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Risk Control Standard and Construction Control Technology of Shield Tunnel Passing through Irregular-Plate Bridge

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Abstract: As a kind of statically-indeterminate point-support structure, the irregular-plate bridge (IPB) is extremely sensitive to the settlement of pier columns, and the stress of the plate is complicated. Because of the limitation of environmental conditions, the newly-built subway circular symmetric shield tunnel needs to pass the pier foundation of the IPB perpendicularly. To control the engineering risks, the pier settlement value must be known, and measures should be taken to reduce the settlement. This paper takes the project of the Beijing subway circular symmetric shield tunnels passing the existing IPB of the Guang'anmen Bridge as an example. First, the stress characteristics and settlement control standards of the IPB are analyzed, and then the technical scheme of synchronous jacking and key points of risk control during the construction of the shield passing the IPB are put forward. The relationship between the excavation face pressure of the shield tunnel and pier foundation settlement, and the ground settlement, are then analyzed. Finally, structural cracking after construction is analyzed, and the analysis shows that synchronous jacking technology can effectively control the settlement value of the subway tunnel passing the IPB. The technology is a feasible method for controlling the safety of a tunnel passing through a sensitive, statically-indeterminate bridge, and this work is a successful experience for similar major risk projects.

Keywords: symmetric shield tunnel; irregular-plate bridge; risk control; synchronous jacking; settlement control

1. Introduction

With a boom in underground transportation in big cities, increasingly more subways must pass the pier foundations of bridges. Different bridge structures have different control requirements for the adjacent construction of subway tunnels. The requirements of a bridge are listed in Table 1 in detail according to the classifications of bridges. Among them, the irregular-plate bridge (IPB) has the most stringent control requirements, and this kind of project has great risks. If risk identification before construction is insufficient, or if risk control measures are not appropriate, cracks will appear in the IPB during subway tunnel passing, and this will affect the normal use and safety of the bridge structure. It is a difficulty for technicians to find suitable control standards and reliable control technologies.

Table 1. Requirements for the construction adjacent to a bridge structure.

Bridge Type	Stress Characteristics of Bridge Structure	Bridge Control Point	Control Standard for Bridge Deformation
Simply supported beam bridge	The superstructure of a bridge is statically-determinate, the force is clear and simple, and settlement of the bearing will not cause additional stress in the superstructure.	Control the damage of bridge deck joints.	The differential settlement of the adjacent pier should not make the beam form an additional longitudinal slope greater than 0.12%, which is generally 20 mm [1,2].
Continuous beam bridge	The superstructure of a bridge is statically-indeterminate, and there is a negative bending moment at the middle support. The differential settlement along the bridge increases the negative bending moment and generates additional stress.	Control the cracking of the main beam and reduce the loss of structural safety and durability.	The differential settlement of adjacent pier foundations shall be calculated according to the stress of the structure, generally within 8 mm [2].
IPB	The superstructure of a bridge is statically-indeterminate, and the distribution of internal forces is complex. The interaction of the bending moment and torsion makes the superstructure have the characteristics of spatial force, and settlement in all directions produces additional stress.	Control the cracking of the bridge plate and reduce the loss of structural safety and durability.	Settlement of each pier foundation should be controlled within 3 mm.

Many scholars have studied the changes of bridge structure force and the control technology of tunnels passing bridges. Poulos studied variations of internal force and settlement of a single pile under horizontal displacement of soil using a laboratory experiment [3]. Makerchian and Poulos introduced a simple algorithm for calculating the settlement of a pile foundation underpinning in the later stage, and compared their data with the field-measured data and with the calculation results of the finite element method [4]. Chen used a two-stage method to analyze the lateral and axial responses of piles caused by tunnels [5]. Mroueh et al. analyzed the influence of tunnel construction on a single pile and a group pile using a two-stage method [6]. Xiaojie et al. analyzed the influence of urban tunnel construction on the bearing capacity of a pile foundation of an adjacent bridge [7]. Their achievements always focus on the behavior of pile foundation in external forces, the strain-stress of a pile due to approaching constructions and the service or remedial measures of the bridge due to the pile disturbance. After studying the behavior of a pile under external forces, some other scholars used a finite element method or test to comprehensively analyze the influence of tunnel excavation on pile foundation and soil. Lognathan, Poulos and Stewart studied the interaction mechanism of pile-soil-tunnel through centrifuge tests [8]. Cheng, Dasari et al. used the finite element method to study the interactions among the tunnel, soil and pile foundation, and used a dynamic method to simulate the response of soil in a tunnel excavation area during excavation [9,10]. Then, some scholars studied the deformation capacity of a bridge superstructure, and proposed control standards. Xiang et al. used structural measurement and analysis to assess the settlement and deformation capacity of an overpass, and they formulated standards for the additional allowable settlement [11]. Helen studied influences of the differential settlement of supports on the performances of low-toughness-reinforced concrete continuous one-way slabs [12]. Gibert and Sakka studied the effects of support settlement and steel toughness on the ultimate strength and ductility of reinforced concrete continuous unidirectional slabs [13]. With the development of subway construction, there are some remedial measures applied to keep the behavior of the bridge structure. Tao et al. used simplified calculations to study the jacking load in the active underpinning of bridge piles [14]. Fang et al. studied the deformation characteristics of surrounding rock during shield tunnel excavation, and proposed zonal reinforcement [15]. Feng studied the optimal technology of active underpinning for a pile foundation in a shield tunneling building [16].

The above research studied the behavior and response during the time a bridge foundation was disturbed, and proposed control standards and corresponding reinforcement measures, such as stratum reinforcement and pile foundation underpinning technology. However, the effect of such measures on controlling the settlement of a bridges is not ideal in the actual project. Also, the control process is complicated, and does not achieve the expected effect. Firstly, this paper is based on the construction of the Beijing Subway Line 7 Tunnel passing through the Guang'anmen IPB, and analyzes the deformability of the IPB. Then, after a scheme comparison between the underpinning pile foundation method and the jacking method, the latter is selected to control the settlement of the irregular-plate. Then, using a finite difference method (FLAC3D: Itasca Consulting Group INC., Minneapolis, MN, USA), the effects of the excavation face pressure that occurs during a shield tunnel excavation on the IPB foundation settlement is studied, and the key points of risk control are emphatically analyzed. Finally, from the construction monitoring data and structural cracking after construction, the control effect of shield tunnel construction is analyzed, and the corresponding improvement measures are presented.

2. Engineering Conditions

The tunnel between Daguanying Station and Guang'anmen Station of the Beijing Subway Line 7 is in the east-west direction and is located in the pebble ⑦ layer in the Beijing area. The elevation of the rail surface is the same as the elevation of the phreatic water. The tunnel was excavated using the shield method and passed through the pile foundation of the Guang'anmen Bridge at close range. The Guang'anmen Bridge is located at the West and 2nd Ring in Beijing, and was built in the early 1990s. The whole bridge is divided into four sections from west to east: West approach bridge, west IPB, main bridge, east IPB, and the east approach bridge. The upper structures of the east and west IPB each have two 70 cm thick pre-stressed plates from north to south. The lower structure adopts independent piers. The arrangement of the piers is scattered, and the bridge foundation consists of friction piles. The subway shield tunnel passes through the east and west IPB perpendicularly, and it successively passes the pile foundations of piers 14-6#, 5-10#, 14-1# and 5-3#. The shortest distance between the top of the tunnel and bottom of the pile is only 4.1 m. During tunnel construction, it is possible to cause the foundation of the pier column to sink or heave, thus generating internal force on the upper irregular-plate structure. Excessive internal forces may cause cracking that affects the performance of the structure. The general layout of the positional relationship between the subway shield tunnel and the IPB is shown in Figure 1, and the sectional positional relationship is shown in Figures 2 and 3.

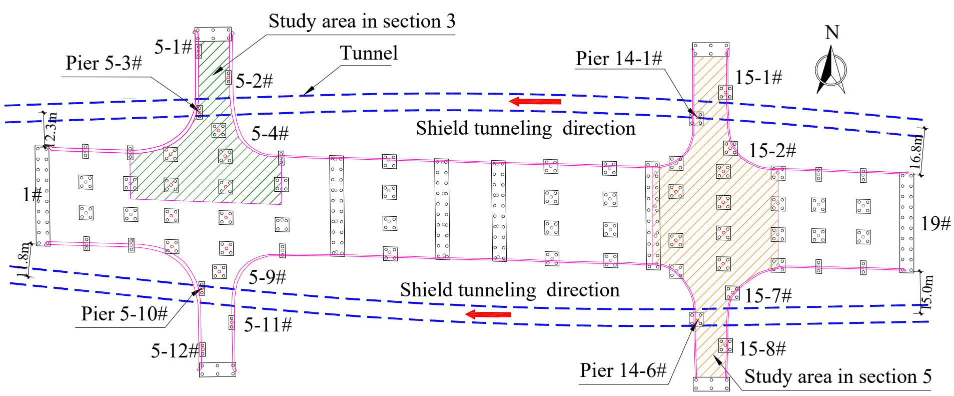


Figure 1. General layout of the shield tunnel and irregular-plate bridge (IPB).

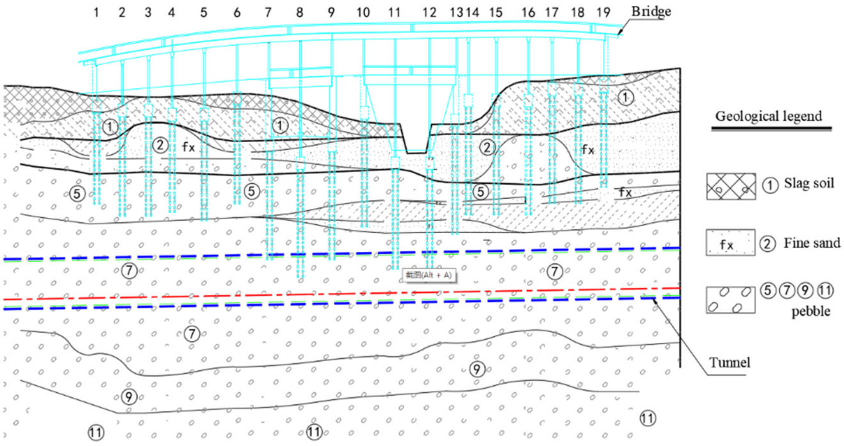


Figure 2. Longitudinal section of shield tunnel and IPB.

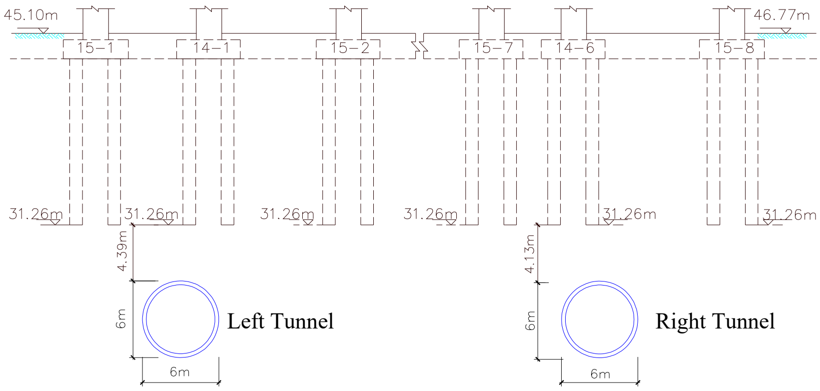


Figure 3. Cross-sectional view of shield tunnel and east IPB.

The structure of the IPB is developed from the "beamless floor" in the construction industry. The upper structure is an irregularly-shaped solid plate, and the lower pier directly supports the upper solid plate. Zhongzhi Shen found that it has the following characteristics [17]:

(1) The irregular-plate is supported by multiple pier points; the bearing capacity of each pier is different, and the middle pier is larger.
(2) The irregular-plate is equipped with shear reinforcement, stirrups and other measures for resisting the counterforce of piers at the fulcrum position, thus dispersing the concentrated force and avoiding the impact on the irregular plate.
(3) Because of the irregular geometric shape, the combined action of self-weight and traffic load causes the irregular-plate to generate larger torque, and this causes stress on the irregular-plate to present a spatial state.

3. Analysis of Deformation Standard of the IPB

Because the internal force distribution of the superstructure of the bridge has spatial characteristics, the northwest part of the Guang'anmen Bridge is selected as the object of finite element analysis. The purpose of the finite element analysis is to get the displacement control standard of the tunnel passing through IPB, so as to take reasonable construction parameters to ensure the safety of the bridge structure. The superstructure of this IPB is a partially pre-stressed concrete structure, and the thickness of the plate is 0.7 m. The superstructure is made of C40 concrete. The bulk density is 25 kN/m^3, the modulus of elasticity is 32.5 GPa, and Poisson's ratio is 0.2. The pre-stressed tendon in the plate is composed of strands, the standard tensile strength of the strands is 1600 MPa, and the plane layout of the strands is shown in Figure 4.

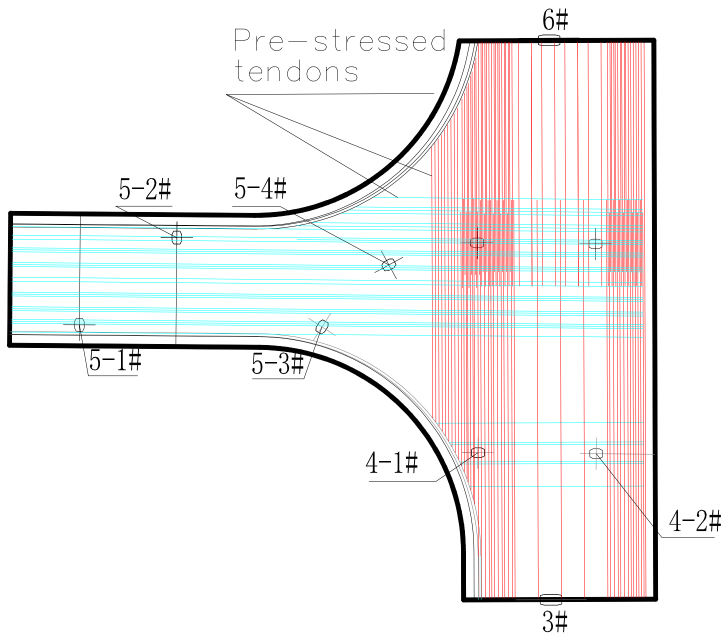


Figure 4. Plane layout of the pre-stressed tendons of a bridge plate.

Finite element analysis uses the Midas civil program to establish the model. The plate element is used to simulate the concrete special-shaped plate, a rectangular plane element is used in the normal straight line area, and a triangular element is used in the special curved-edge area. A truss element is used to simulate pre-stressed tendons in the plate, and the cooling method is used to achieve the pre-stressing of the truss element (i.e., by reducing the temperature of the pre-stressing tendons, thus making it shrink to obtain the pre-stressing force), and taking into account the pre-stressing loss of each stage. The beam element is used to simulate the structure of the pier, pile cap and pile foundation. The constraints of the bridge deck and other structures are vertical displacement. The rubber bearing and spherical bearing between the bridge deck and pier are simulated using a rigid connection. The connection between the pier and the pile foundation is simulated using a rigid connection, the boundary condition of the pile bottom is simulated using a fixed constraint, and the calculation model is shown in Figure 5.

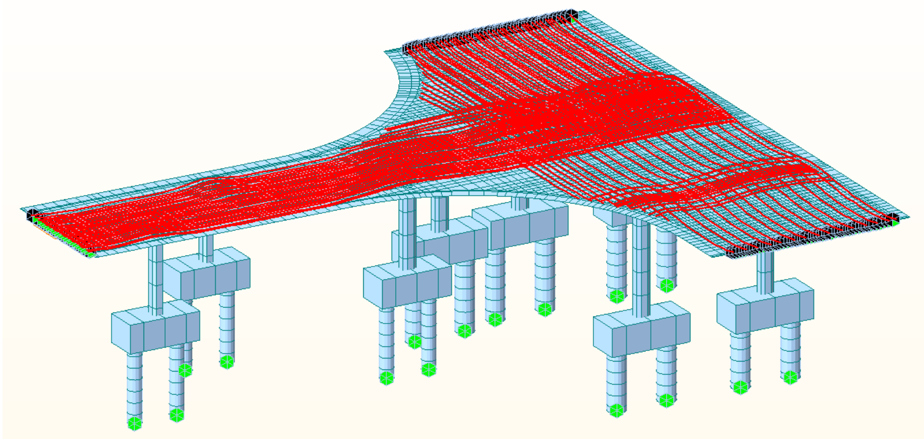


Figure 5. Calculation model diagram of the IPB.

Because the live load is much smaller than the self-weight of the structure, (only considering the influences of the self-weight of the structure), the pre-stress of the plate and the vertical (Z-direction)-forced displacement of the pier, the finite element model is loaded and calculated.

Internal force changes in the irregular-plate under three conditions of settlement (2 mm, 4 mm and 6 mm) of pier 5-3# are analyzed. Because the stress magnitude and change rate of the irregular-plate in the support and midspan are different, and because these locations are easily destroyed, the stress monitoring points are set at the top of the plate corresponding to the piers 5-1# to 5-4#, and at the bottom of the plate of four midspans. The stress monitoring points are shown in Figure 6.

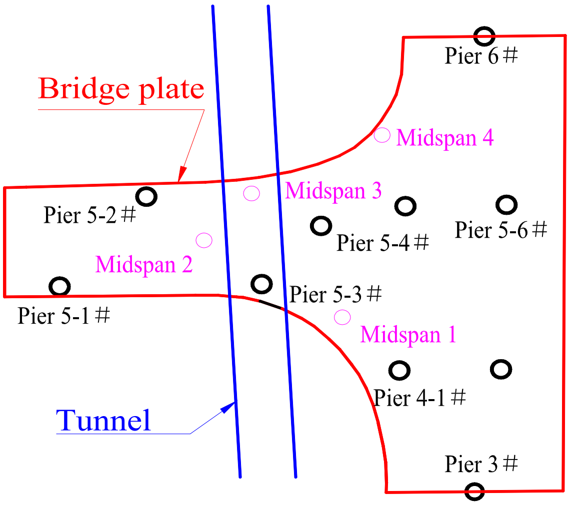
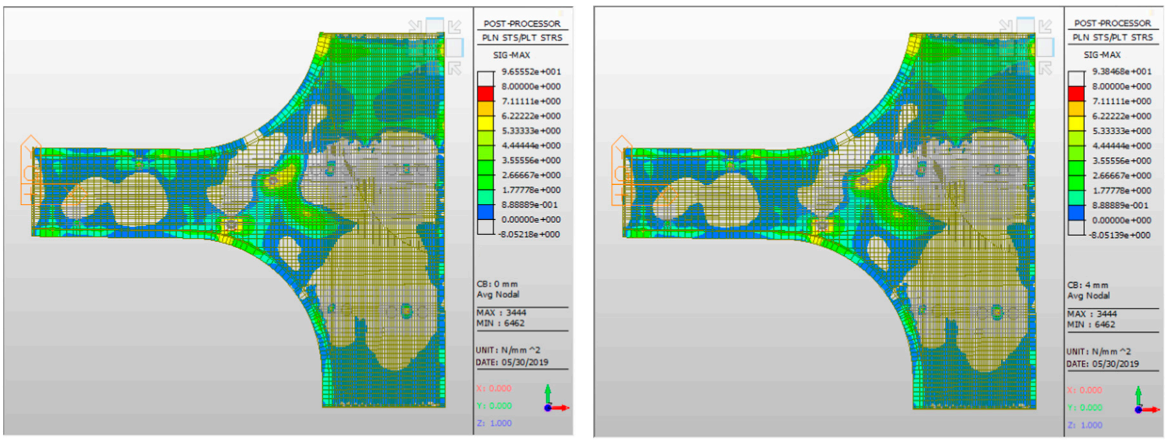


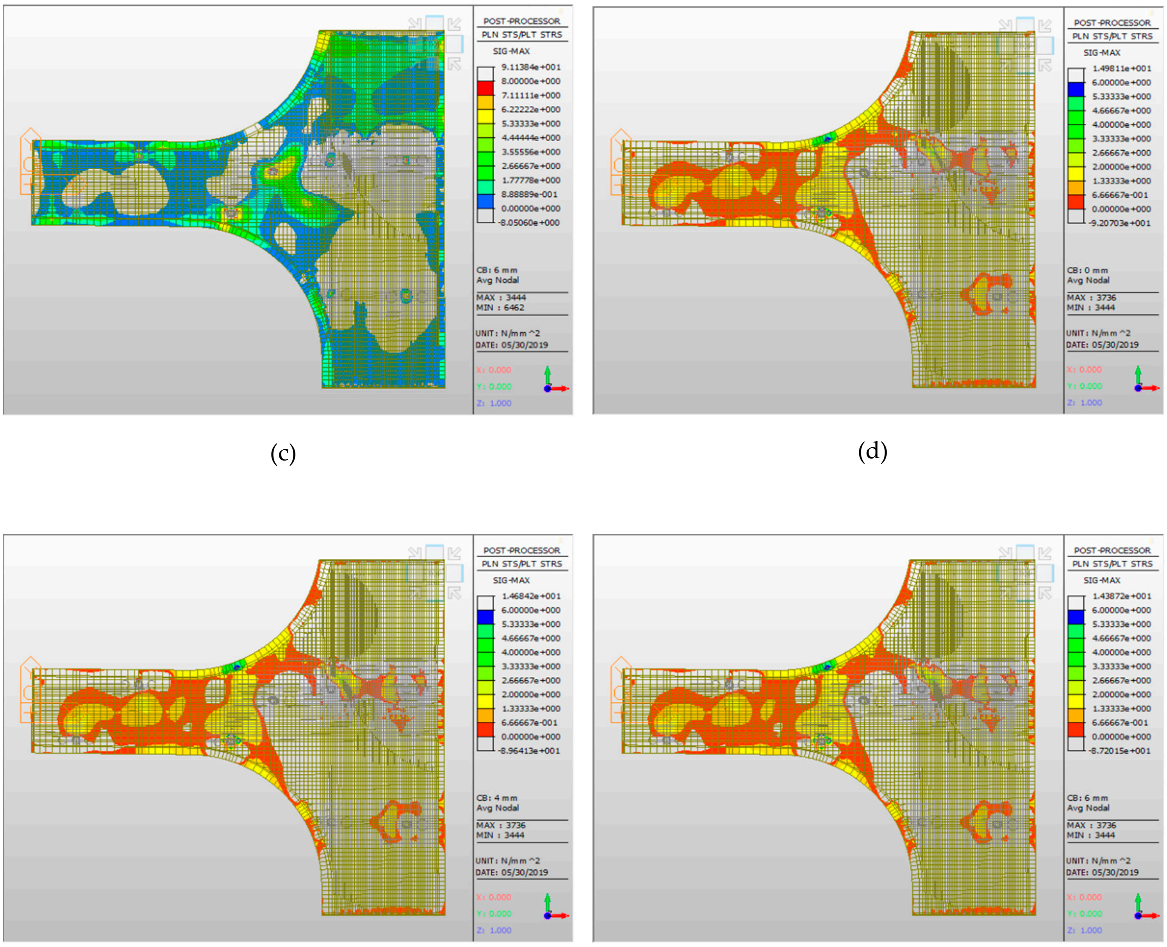
Figure 6. Schematic diagram of the stress measuring points.

For the case of the settlement of pier 5-3# (forced displacement is applied), some stress nephograms of the irregular-plate are shown in Figure 7, and the stress change curve of each monitoring point is shown in Figure 8.



(a) (b)

Figure 7. *Cont.*



(c) (d)

(e) (f)

Figure 7. (**a**) Tensile stress of the top of bridge plate in its original state; (**b**) Tensile stress of the top of bridge plate in the Settlement of the 4 mm state; (**c**) Tensile stress of the top of bridge plate in the Settlement of the 6 mm state; (**d**) Tensile stress of the bottom of bridge plate in its original state; (**e**) Tensile stress of the bottom of bridge plate in the Settlement of the 4 mm state; (**f**) Tensile stress of the bottom of bridge plate in Settlement of the 6 mm state.

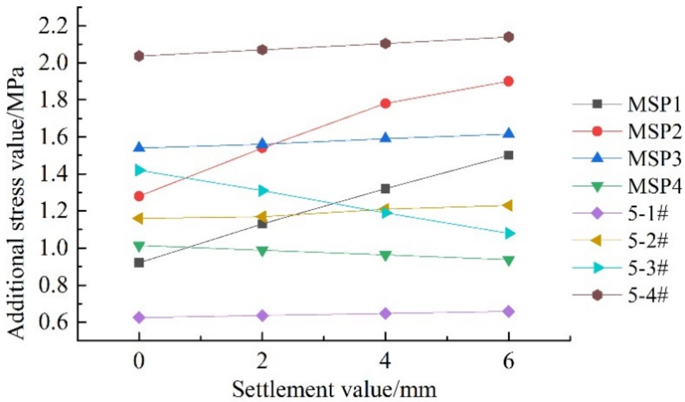


Figure 8. Curves of tensile stress of irregular-plate changes with pier settlement.

From the above analysis of additional stress caused by the settlement of the pier, it can be seen that:

(1) The tensile area (Yellow and Orange areas in Figure 7) at the bottom of the plate is concentrated at the midspan of piers 5-1# to 5-4#. During the settlement process, the tensile stress at the bottom of the plate at the midspan is close to the tensile strength of concrete, and cracks occur easily.

(2) With a gradual increase in the settlement, the tensile stress of at the top of the plate on the pier 5-3# gradually decreases, but the tensile stress at the top of the plate on adjacent piers increases.

(3) The tensile stress of the plate at the midspan positions 1 (MSP1) and 2 (MSP2) of pier 5-3# are sensitive to the settlement of the pier, and the additional stress change rates of the irregular-plate at the midspan position 2 is 0.12 MPa/mm. When the foundation settlement reaches 3 mm, the total stress at the midspan position 2 is 1.66 MPa, and this value exceeds the C40 concrete tensile design value (1.65 MPa) and causes the bottom surface of the plate to crack.

(4) While it can be seen from Figure 8 that the maximum tensile stress in the irregular-plate is located at the top of the plate on the pier 5-4#, because the joint structure of the plate on the pier was reinforced at the beginning of the design, this is not the most unfavorable control point of the irregular-plate.

To observe the internal force changes of the irregular-plate during construction, the strain measurement points were arranged to monitor the stress change. The arrangement of the measuring points is shown in Figure 9, and the monitoring results are shown in Figure 10.

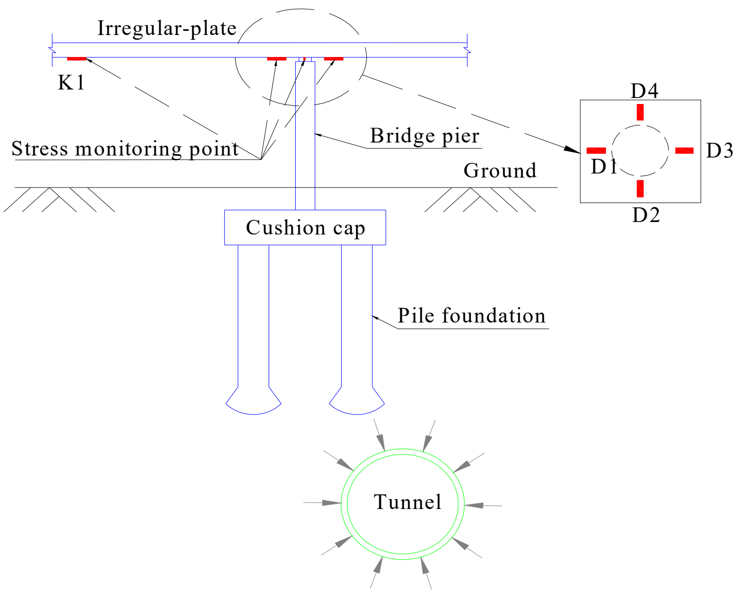
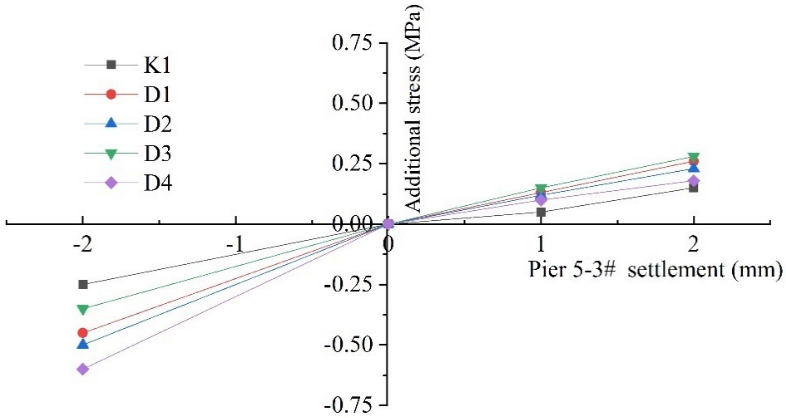


Figure 9. Monitoring point diagram of the additional stress of the irregular-plate at pier 5-3#.

As seen in the curves of Figure 10, because pier 5-3# is raised by the grouting of the pile bottom in the preparation stage of the shield tunnel passing the IPB, the stress at the bottom of the irregular-plate of the support position is reduced, and the stress in the span is also reduced. During the construction of the tunnel passing the IPB, pier 5-3# sinks, the stress of the irregular-plate increases at the support position, the stress at the midspan position increases by 0.25 MPa and the rate of change is 0.125 MPa/mm. These results are basically in agreement with the modeling analysis.



Note: the increase of the stress is positive, and the decrease of this same stress is negative.

Figure 10. Actual change diagrams of the stress at the bottom of the plate around pier 5-3#.

4. Risk Analysis of Shield Tunnel Passing the IPB

4.1. Technology Scheme for Shield Tunnels Passing the IPB

At present, the protection scheme for the tunnel passing through the IPB mainly includes the active underpinning technology of the pile foundation, but the process of active underpinning technology is complicated. At the same time, normal traffic should be ensured under the Guang'anmen Bridge, and there is no room for underpinning operations. On the basis of the above situation, it is necessary to develop a new set of passing technology schemes, which needs to have two advantages. On the one hand, it can strictly control the settlement of tunnel excavation; on the other hand, it can compensate the settlement of the irregular-plate in time. The comprehensive technology for controlling these two aspects at the same time is called synchronous jacking technology. This technology considers the upper and lower structures of the bridge separately, and separates the risk source (construction excavation) and the risk object (existing bridge) in the process of the tunnel passing the bridge. When the deformation of the irregular-plate occurs due to the settlement of the pile foundation, the jacking will lift the irregular-plate to the original position. The technical principles are shown in Figure 11, and the technical process content is shown in Figure 12.

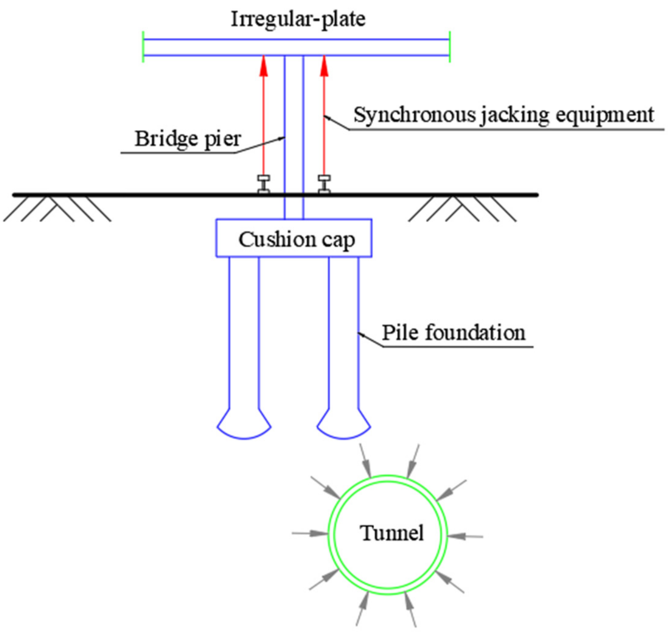


Figure 11. Schematic diagram of stratum subsidence and synchronous jacking.

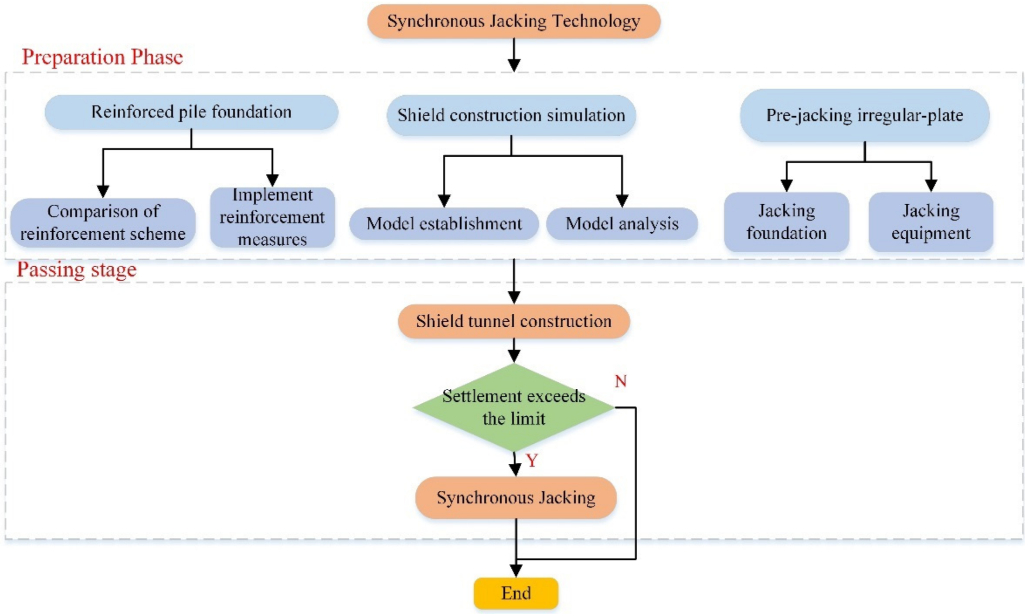


Figure 12. Synchronous jacking technology for the shield tunnel.

The synchronous jacking of the shield tunnel passing the IPB is a dynamic control process, and it needs to be adjusted in time according to the settlement of the upper structure during the construction process; its purpose is to ensure that the bridge can always be kept in a safe stress state. Because the settlement control value of the irregular-plate is very small, so the requirements of synchronous jacking in this project are strict, and are as follows:

(1) Effective measures should be taken in construction of the subway shield tunnel to ensure that the bridge does not suffer sudden changes in settlement, and the settlement rate of the pier should be less than 1 mm/d.

(2) Jacking uses a combination of mechanical jacks and hydraulic jacks. The hydraulic jacks are used to control the jack-up process. After jacking to its place, the mechanical jacks are used for locking. The self-locking performance of the mechanical jacks is stable, and its long-term settlement is not more than 0.5 mm.

4.2. Construction Risk Analysis of Shield Tunnels Passing the IPB

The possibility of settlement of the irregular-plate in the main construction links is analyzed in terms of construction sequence, and the key control procedures are judged, as shown in Table 2:

Table 2. Risk analysis of the main construction steps.

Construction Steps	Main Construction Contents	Preliminary Risk Analysis	Importance
Working procedure I	Conduct a shield construction test to find out effective excavation parameters that meet the settlement control value of the IPB.	Synchronous jacking is difficult to achieve without effective stratum settlement control technology.	Critical working procedure
Working procedure II	Punch from the ground to the bottom of the pile, and then use grouting to strengthen the pile foundation.	An auxiliary measure is used to improve the bearing capacity of the stratum around the pile foundation before excavation of the shield tunnel.	Noncritical working procedure

Table 2. *Cont.*

Construction Steps	Main Construction Contents	Preliminary Risk Analysis	Importance
Working procedure III	Install jacking equipment such as jacking supports and jacks; debug synchronous jacking equipment with an accuracy of 0.5 mm.	The active compensation of irregular-plate settlement and accuracy control is very important.	Noncritical working procedure
Working procedure IV	Shield tunneling is linked with synchronous jacking information to restore the spatial location of the irregular-plate in time. When the maximum settlement of piers exceeds 80% of the control value, the jacking is started.	Timeliness is crucial.	Slightly critical working procedure
Working procedure V	Real-time monitoring of the elevation of the plate bottom during jacking; measuring accuracy is 0.1mm.	Timeliness is crucial.	Slightly critical working procedure

5. Analysis of Influences of Shield Tunnel Construction on Pile Foundation

From the results of the above preliminary risk analysis, it is necessary to conduct an in-depth analysis of the influences of different tunneling construction parameters on the adjacent bridge pile foundation. A finite element model is established to analyze the degree of influence of shield tunnel construction on the adjacent bridge pile in combination with environmental conditions and engineering conditions. In this analysis, key construction control parameters are analyzed.

5.1. Calculation Model and Parameters

The FLAC3D program uses the towed coordinate system to analyze the large deformation problem, and it has obvious advantages for analyzing the large deformation of the stratum caused by tunnel excavation. This paper uses the FLAC3D program to analyze the influence of shield tunnel excavation on the IPB. The bridge structure at the east end of the Guang'anmen Bridge is chosen as the calculation model, the size of the model is 80 m × 180 m × 50 m and the model is shown in Figure 13.

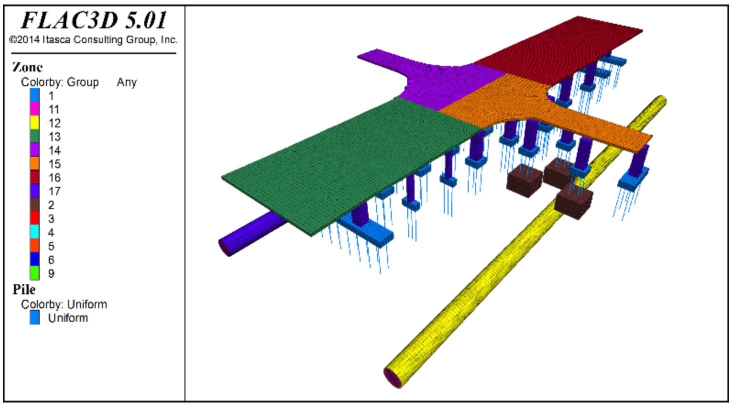


Figure 13. Shield construction calculation model.

The main calculation parameters of the contact surface in FALC3D are tangential stiffness and normal stiffness, and the relationship between these parameters is as follows [18]:

$$K_n = K_s = 10\max\left[\frac{(K + 4/3G)}{\Delta z_{\min}}\right] \tag{1}$$

where K_n is the normal stiffness (N/m^3), K_s is the tangential stiffness (N/m^3), and $\Delta z_{\min}$ is the minimum size of the connection area in the normal direction of the body contact surface. The relationship between bulk modulus and elastic modulus and that between shear modulus and elastic modulus are as follows:

$$K = \frac{E}{3(1 - 2\mu)} \tag{2}$$

$$G = \frac{E}{2(1 + \mu)} \tag{3}$$

where K is the bulk modulus (N/m^2), E is the elastic modulus (N/m^2), G is the shear modulus (N/m^2), and μ is Poisson's ratio.

The shield shell is defined as an elastic material that has an elastic modulus (E) of 210 GPa. The supporting force at the top of the tunnel is 0.06 MPa, and the supporting force at the bottom is 0.17 MPa. The total thrust of this jacking is 1.7×10^4 KN, and the friction stress of the shield shell is 0.065 MPa (The total thrust of jacking is equal to the sum of the total support force at the excavation face and the total friction resistance around the shield shell.). The grouting pressure is 0.2 MPa. The backfill grouting layer after tunnel excavation is simulated using equivalent layers with a thickness of 15 cm, and takes different parameters before and after the grouting material hardens. Calculation parameters are shown in Tables 3 and 4.

Table 3. Stratum calculation parameters.

Name of Soil Layer	Density (g/cm^3)	Compressive Modulus (MPa)	Poisson's Ratio	Cohesion (kPa)	Internal Friction Angle (°)	Thickness (m)
Artificial filling	1.65	6	0.4	5	10	2
Silt, clay	2.0	7.5	0.31	30	10	8
Fine sand	2.0	30	0.26	0	35	6
Roundstone, pebble	2.05	65	0.2	0	40	10
Pebble	2.10	75	0.2	0	45	24

Table 4. Structure calculation parameters.

Material Name	Density (g/cm^3)	Elastic Modulus (MPa)	Poisson's Ratio	Dimension (m)
Pier	2.5	30,000	0.2	1.2 × 0.9
Cushion cap	2.5	30,000	0.2	5 × 5 and 5 × 2
Pile	2.5	30,000	0.2	D = 1
Segment	2.5	24,150	0.2	0.3 m Thickness
Grouting layer material (soft)	2.1	180	0.25	0.15 m Thickness
Grouting layer material (hard)	2.1	1,800	0.2	0.1 5m Thickness
Pile bottom underpinning layer	2.1	2,000	0.2	10 × 10 × 9

Note: Because the segment joint screws have a certain weakening effect upon the segment, the elastic modulus of the segment is calculated with a reduction of 0.7.

The simulation process for the shield tunnel construction is as follows:

(1) Setting soil parameters and boundary conditions: Only the self-weight effect is considered, the initial stress field is calculated and the displacement field and velocity field are cleared.
(2) Setting the material parameters of the bridge structure: The structural weight is taken into account. The equivalent load of the upper structure on the cap is applied. The stress field before the construction of a new tunnel is obtained, and the displacement field and velocity field are cleared.
(3) Shield excavation: First, the first ring soil and shield segment are passivated, and a support force at the excavation surface is applied. Second, the contact surface between the shield shell and the soil is established, the stiffness parameter is assigned to simulate the friction between the shield shell and the soil, and the shield shell unit is activated. Third, a thrust with the jack at the position of the segment is applied. Fourth, the grouting layer of the shield tail is changed to the equivalent layer parameter before hardening, and grouting pressure is applied. Next, an equivalent layer is assigned to the hardened parameters, and the above steps are repeated until construction is completed.

5.2. Analysis of Influences of Shield Tunnel Construction on Pile Foundation

5.2.1. Analysis of Influences of Different Shield Supporting Forces on Bridge Pile Settlements

Four working conditions were established to simulate the influence of excavation face pressure changes of shield tunnels excavation on the settlement of piers, and these working conditions are shown in Table 5.

Table 5. Calculation working conditions.

Excavation Face Pressure	**Working Condition 1**	**Working Condition 2**	**Working Condition 3**	**Working Condition 4**
Upper part of excavation face (MPa)	0.03	0.06	0.09	0.12
Bottom part of excavation face (MPa)	0.14	0.17	0.20	0.23
Average excavation face pressure (MPa)	0.085	0.115	0.145	0.175

Figure 14 shows the curve for the relationship between the average excavation face pressure and the maximum settlement of the pier foundation under the four working conditions. Figure 15 shows the duration curve of pier 14-1# with maximum settlement under different working conditions. As seen from the figure, the maximum settlement of the pier foundation gradually decreases with an increase in the excavation face pressure. Under working condition 1, an insufficient excavation face pressure on the excavation face results in over-excavation of shield construction, and the pier foundation settlement is relatively large. Under working conditions 3 and 4, the excavation face pressure of the excavation face is large, and it effectively controls the pier settlement. However, the pier foundation first heaves and then subsides, and the stress of the irregular-plate varies greatly. This should be avoided as much as possible during construction. Therefore, the excavation face pressure simulated in working condition 2 is closer to the excavation face pressure of the actual stratum, and this is taken as the simulated case.

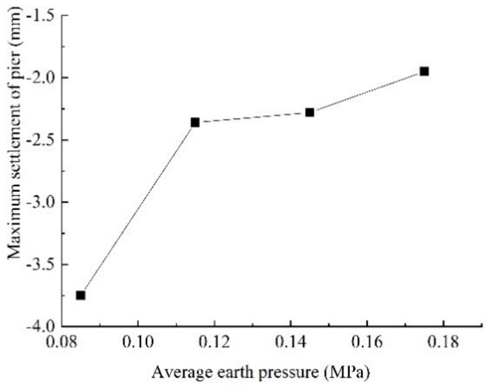


Figure 14. Relationship curve between the maximum settlement of the pier and average excavation face pressure.

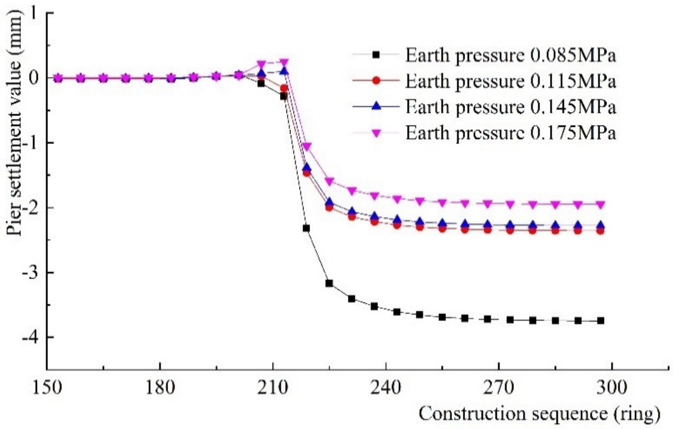
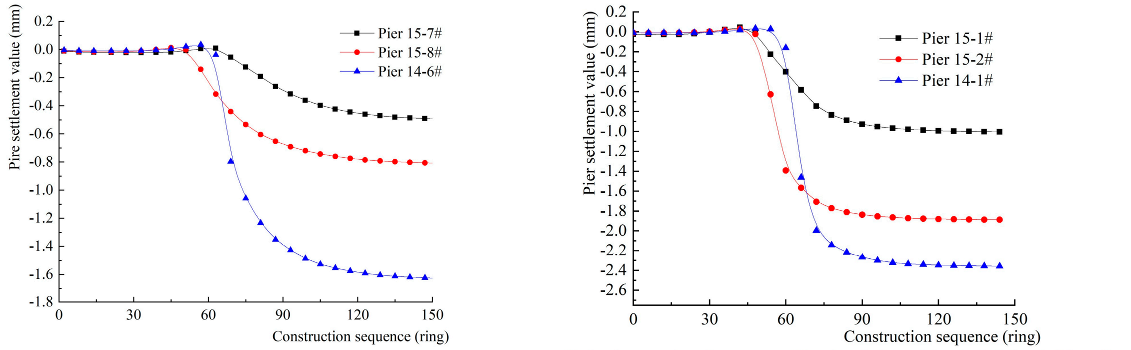


Figure 15. Settlement duration curve of pier 14-1 # under the different excavation face pressure.

5.2.2. Overall Analysis of Settlement of IPB Piers during Shield Tunnel Construction

From the simulation of the excavation face pressure working condition, the upper excavation face pressure of the shield excavation face is 0.06 MPa, and the bottom excavation face pressure is 0.17 MPa. The following analysis focuses on the vertical settlement of bridge piers at different positions under this condition. Figure 16 shows the settlement duration curve of the main bridge piers of the east irregular-plate. When the shield cutter head does not reach the pier foundation, settlement basically does not occur. The pier settlement is large during the shield passing, and it tends to be stable after passing. After the excavation of the right line is completed, the settlement values of piers 14-6#, 15-7# and 15-8# are 1.62 mm, 0.49 mm and 0.81 mm, respectively, and the settlement values of the other piers are small. After excavation of the left line is completed, the settlement values of piers 15-2# and 14-1# are 1.89 mm and 2.36 mm, respectively, and the settlement values of the other piers have little change. Obviously, excavation of the right line has a greater impact on piers 14-6#, 15-7# and 15-8#, whereas excavation of the left line has a greater impact on piers 14-1#, 15-1# and 15-2#. (See Figure 3 for the positional relationship of these sections.) During the construction process, it is necessary to strengthen the settlement monitoring frequency and to strictly control the settlement.



(a) Settlement duration curve of the simulation of the the right line bridge piles (b) Settlement duration curve of the simulation of the the left line bridge piles

Figure 16. Settlement duration curve of main bridge piers at the east end of the IPB.

6. Analysis of Construction Control Results of Shield Tunnels

From the analysis of the construction plan and the simulation of the shield construction, the key to the synchronous jacking technology is the excavation face pressure control of the shield tunnel excavation bin and the synchronous compensation of the settlement of the irregular-plate.

In the following section, the relationship between the excavation face pressure during the shield construction process and the pile foundation settlement of the IPB are analyzed, the settlement and cracking of the irregular-plate are also analyzed, and the difference between the theoretical analysis and the actual construction is discussed.

6.1. Analysis of Control Effect of Excavation Face Pressure on Pile Foundation Settlement of Shield Tunnel

The construction of the shield tunnel passing through the Guang'anmen Bridge is divided into four sections. Table 6 presents the data of the excavation face pressure, shield tunneling speed and final settlement of the pier during the construction. Figures 17–21 show the relationship between pier settlement and excavation face pressure in different sections.

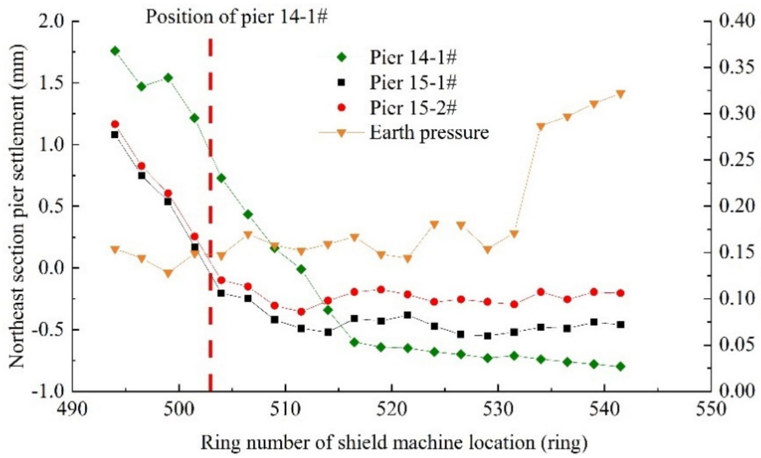


Figure 17. Relationship between pier settlement and excavation face pressure of northeast section.

Table 6. Main construction parameters of shield tunnel passing through the IPB.

Construction Parameters	**Pier Number**			
	5-3#	**14-1#**	**14-6#**	**5-10#**
Shield average earth pressure (MPa)	0.14	0.16	0.19	0.22
Shield average speed (mm/min)	11.86	9.82	7.52	7.33
Pier settlement (mm)	2.02	2.56	2.84	1.88

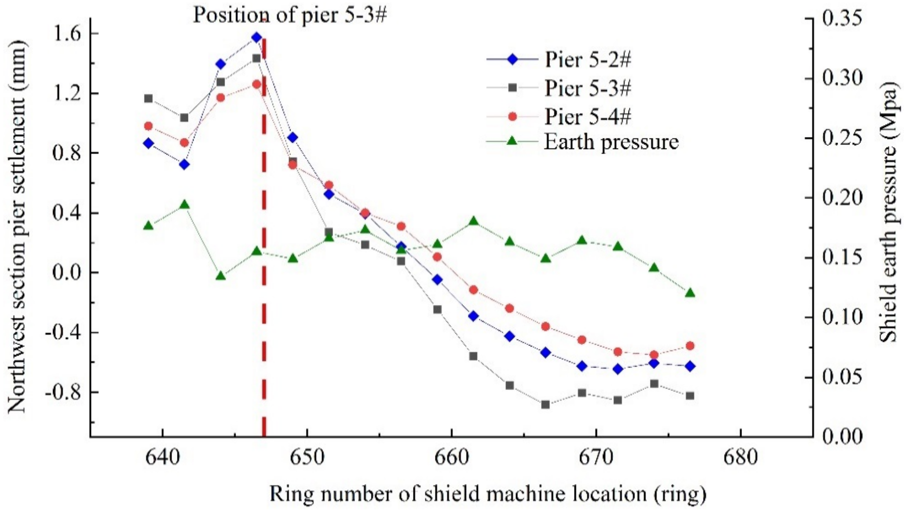


Figure 18. Relationship between pier settlement and excavation face pressure of northwest section.

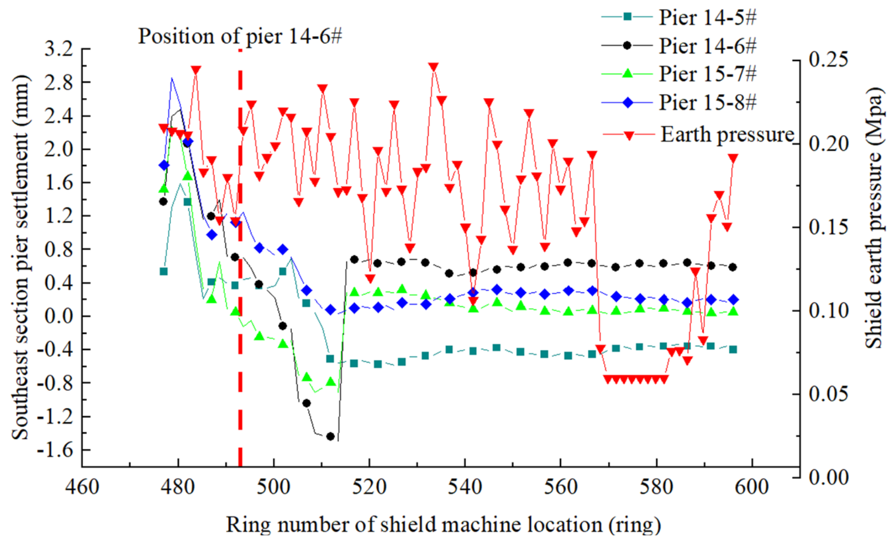


Figure 19. Relationship between pier settlement and excavation face pressure of southeast section.

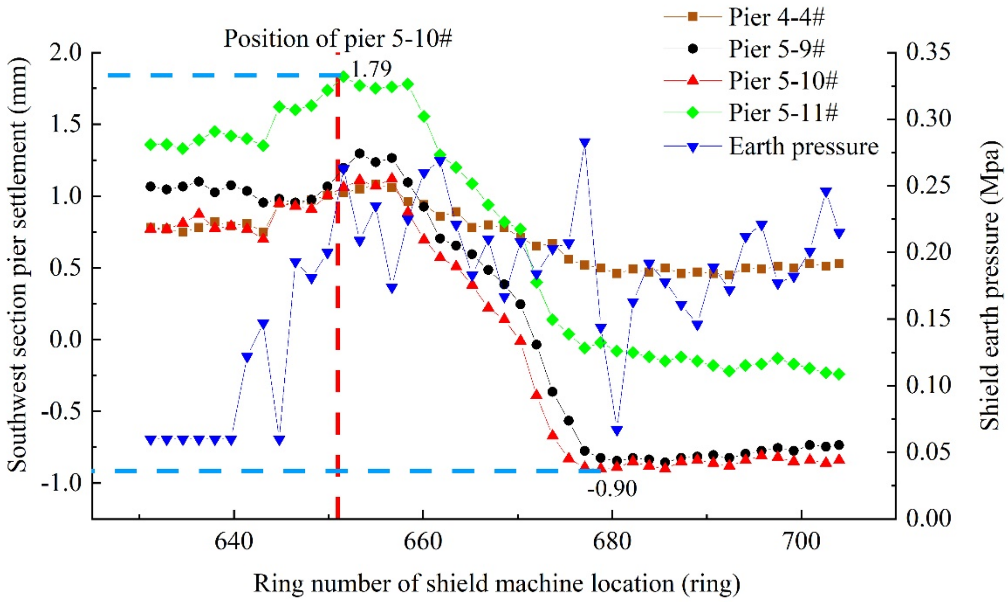


Figure 20. Relationship between pier settlement and excavation face pressure of southwest section.

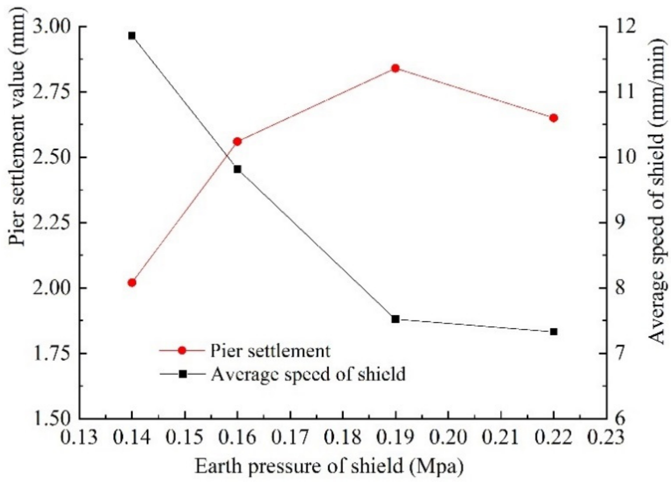


Figure 21. Relationship between piers settlement and excavation face pressure of shield.

From an analysis of the above figures and table, the following ideas are drawn:

(1) Fluctuation of the shield excavation face pressure at the northeast and northwest sections is small, so the settlement laws of the piers are similar, and the settlements are small.

(2) The pier in the southeast section has a large settlement and a large earth pressure fluctuation during shield tunneling. The settlement of piers 14-6# and 15-7# reached a pre-warning value (1.5 mm), and then jacking was started. Using pier 14-6# as an example, the settlement reached 1.44 mm when the shield tunneling reached 517 rings, and the irregular-plate was jacked up by 2.0 mm.

(3) Excavation face pressure fluctuation during shield tunneling in the southwest section is the largest, and an obvious increase in excavation face pressure leads to a further heave in the pile foundation. The maximum heave value of pier 5-11# reaches 1.79 mm. After the shield tunnel passed, the pile foundation rapidly settles, and the maximum settlement of pier 5-10# is 0.9 mm.

(4) Pier settlement in the southeast section is the largest of the four underpass sections. With an increase in excavation face pressure, the settlement of pier in the southeast increases, and there are certain differences from the results of numerical calculation. From analysis, the main reason for the difference is that the excavation face pressure obviously increases during the shield underpass,

and this results in the large torque of the cutter head and lower excavation speed. Thus, the disturbance time to the outer layer of the tunnel increases. The large loss of ground stress causes an increase in pier settlement.

From comprehensive analysis, it is determined that excavation face pressure should be kept above the minimum value at all times during construction of the shield. Reducing the torque of the cutter head and accelerating the shield excavation by reducing the excavation face pressure are not allowed.

6.2. Settlement Control Results of Pile Foundation and Its Corresponding Ground Surface

The settlement of pier and the ground surface were monitored during the shield tunnel construction, and the results are listed in Table 7. The relationship curves between the settlement of four underpass piers and the settlement of the corresponding ground surface are shown in Figures 22–25.

Table 7. Statistics settlement of pier and ground surface.

Settlement	Pier Number			
	14-6#	5-10#	14-1#	5-3#
Pier (mm)	2.84	1.88	2.56	2.02
Ground surface (mm)	8.05	13.24	5.5	9.24

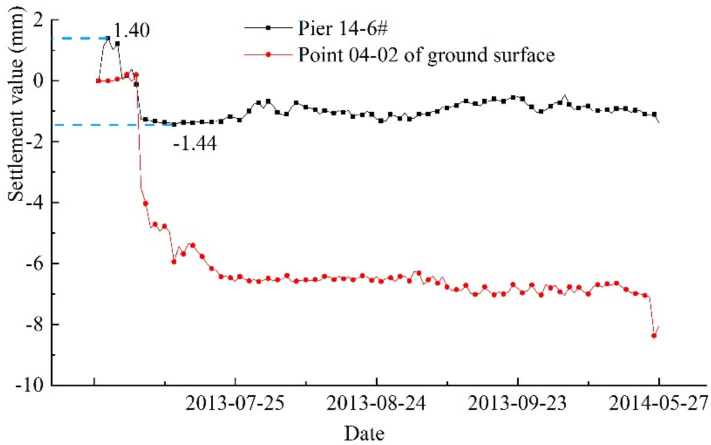


Figure 22. Settlement relationship between pier 14-6 # and the ground surface.

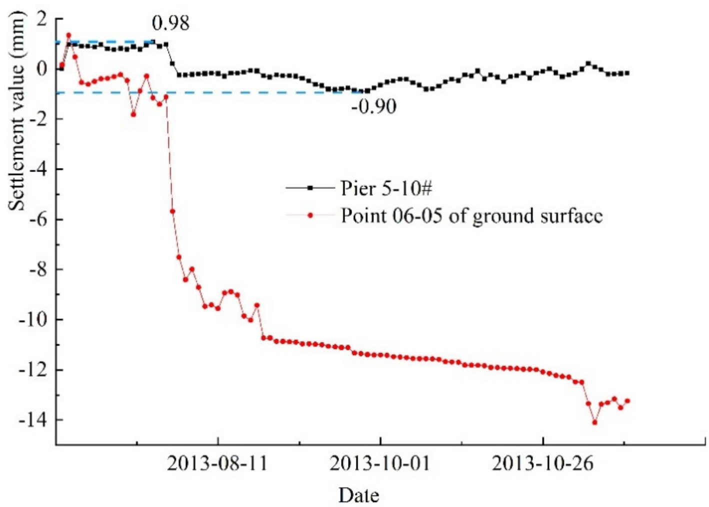


Figure 23. Settlement relationship between pier 5-10 # and the ground surface.

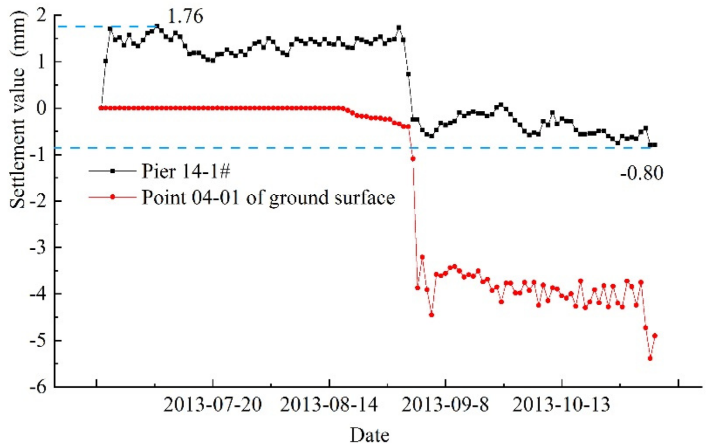


Figure 24. Settlement relationship between pier 14-1# and the ground surface.

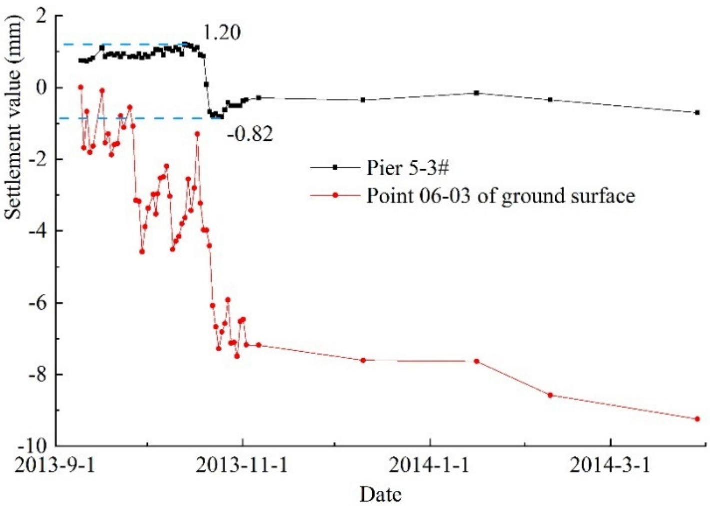


Figure 25. Settlement relationship between pier 5-3# and the ground surface.

On the basis of the above data, it is determined that pier settlement and ground surface settlement have similar laws. However, ground surface settlement is larger than pier settlement, and a later settlement of the ground surface lasts for a long time. In particular, because of shield shut down at pier 5-10#, shield disturbance lasts for a long time, and the ground surface settlement is the largest. This indicates that ground surface settlement has a larger time effect.

6.3. Control Results of Settlement and Cracking of the Irregular-Plate

During the time in which the shield tunnel passed through the Guang'anmen IPB, jacking equipment was set up around the piers according to the overall construction plan. During the construction, only pier 14-6# had excessive settlement. Jacking operation was carried out to restore the spatial position of the irregular-plate in time, so no new cracks increased in the bottom of the plate. Because of the effective control of shield excavation, the settlements of the piers in the other three sections are within the control standard, and jacking was not adopted, but a small number of cracks were generated, and this further verified the complexity of the stress distribution at the bottom of the irregular-plate. The temperature stress and shrinkage stress of the concrete structural plate are discrete and difficult to simulate. Settlements of the piers above all the tunnels are shown in Table 8, and new cracks in the plate bottom are shown in Figures 26–28.

Table 8. Settlement of plate at different stages.

Different Stages	Pier Number			
	14-6#	**5-10#**	**14-1#**	**5-3#**
Pile foundation grouting heave stage (mm)	+1.4	+0.98	+1.76	+1.2
Pile foundation settlement stage (mm)	−2.84	−1.88	−2.56	−2.02
Construction completion stage (mm)	+0.56	−0.90	−0.80	−0.82

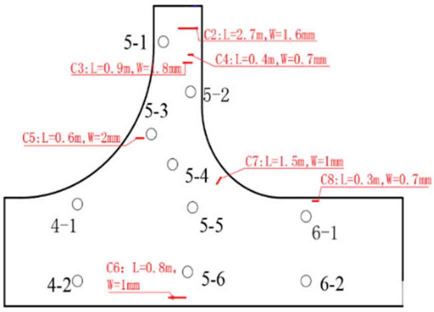


Figure 26. Distribution of cracks at the bottom of the bridge plate on the north side of the west end of the IPB.

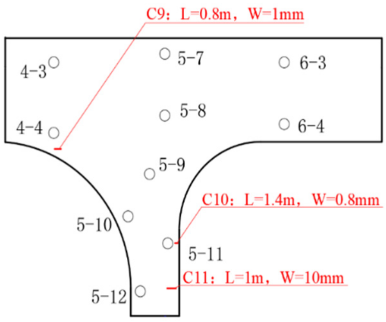


Figure 27. Distribution of cracks at the bottom of the bridge plate on the south side of the west end of the IPB.

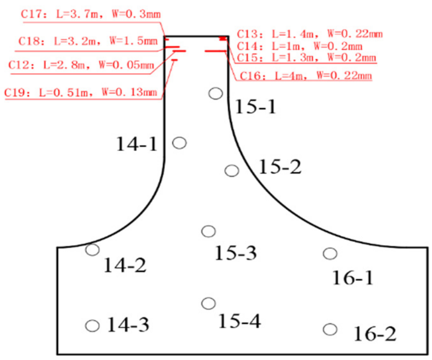


Figure 28. Distribution of cracks at the bottom of the bridge plate on the north side of the east end of the IPB.

7. Conclusions

(1) Theoretical analysis shows that when the foundation settlement of the IPB reaches 3mm, the stress at the bottom of the irregular-plate will exceed the tensile strength of concrete, and this will cause some cracks at the bottom of the irregular-plate. During the tunnel construction, reasonable measures were taken to control the settlement of the foundation, which does not exceed 2 mm, and there are few cracks at the bottom of the irregular-plate. This indicates that the settlement

control standard of the Midas civil program simulation analysis is basically reasonable. The reason for the deviation of the analysis is that the concrete structure generates temperature stress and shrinkage stress during use, and the distribution of these stresses is discrete, so it is difficult for MIDAS to analyze these stresses.

(2) Excavation face pressure always fluctuates during shield excavation. It should be ensured that excavation face pressure is always kept above the minimum value, and this can provide that the regular-plate bridge is in a safe state during the process of the subway tunnel passing. When excavation face pressure is too high, excavation speed will decrease, and this will increase the disturbance of the stratum and the settlement of the bridge piles. Therefore, the unearthed volume should be increased in time to reduce excavation face pressure and to speed up shield excavation.

(3) Synchronous jacking technology can be used for effectively controlling the great risks of a shield tunnel passing through the IPB. When settlement of the pier reaches 80% of the control value, the active jacking was used in time to compensate for the settlement of the irregular-plate, and this prevents the irregular-plate from cracking.

(4) Pier settlement and ground surface settlement caused by shield tunnel being excavated have similar laws, but ground surface settlement is larger and has a longer time effect.

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