distribution curve are shown in Figure 7-10.

As shown in Figure 7(a) below, when the shield tunnels to the left half of the width of the platform under the bridge, due to the combined influence of tunnel excavation and train load, the piers and abutments of the existing bridge will cause settlement. The whole settlement occurred. From the Figure 7(b), the maximum value is 16.5mm on the side of the shield excavation, which is within the allowable range of the settlement value of the high-speed train bridge.



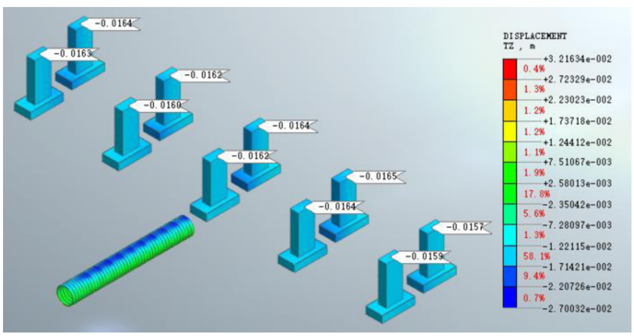
(a) Vertical displacement cloud diagram of pier center point



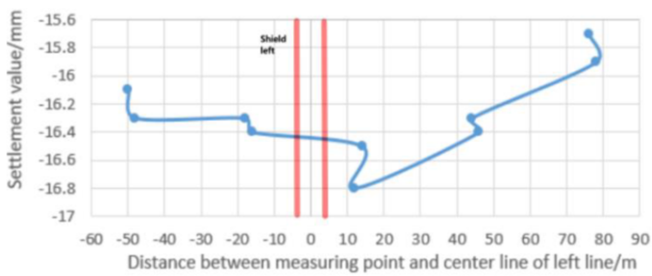
(b) Vertical displacement deformation curve of measuring point

Figure 7. Working condition 2’s Vertical displacement

When the left shield tunnel was driven to 1/2 of the width of the platform above the bridge, most of the settlement has been caused due to the previous excavation and the train load, as shown in Figure 8 (a) and (b) below. The settlement state of the center point of the pier is similar to the condition 2, the maximum settlement value increases slightly and appears on the side of the upper cap excavation, and the settlement value is within the allowable range.



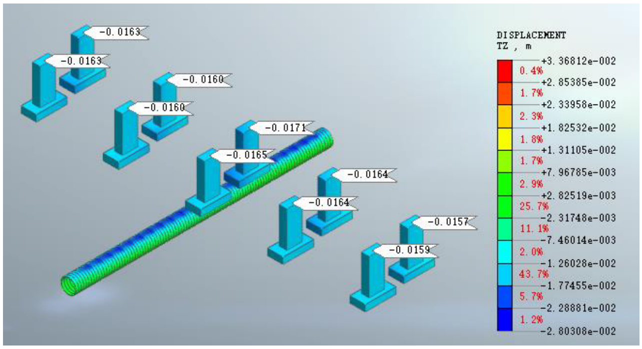
(a) Vertical displacement cloud diagram of pier center point



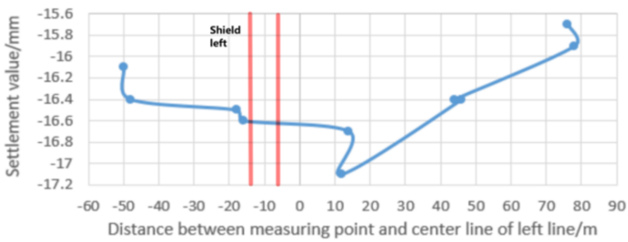
(b) Vertical displacement deformation curve of measuring point

Figure 8. Working condition 3’s Vertical displacement

When the left line of the shield is fully penetrated, the piers on both sides of the shield tunnel are basically in a stable settlement state, as shown in Figure 9 (a) (b) below. At this time, the deformation state of the pier and abutment is similar to that of working condition 4. There is not much change, the maximum settlement value is 17.2mm, and the settlement value is within the allowable range.



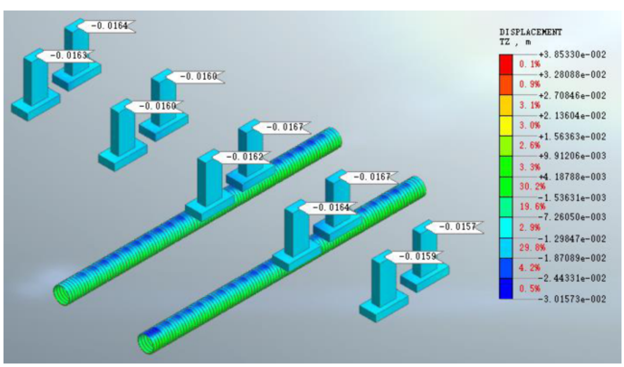
(a) Vertical displacement cloud diagram of pier center point



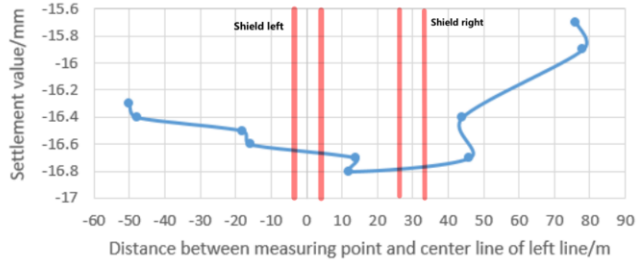
(b) Vertical displacement deformation curve of measuring point

Figure 9. Working condition 4's Vertical displacement

When the construction of the right line of the shield is completed, that is, when the two-line shield tunnels pass through the high-speed rail pile foundation, when the train load is added, as shown in Figure 10(a) below, the settlement of the center point of the pier is basically in a stable state, causing the top of the pier The maximum settlement value of 16.7mm is shown in the following Figure 10(b). Compared with the maximum value when the left line penetrates, the maximum settlement value is reduced, and the overall settlement value of the measuring point increases.



(a) Vertical displacement cloud diagram of pier center point

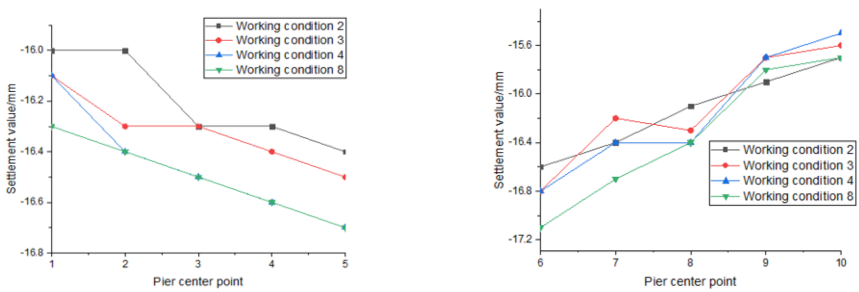


(b) Vertical displacement cloud diagram of pier center point

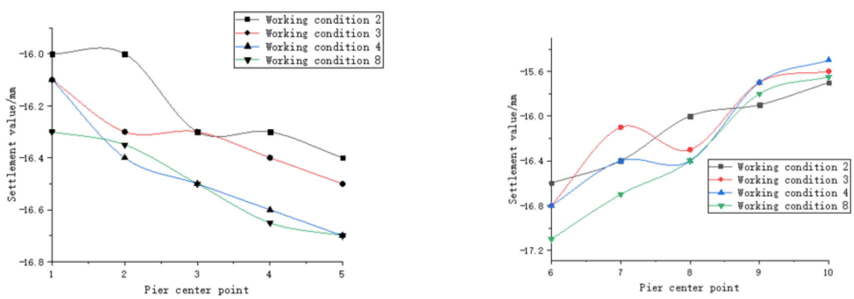
Figure 10. Working condition 8's Vertical displacement

5.3 Analysis of the Displacement of the Center Point of the Pier Top

During the construction of the shield tunnel, the simulation and measured data of the vertical displacement distribution of the center point of the pier above the shield tunnel are shown in Figures 11(a) and 11(b).



(a) Vertical displacement change (simulation)



(b) Vertical displacement change (measured data)

Figure 11. Vertical displacement change of the center point of pier and abutment

According to working conditions 2, 3, 4, and 8, it can be seen that under the combined action of shield excavation and train load, a certain amount of settlement will occur to the surrounding bridge piers. The settlement value, with the existence of excavation stability and grouting pressure, the settlement value gradually tends to be stable, but its maximum settlement is still about 16mm.

5.4. Pile Deformation Analysis

During shield construction, due to various forces such as the excavation force during tunneling, the jack reaction force and the train load, the soil around the high-speed rail bridge will be disturbed to a certain extent, and the soil stress will be released, so the bridge pile foundation will sink slightly Therefore, ten pile foundations at different positions are selected in the construction shield simulation process to carry out corresponding settlement monitoring. The monitoring pile is shown in Figure 12 .

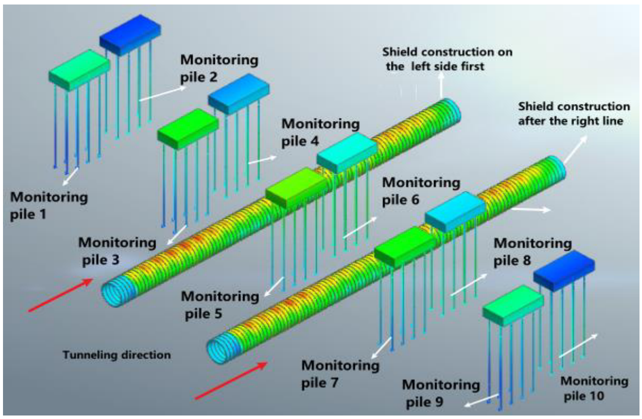
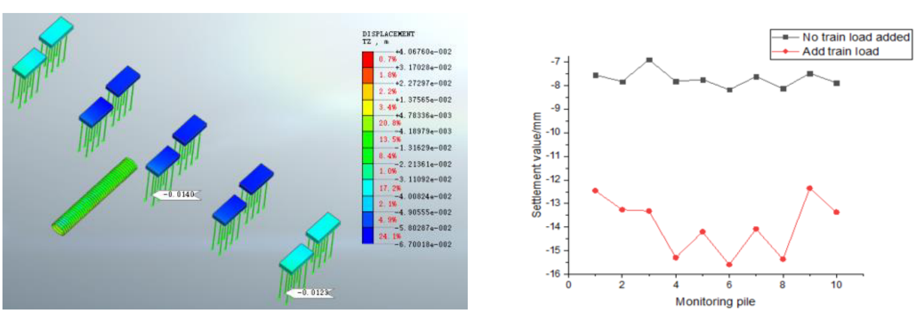


Figure 12. Layout of monitoring piles

Here, the vertical displacement cloud diagram of the pile foundation in working conditions 2, 3, 4, and 8 is selected, which is divided into two parts: the shield adds the train load and the shield does not add the train load. The vertical displacement curve of each monitored pile is shown in the Figure13-16.

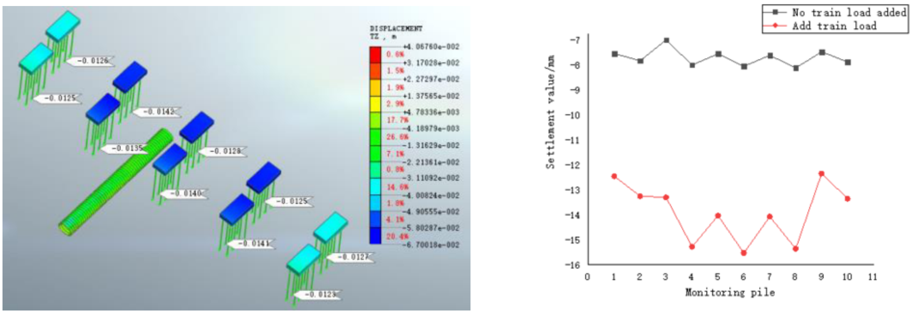
It can be seen from the figure 13 below that when the shield tunnels to the left side of the beam to 1/2 of the width of the cap below the beam, the excavation of the shield causes the surrounding soil stress to be released, which leads to a certain range of settlement of the surrounding pile foundation. From the figure13 (a) The maximum settlement of the pile foundation caused by shield excavation around the excavation surface is about 7mm. From the figure13 (b) below, it can be seen that after the train load is added, the maximum settlement value of the surrounding No. 5 pile foundation reaches about 15mm.



(a)Cloud diagram of pile foundation settlement (b)Pile foundation settlement change chart

Figure 13. Working condition 2's Pile tip settlement

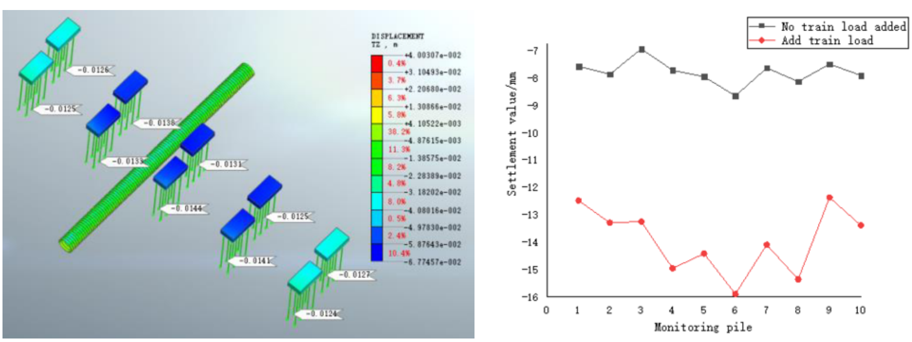
When the shield on the left line reaches 1/2 of the upper cap, it can be seen from Figure 14(b) that the maximum settlement of the pile foundation reaches about 8mm without train load, which is located at No. 6 on the right side of the excavation face of the shield. Monitoring pile, after adding train load, the maximum settlement is located at No. 4 detection pile on the left side of the excavation face of the shield tunnel, reaching 14.2mm



(a)Cloud diagram of pile foundation settlement (b) Pile foundation settlement change chart

Figure 14. Working condition 3's Pile tip settlement

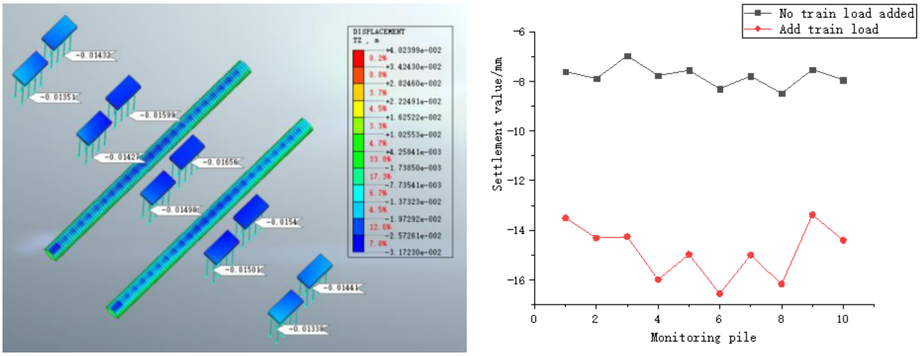
When the left line is fully penetrated, the settlement of the pile foundation is basically in a stable state. As shown in Figure 15 below, the settlement value of the pile foundation is basically similar to the case 3, and the maximum settlement value is about 8mm without the train load. When the load is added, the maximum settlement value increases slightly, and the settlement value is about 16mm within the allowable range.



(a)Cloud diagram of pile foundation settlement (b) Pile foundation settlement change chart

Figure 15. Working condition 4's Pile tip settlement

When the right line of the shield is fully penetrated, as shown in Figure 16 below, when the left line of the case 4 is through, the settlement value of the pile foundation without adding the train load is considered because of the completion of the segment grouting and other factors, its overall settlement value Slightly reduced, the maximum value is about less than 8mm, and the maximum settlement is still about 16mm when the train load is added, which is very small compared to the case 4 when the left line is through.

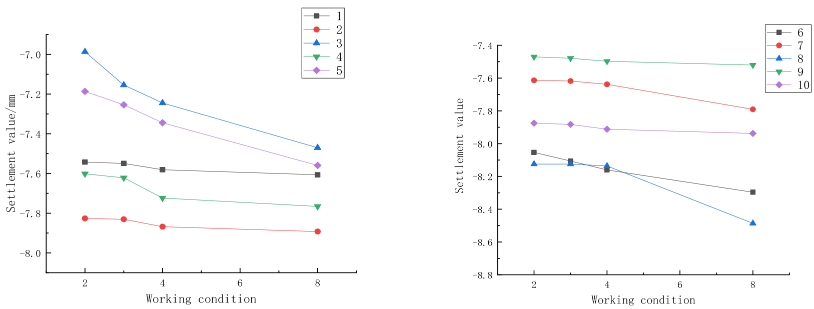


(a)Cloud diagram of pile foundation settlement (b) Pile foundation settlement change chart

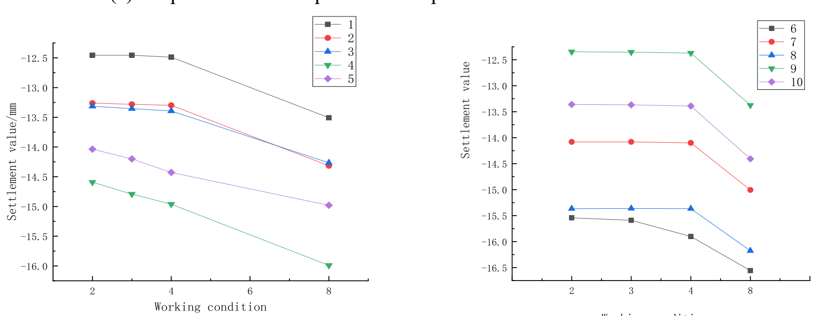
Figure 16. Working condition 8's Pile tip settlement

5.5. Analysis of Vertical Displacement of Pile Foundation

Analyze the calculated value of the vertical displacement of each pile foundation with and without train load under each working condition. The development of the vertical displacement of the pile foundation is shown in Figure 17.



(a) Graph of vertical displacement of pile foundation without train load



(b) Graph of vertical displacement of pile foundation with train load

Figure 17. Vertical displacement change of pile foundation

It can be seen from the above Figure 17 that when the left line of the shield is excavated to 1/2 of the width of the cap under the bridge (condition 2), the soil is disturbed by the excavation force of the shield, which causes the pile foundation A certain settlement, the closer to the excavation surface, the greater the settlement of the pile foundation.

According to working conditions 2, 3, 4, and 8, it can be seen that during shield excavation, shield excavation will have a certain impact on the settlement of the pile foundation. The maximum value is about 8mm. Under the common influence, the maximum settlement of the pile foundation is about 16mm. At the same time, during the shield tunneling process, the initial stage of shield excavation has a greater impact on the settlement of the pile foundation, and the settlement of the pile foundation is basically stable in the later stage.

5.6 The Design and Protection Scheme of the Section Tunnel Crossing the Railway Bridge

According to the relationship between the interval tunnel and the railway bridge, the engineering geology and hydrogeolgy of the side crossing, the protection plan of the isolation pile is proposed, that is, the isolation pile is set within a distance of not less than 9m along the tunnel through the pier, and the isolation pile is Φ800 @1000 layout, establish a shield tunnel model with isolation piles as shown in Figure 18.

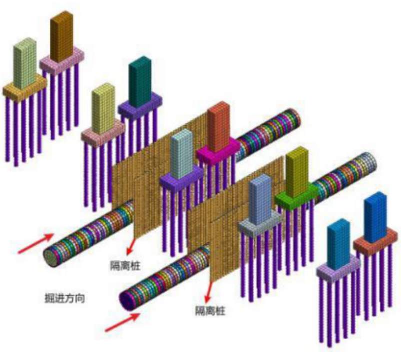


Figure 18. Shield tunnel grid division (+isolated pile**)**

In order to explore the feasibility of the isolation pile protection scheme, the settlement of the center point of the pier and abutment at working condition 4 and working condition 8 when the isolation pile scheme is added is analyzed. As shown in Figure 19.

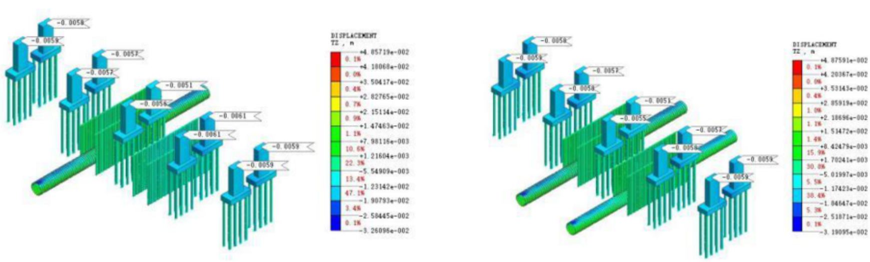
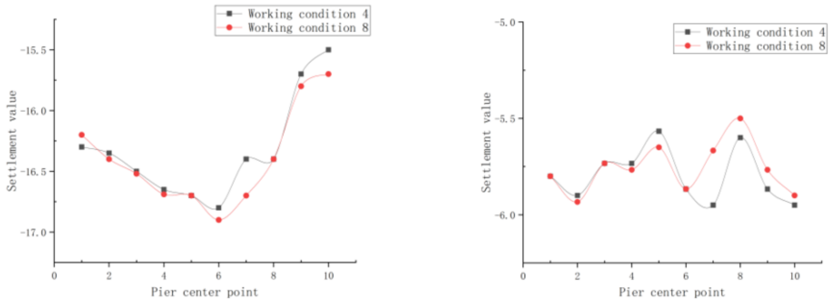


Figure 19 . Vertical displacement cloud diagram of pier center point (+isolated pile)



(a)No isolation pile added (b) Added isolation pile

Figure 20. Vertical displacement change diagram of the center point of the pier

It can be seen from Figure 20 Working Condition 4 and Working Condition 8 that the isolation protection pile is added in the numerical simulation. After the double-track shield tunnel completely passes through the railway pile foundation, the maximum settlement of the pier center point is about 5.8mm. The isolation protection pile is added Afterwards, the settlement deformation at the center point of the pier and abutment is significantly reduced. The isolation pile reinforcement measures can improve the ground deformation caused by the shield and train load. Therefore, the corresponding isolation protection pile can be set before the shield construction

6. Conclusions and Recommendations

This paper is based on actual engineering as well as uses numerical analysis to evaluate the safety of existing bridges under the combined influence of double-track shield construction and train load. After analyzing the vertical displacement laws and changes of piers and pile foundations , The deformation of the bridge meets the requirements of relevant regulations. From the perspective of the safety of the existing bridge structure, the plan of shield crossing the high-speed rail bridge is feasible.

In order to reduce the structural safety risks of existing high-speed rail bridges during shield construction, conclusions and recommendations are drawn as follows:

(1)The joint action of shield and train load will cause certain settlement to the pile foundation of the existing bridge. Among them, the joint action of the initial stage of shield excavation and the train load will have the greatest impact on the settlement of the pile foundation, and the maximum settlement The settlement value of the pile foundation of the shield excavation side is close to about 16mm. With further excavation and excavation, the settlement value gradually stabilizes. When the double-line shield construction is completed, the settlement value of the pile foundation decreases slightly.

(2)When the shield tunnel is constructed in sequence, the subsequent construction of the shield tunnel has a certain compensation effect on the settlement caused by the first construction of the tunnel. The settlement of part of the pile foundation will be reduced, but the overall settlement range of the bridge will be slightly increased, and eventually tend to stable state. This situation may be related to the cut pressure of the right-line shield. Generally, the greater the shield cut pressure, the lower the settlement of the superstructure. However, if the cut pressure is greater, the uplift of the surrounding soil will also cause a certain compensation effect. During construction, the shield tunneling pressure is adjusted in real time according to the actual situation on site.

(3) In order to avoid the impact on the deform action of the top of the high-speed rail pier, the corresponding protective pile design should be adopted during the shield tunneling.

(4) During the construction and operation of the ground, it is recommended to carry out corresponding deformation monitoring of the existing high-speed rail bridge during the shield crossing period, and designate the corresponding treatment plan.

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