

Article

Investigation on the Influence of Active Underpinning Process on Bridge Substructures during Shield Tunnelling: Numerical Simulation and Field Monitoring

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Abstract: The pile foundation cutting and underpinning process during shield tunnelling significantly impacts the stability of bridge substructures. In this paper, the shield tunnel area from Hongguzhong Avenue Station to Yangming Park Station of Nanchang Metro Line 2 was taken as the research subject, which crosses the pile foundation underpinning project of the south approach section of Bayi Bridge. Through numerical simulation and on-site monitoring analysis, the influence of the active underpinning process of shield tunnelling pile foundation on the deformation of bridge substructure was studied. First, through analyzing on-site conditions and comparing technical solutions, an active gantry bridge pile foundation underpinning technology was proposed, and the specific construction steps were determined. On this basis, for the C15 pile foundation with the most complex working conditions, ABAQUS software was applied to simulate the jack-up, unloading and pile-cutting process during the pile foundation underpinning construction, and the displacement development of the bridge pier, underpinning beam and new pile during the whole construction process were analyzed. Finally, through on-site monitoring data analysis, the technology's feasibility and safety were further verified. At the same time, according to the analysis of the monitoring results of the bridge piers, underpinning beams and new piles, the results from the finite element software were nearly the same as the trend shown by the monitoring results, and the displacement of the main structures of the lower part of the bridge was small and within the control range. The above research work verified the applicability of the active gantry type bridge pile foundation underpinning technology in the pile foundation underpinning condition of the single-column single-pile bridge in the narrow space curved bridge section, and is worthy of further promotion and application.

Keywords: shield tunnelling; active underpinning; bridge substructure; 3D FEM modelling; field verification



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1. Introduction

With the rapid urban development in China, an increasing number of metro tunnels are being constructed in major cities to alleviate traffic pressure and improve transportation efficiency [1–3]. According to statistics offered by China Association of Metros, there are more than 50 metro cities in China, and the total length of metro lines in operation exceeded 7209.7 km up to December 2021. Benefiting from unique advantages, such as high automation in facilities, fast construction speed, and little disturbances to ground traffic [4–8], the shield technique has been widely used in metro tunnelling. However, since metro lines usually go across densely populated urban areas, shield tunnel excavation inevitably disturbs the surrounding environment, leading to ground uplifting or settlement [9–13], further inducing deformation and even damage of adjacent structures, including buildings, bridges, buried pipelines and existing tunnels [14–17]. Hence, how to minimize the interference of shield tunnel construction process on adjacent structures has been a key issue in

the field of geotechnical engineering, which has attracted more and more attention from engineers and scholars [18–21].

As one of the most typical engineering cases, once the existing pile foundations of the adjacent buildings and structures intrude into the designed shield tunnel line, the intruded piles are usually cut off and new piles are constructed, acting as an underpinning foundation to continuously support the upper structures [19,22]. In this underpinning process, the overlying load of the upper structures should be smoothly transferred to the underpinning pile foundation to ensure the stability of the buildings and the safety of shield digging [16]. It is a very complex construction process involving complicated interactions between the tunnel, soil, and pile foundation [23], which merit detailed investigation.

In recent years, many efforts have been made by researchers to study the mechanical responses during pile foundation underpinning and the optimization of underpinning schemes through laboratory experiments, numerical simulation, and field tests [16,24]. Stulgis et al. [25] revealed that the pile foundation should be replaced before the destructive settlement of the building by installing grouting micro-piles in the replacement area to ensure the safety of the structures based on the case study of expansion project of St. Joseph Mercy Hospital in Georgetown, Guyana. Ma and Wang [26] theoretically analyzed the bearing capacity of a single pile and the joist deformation according to the structural design and found that the pile foundation underpinning method in the Xi'an Metro shield tunnel project was valid. Yan et al. [27] obtained the formula of shear force of a pile foundation underpinning structure through theoretical analysis and field model tests, which enabled calculation of the shear bearing capacity. Taking Beijing Metro Line 8 as an engineering case, Yao et al. [27] numerically analyzed the pile foundation underpinning scheme using FLAC^{3D} software to improve the effectiveness of the underpinning in reducing the deformation of structures and isolating piles. Xu et al. [22] proposed a pile underpinning technology for shield tunnel cross through group pile foundation in a shield tunnel interval in Shanghai Metro Line 10, and improved the rationality of the scheme by theoretical and numerical analysis as well as field monitoring tests. Park et al. [28] proposed and verified the application of a modified underpinning method in the new subway #9 line in Seoul Metropolitan in South Korea, which was able to reduce construction period by 1.5 times and the construction cost by 1.2 times compared with conventional methods. In addition to the aforementioned studies on pile foundation underpinning schemes, many scholars have focused on the pile cutting process [19,29,30]. Fu [31] numerically investigated the feasibility of the direct shield cutting pile foundation construction technology in cutting plain concrete, glass fiber concrete, and reinforced concrete, based on the mechanical response of the shield cutterhead as well as the tunnelling parameters are analyzed. Chen et al. [32] analyze the effect and mechanism of large-diameter pile cutting process during shield tunnelling and obtained the characteristics of cutting parameters and the damage law of cutting tools through field tests. To achieve stable and effective pile cutting process, a new cutterhead configuration as well as pile cutting scheme were proposed by [33], suggesting that the shield advance rate should not exceed 2 mm/min, and the rotation speed should be controlled at a relatively low level.

In the pile foundation underpinning–cutting scheme, dynamic control of the displacement of superstructure and the underpinning foundation is crucial to the safety and efficiency of this process [16], which still remains to be explored in detail. Moreover, complex geological conditions and differences in the surroundings often make it hard to determine an appropriate underpinning scheme. Considering that several single-column and single-piles in the upper Bayi Bridge invaded the tunnel, the shield tunnel section pile foundations from Hongguzhong Avenue Station to Yangming Park Station of Nanchang Metro Line 2 need to be underpinned, which will inevitably have a great impact on the substructure of the bridge and the surrounding engineering environment, and the construction risk is extremely high. Therefore, in this paper, based on the analysis of on-site working conditions and the comparison of technical solutions, an active gantry type bridge pile foundation underpinning technology was proposed, and the corresponding specific

construction steps were designed. On this basis, for the pile foundation C15 with the most complex working conditions, the 3D finite element ABAQUS numerical simulation was used to analyze the underpinning process. Moreover, the influence of three key stages of the underpinning scheme, i.e., jack lifting, unloading and pile cutting on the bridge pier, underpinning beam and new underpinning pile were studied in detail, and the feasibility and safety of the underpinning technology were preliminarily verified. Finally, by monitoring and analyzing the three important stages of jacking, unloading and pile cutting of the C15 pile, it was further verified that the technical solution is reliable and worthy of further promotion and application.

2. Engineering Background

2.1. Project Introduction

The left line from Hongguzhong Avenue Station to Yangming Park Station of Nanchang Metro Line 2 is 2335 m long, and the minimum plane curve radius is 600 m. In this section, the mud–water balance shield construction technique was adopted, and several bridge piles of the south approach bridge of Bayi Bridge invaded the tunnel section, as shown in Figure 1. For the invaded the subway tunnel line, there are seven pile foundations in ramp C and ramp F, of which ramp C has a deck width of 11 m, and the upper structure of the bridge is a two-box multi-span reinforced concrete continuous box girder bridge. The ramp F has a deck width of 7 m, and the superstructure of the bridge is a single-box multi-span reinforced concrete continuous box girder bridge. The pile foundations intruded into the tunnel are all single-column and single piles, so these invaded pile foundations need to be underpinned. The Bayi Bridge spans the Ganjiang River, and is an important transportation hub in Nanchang, hence there are strict requirements on structural deformation and stability. However, in this project, performing the single-column and single-pile underpinning is extremely risky in the narrow space of the curved and unclosed bridge section, and it is extremely difficult to control the stability of the underpinning pile foundation and bridge structure during the construction process.

2.2. Engineering Geological Conditions

The upper part of the stratum from Hongguzhong Avenue Station to Yangming Park Station is mainly artificial fill <Q4al>, Quaternary Holocene shock layer <Q4al>, Pleistocene alluvial <Q3al>, and the underlying bedrock is mainly the third Xinyu Group (Ex) argillaceous siltstone, etc. According to lithology and engineering geological characteristics, the site stratum can be divided into miscellaneous fill <1-1>, plain fill <1-2>, silty clay <2-1>, silt <2-2>, fine sand <2-3>, medium sand <2-4>, coarse sand <2-5>, gravel sand <2-6>, round gravel <2-7>, silty clay layer <3-1>, fine sand <3-3>, fine sand layer <3-4>, coarse sand <3-5>, gravel sand layer <3-6>, round gravel layer <3-7>, pebble <3-8>, argillaceous siltstone layer <5-1>, glutenite <5-2>, and mudstone <5-3>. In the section between Hongguzhong Avenue Station and Yangming Park Station, shield tunnels mostly pass through the Quaternary overburdened soil layer, the surrounding rock types are VI to IV which mainly consists of weathered argillaceous siltstone, as shown in Table 1.

2.3. Position of Bridge Pile Foundation and Shield Tunnel

The structures corresponding to the pile foundations that need to be underpinned for the south approach bridge of the Bayi Bridge are all multi-span reinforced concrete box girder structures. The pavement of the bridge deck consists of 6 cm expanded metal mesh on the lower layer, C40 concrete and 4 cm thick asphalt concrete on the upper layer, and the horizontal width of the guardrail on both sides is 0.44 m. The lower structure is a single circular column and single pile structure. Among them, the upper structure of ramp C is a double-boxed reinforced concrete continuous girder bridge with a bridge deck width of 11.88 m. The bridge deck layout and related size parameters are shown in Figure 2. The bridge piles on ramp C are relatively complex, and there are different distances between new underpinning piles and the old piles, resulting in eccentricity. In this paper, the bridge

pile C15 with the most complex working conditions was selected for research. The column diameter is 1.5 m and the column height is 9.7 m. The pile diameter is 1.5 m, the pile length is 24.9 m, and its intrusion length is 3.5 m.

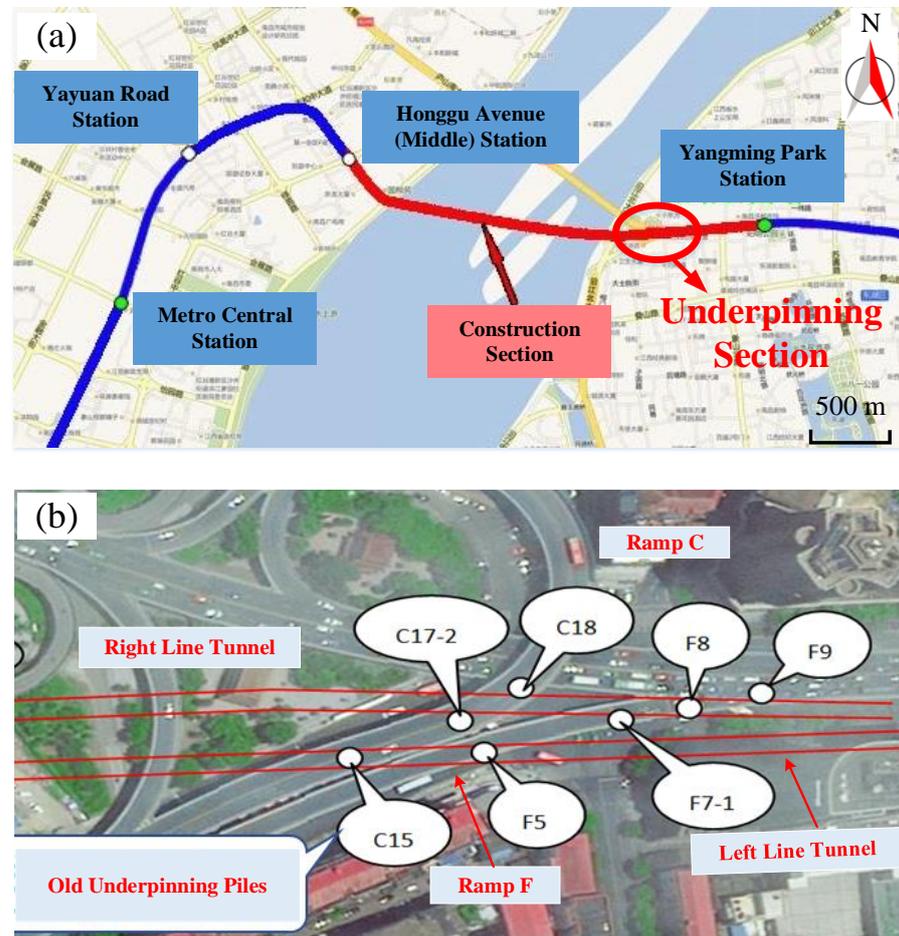


Figure 1. Engineering background of the shield tunnel of Nanchang Metro Line 4 passing through the bridge pile foundation of Baiyi bridge: (a) location of the underpinning section; and (b) layout of the underpinning piles.

Table 1. Classification of surrounding rock in shield tunnel section.

Line	Classification of Surrounding Rock			Surrounding Rock Classification	Stratum Passed by Tunnel
	Tunnel Top	Tunnel Wall	Tunnel Bottom		
Left line	VI	VI~IV	IV	IV	Cave top: <2-1>, <2-2>, <2-3>, <2-4>, <2-5>, <2-6>, <2-7> Cave wall: <2-4>, <2-6>, <2-7> Cave bottom: <2-4>, <2-6>, <2-7>, <5-1-1>, <5-1-2>
Right line	VI	VI~IV	IV	IV	Cave top: <2-1>, <2-2>, <2-3>, <2-4>, <2-5>, <2-6>, <2-7> Cave wall: <2-4>, <2-6>, <2-7> Cave bottom: <2-4>, <2-6>, <2-7>, <5-1-1>, <5-1-2>

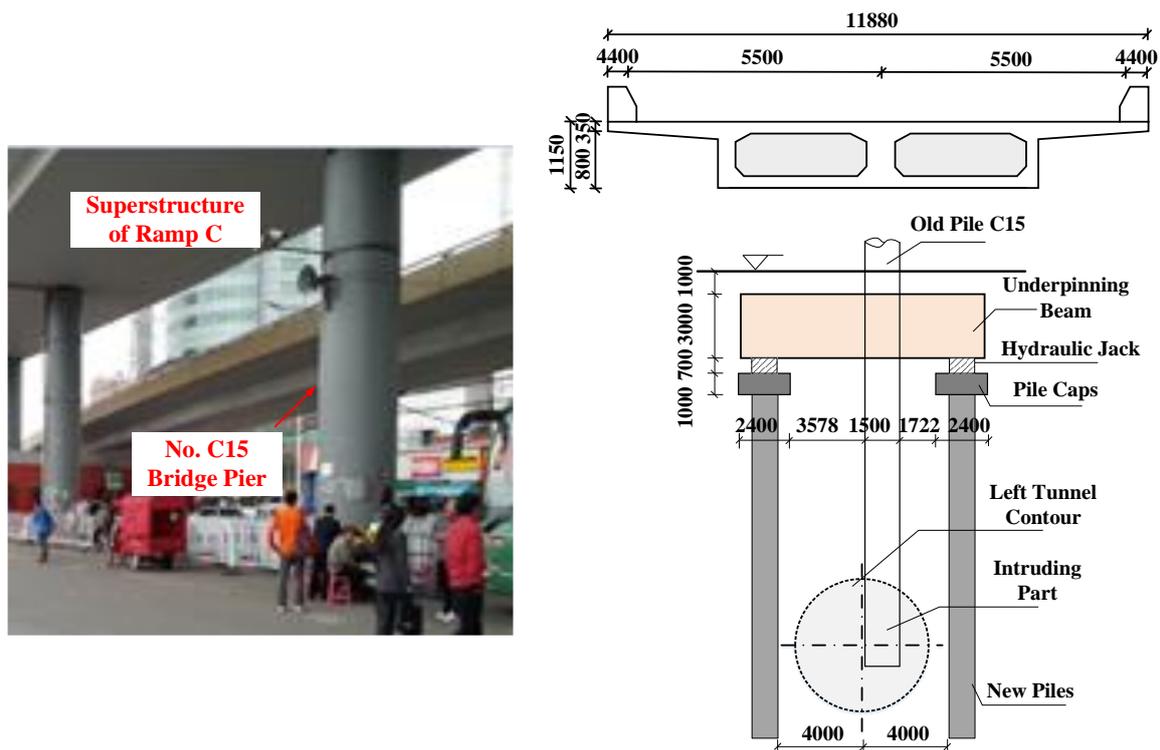


Figure 2. Pile underpinning scheme of C15 bridge pier and the corresponding parameters.

3. The Underpinning Scheme of Bridge Pile

In order to ensure that the Bayi Bridge can still operate normally during the construction, an active underpinning method was adopted to deal with the problem of pile foundation intruding into the tunnel so as to minimize the impact of the construction on the upper bridge structure. The underpinning structure selected was a gantry-type underpinning system consisting of new underpinning piles and underpinning beams. Before the pile foundation underpinning, the new underpinning pile and the foundation pit enclosure structure were to be constructed sequentially. The underpinning beam construction and pile underpinning operation were carried out in the foundation pit. The underpinning steps are as follows:

- (1) A jack is set on the underpinning platform, the underpinning beam and the underpinning pile are constructed independently, and a rigid overall structure is formed after the underpinning force of the pile foundation is converted. When the underpinning pile, underpinning beam and underpinning platform concrete reach the design strength, the loading underpinning construction will be carried out;
- (2) During underpinning, a jack is set up between the underpinning beam and the underpinning cap to transfer the load of the superstructure to the new underpinning pile and make most of the displacement of the new pile to offset the preload of the jack simultaneously, making the new underpinning pile can replace the force of the original pile through active loading;
- (3) During the underpinning process of pile foundation, the PLC hydraulic synchronous control system is used to jack up the underpinning beam and preload the underpinning pile. At the same time, the load and displacement changes of the underpinning pile are monitored to ensure the settlement of underpinned pile does not exceed the control value. The loading is divided 10 times, with 10% of the total jacking force as the interval;
- (4) After the end of the jacking stage, the unloading stage begins, and the unloading process is divided 5 times, with 20% as the interval;

- (5) Considering that the structure above the underpinning beam needs to remain balanced, the original pile foundation is cut off using a wire saw. The cutting height of the pile is controlled within the range of 300~500 mm, and the cutting gap is 5~10 mm. After the first cutting is completed, it is necessary to ensure continuous monitoring for more than 1 h, and the second cutting can only be carried out after the settlement becomes stable. During the pile cutting process and after the pile cutting is completed, the jacking force should be monitored and adjusted to ensure that the original column elevation remains unchanged. The construction process of the underpinning pile foundation is shown in Figure 3.

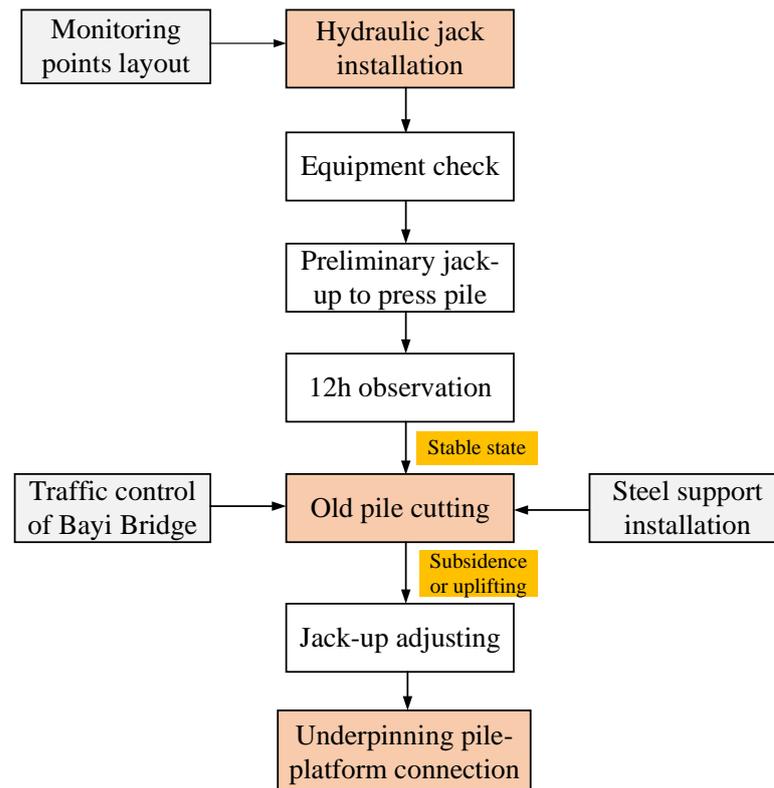


Figure 3. Construction process of underpinning pile foundation.

4. Numerical Simulation of Pile Foundation Underpinning Process

During the underpinning construction, the stress and deformation of the new underpinning pile, the underpinning beam and the underpinning pile are relatively complex, and at the stage of jack loading, unloading and pile cutting, the deformation control of the new pile and underpinning beam, such as settlement, inclination and horizontal displacement of pile top is the key to pile underpinning technology [16]. In many previous studies in the literature, finite element method software ABAQUS 3D has been used in the numerical simulation of shield tunnelling and pile foundation underpinning process, which has proved the validity in capturing the mechanical behaviors of the tunnels and the surrounding pile foundations [16,19]. Hence, in this part, ABAQUS 3D finite element simulation was used to analyze the deformation of the bridge substructure of the C15 pile foundation in the three stages of jacking, unloading and pile cutting so as to verify the feasibility and safety of the underpinning technology.

4.1. The Establishment of Model

As shown in Figure 4, the model size is set as 50 m (length) × 80 m (width) × 50 m (height) to avoid boundary effects [19], and the size of the foundation pit is 14 m (length) × 5.2 m (width) × 5.9 m (height). The dimensions of other components, such as old pile,

cap, underpinning beam, and new underpinning pile are also the same as those of the engineering case. The two new underpinning piles are 1.2 m in diameter and 27 m in length. The model unit is C3D8R, and the total number of units is 32,700.

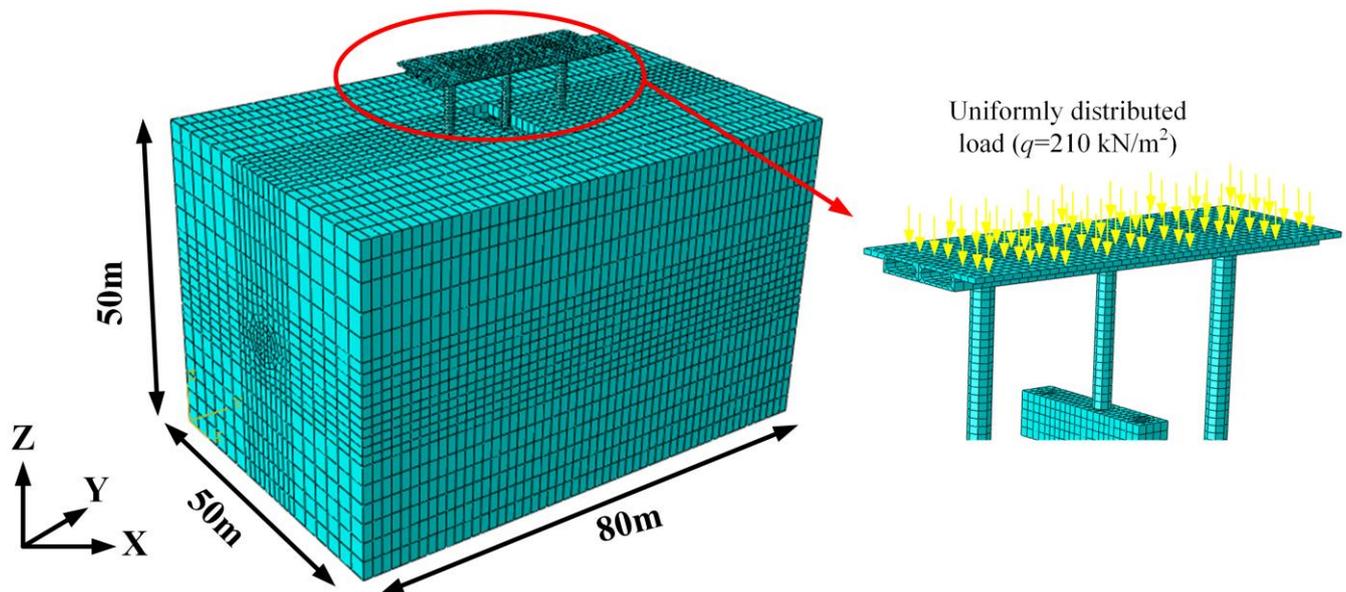


Figure 4. 3D-FEM modelling configuration and boundary conditions.

The left and right boundaries of the model are constrained in the X direction, the front and rear boundaries are constrained in the Y direction, the bottom boundary is fixed, and the top boundary is free. The mechanical behavior of the soil obeys the Mohr–Coulomb criterion, and the underpinning beams, caps and piles are assumed to be homogeneous and linear elastic materials [19]. The corresponding model material parameters are listed in Table 2. A parametric study was conducted for the variability that the surrounding terrain could bring to the structural analysis, and the results improve that the model parameters adopted in the simulation can effectively avoid boundary effects. Considering that only the impact of the construction process on the substructure of the bridge can be analyzed in numerical simulation, continuous mechanical change cannot be monitored in the same way as the engineering. Therefore, in the modelling process, the “jack” was directly regarded as the concrete block after the pile sealing has been completed. The details of the underpinning are shown in Figure 5a, and the relationship between the underpinning pile and the tunnel is shown in Figure 5b.

Table 2. Material parameters used in numerical modelling.

Material Type	Density (ρ) /kg/m ³	Young's Modulus (E)/MPa	Poisson's Ratio (ν)	Friction Angle (φ)/°	Cohesion (c)/kPa	Thickness (h)/m
Miscellaneous fill	1780	7	0.32	10	5	4
Silty clay	1870	8	0.34	15	25	3.4
Coarse sand	1900	20	0.32	29	0	3.9
Pebble	2000	30	0.33	30	0	7
Strongly weathered argillaceous siltstone	2100	140	0.32	28	38	3.7
Moderately weathered argillaceous siltstone	2450	4×10^3	0.3	38	1000	28
Concrete (underpinning beam, platform, piles)	2400	3×10^4	0.23	—	—	—

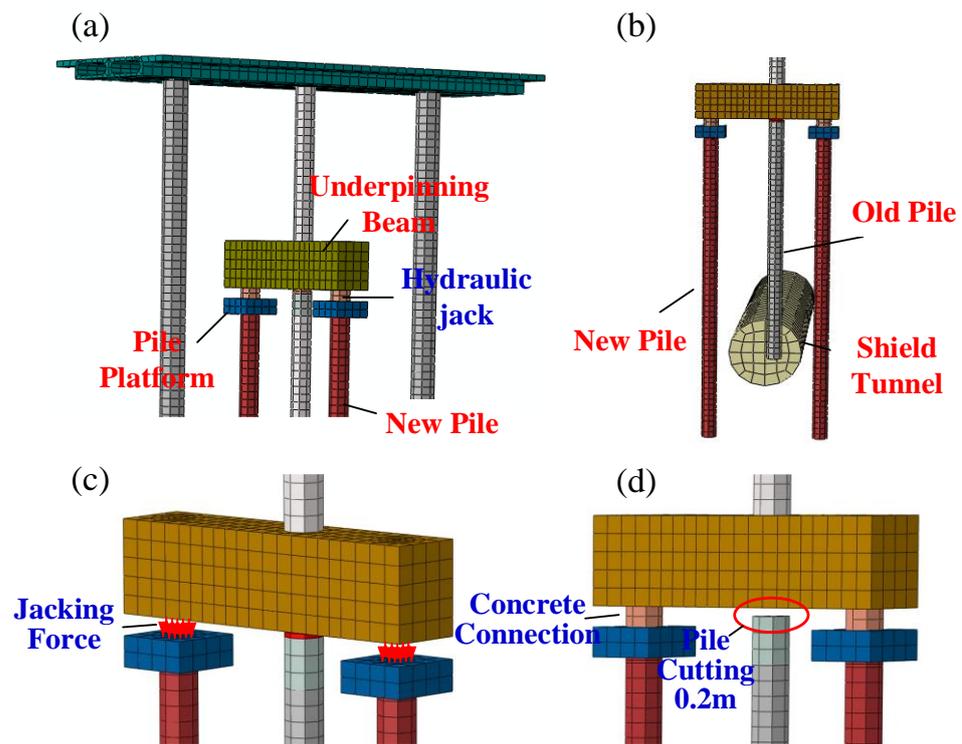


Figure 5. Details of the 3D-FEM modelling: (a) underpinning diagram; (b) location of the underpinning pile and shield tunnel; (c) application of jacking force; and (d) old pile cutting and new pile sealing.

4.2. Simulation Procedure

There are 17 steps in the model analysis, and the specific settings are as follows:

- (1) Step 0: the balance of earth stress;
- (2) Before the underpinning, because the “jack” does not work between the underpinning beam and the bearing platform, the “jack” concrete block is not activated first;
- (3) According to the “General Code for Design of Highway Bridges and Culverts” (JTG D60-2015) [34], the standard value of the uniformly distributed load of the I-level lane is $q_k = 10.5 \text{ kN/m}$, and the span is 20 m, hence a uniformly distributed load of 210 kN is applied to the bridge deck to simulate the traffic load;
- (4) Step 1–10 jacking stage: as shown in Figure 5c, jacking force is subjected to the bottom of underpinning beams and the upper part of the cap at two sides. According to the construction scheme, the loadings applied to the left and right pile platforms are 3466 kN and 4588 kN, respectively, which are converted into equivalent pressure in Table 3. The loading is divided 10 times, and 10% of the total jacking force is applied each time;
- (5) Step 11–15 unloading stage: after the lifting is completed, unloading is carried out. The unloading interval is 20% of the total lifting force, and the unloading is carried out 5 times;
- (6) Step 16 Pile cutting and sealing stage: In the actual project, the truncation is carried out in two steps. In this simulation, it is simplified to activate the “jack” concrete block to simulate the completion of the pile sealing and truncate the old pile to be separated by 0.2 m, as shown in Figure 5d.

Table 3. Equivalent jacking pressures applied on the pile platforms.

Pile No.	Total Pressure on Left Pile Platform/kPa	Pressure on Left Pile Platform Each Loading Step/kPa	Pressure on Left Pile Platform Each Unloading Step/kPa	Total Pressure on Right Pile Platform/kPa	Pressure on Right Pile Platform Each Loading Step/kPa	Pressure on Left Pile Platform Each Unloading Step/kPa
C15	3066	306.6	613.2	4058	405.8	811.6

4.3. The Analysis of Simulation Result

In the process of pile foundation underpinning, the displacement changes of bridge piers, underpinning beams and new piles are the key monitoring contents. The data extraction points of numerical simulation are shown in Figure 6. Because the whole construction process is simulated, the displacement changes of each extraction point in the whole construction process were analyzed. During the jacking process of pile foundation underpinning, the new underpinning pile will experience settlement due to the different engineering environments, such as insufficient foundation bearing capacity, pile bottom sediment, etc., which will induce additional stress to the upper structure to damage the beam body, which is very important in the study of the settlement law of new piles.

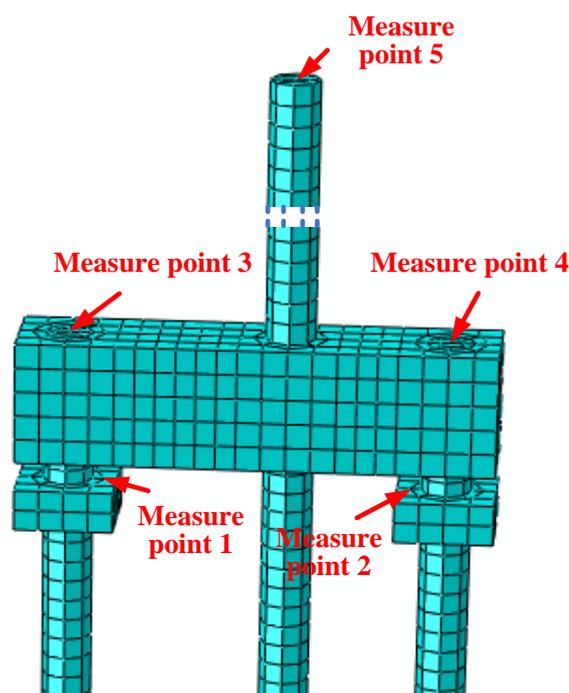
**Figure 6.** Data extraction points of the numerical model.

Figure 7 shows the changing trend of the new pile displacement during the pile foundation underpinning process, and it is the same as the changing trend of the displacement of the bridge pier and the underpinning beam. In the first five times of jacking, this new pile displacement has a relatively stable increase, and it starts to increase from the sixth jacking, especially the settlement of new piles near the old pile side are increased by 40% compared to the previous in the last jacking. The maximum settlement of the new pile on the side far from the old pile is 2.12 mm, and the maximum settlement value of the new pile is 3.48 mm, which has reached the warning value during monitoring but not the control value. Therefore, during the jack-up process of the pile foundation underpinning, it is necessary to focus on the settlement changes of the new piles near the old piles [19].

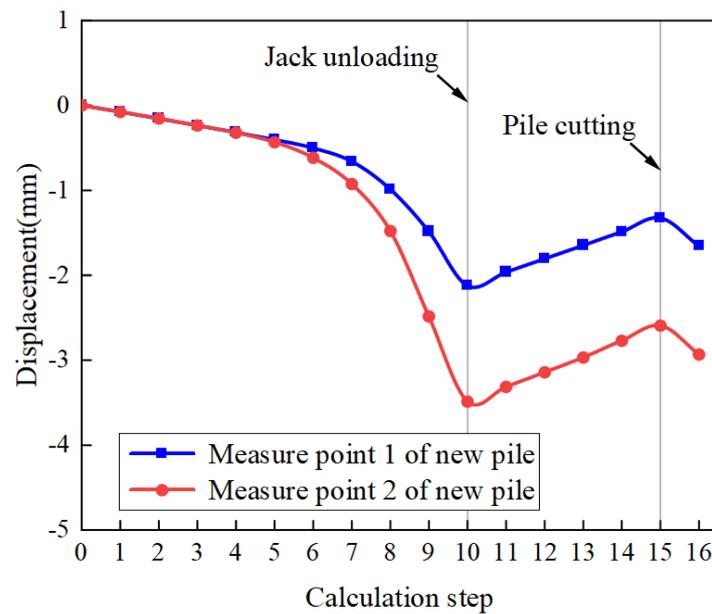


Figure 7. Displacement of the new piles calculated by numerical modelling.

Figure 8 shows the displacement change curve of the underpinning beam. It can be seen that the displacement changes of the underpinning beam on the side away from the old pile is small, and the corresponding growth rate is small, while the displacement of the underpinning beam close to the old pile side changes greatly, and the maximum displacement is 0.88 mm, but it is still within the early warning. The displacement of the underpinning beams on both sides changes smoothly during the unloading stage, and it has no sudden change when the old pile is truncated.

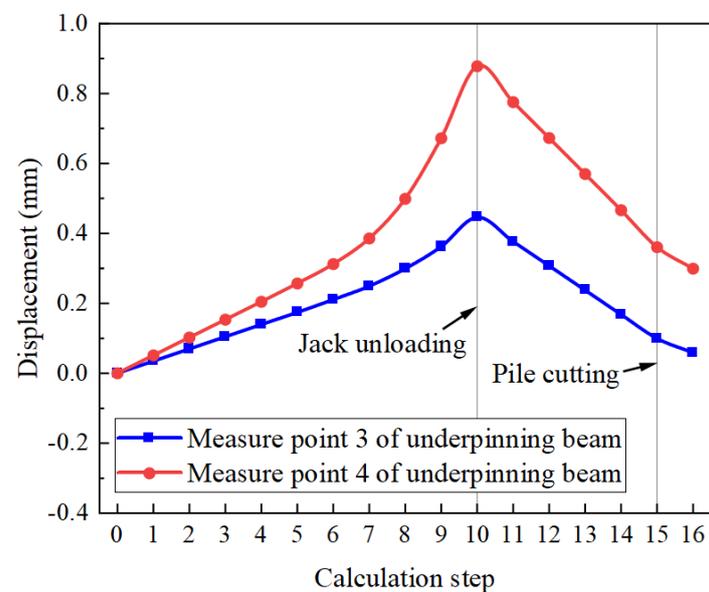


Figure 8. Displacement of the underpinning beam calculated by numerical modelling.

The difference in settlement of the new piles on both sides is caused by the difference in the lifting force. However, with the end of the jacking, this difference becomes small, indicating that the deformation of the superstructure is well controlled in the underpinning process, and the design of the jacking force in the underpinning construction is feasible.

The displacement of the bridge pier calculated by numerical modelling is given in Figure 9. It can be seen from the figure that in the first five times of the jack lifting

process, the displacement increased relatively stable. However, its growth rate starts to increase from the 6th jacking to the end, and the maximum displacement is 0.68 mm. The displacement is gradually decreased by 0.43 mm when unloading, indicating that the load is well transferred. In the final jacking, the old pile is cut off, and the displacement continues to drop by 0.06 mm, indicating that the load transfer is completed in the underpinning construction, and the new pile is able to sustain the load safely. In addition, there is no sudden change in displacement during the whole simulation process, and all the displacement changes are also within the warning value. In general, the underpinning technical solution was preliminarily verified to be safe and feasible.

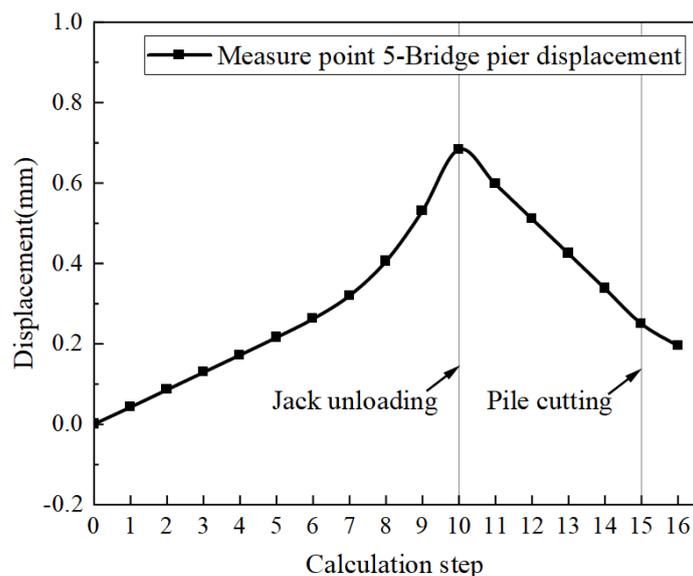


Figure 9. Displacement of the bridge pier calculated by numerical modelling.

5. Field Verification of Pile Foundation Underpinning Scheme

5.1. Monitoring Content and Methods

Pile foundation underpinning is very difficult and has a high construction risk; construction monitoring is the key to ensuring construction safety, and the setting of construction monitoring control values and early warning values is crucial. The monitored data are the deformation of the bridge pier and the underpinning beam during the underpinning process. The monitoring content and warning control value are shown in Table 4. The settlement of the bridge piers is monitored by a crystalline silicon static level instrument, and each bridge pier is installed with a static level measuring point installed on the upper part of the pier column. The inclination of the bridge pier is measured by a dual-axis inclinometer that is installed on the side of the pier parallel to the bridge axis at the top of the pier column. During the monitoring, each pier is installed with a dual-axis inclinometer. Two static level monitoring points are set at the top of the two new piles to monitor the settlement using the static level instrument. By monitoring the relative settlement of the new pile top and the pier body, the absolute settlement of the new pile top can be obtained. Thus, the settlement change of the new pile and the difference in the displacement of new piles on both sides of the main beam during the jacking process. During the underpinning process, due to the inconsistency of the jacking force on the left and right sides, the underpinning beam may be inclined to induce additional loads on the pier body and the main beam, affecting the safety of underpinning construction and bridge structure. Therefore, the monitorization of settlement of the underpinning beam is very necessary. The settlement of the underpinning beam is monitored by a static levelling instrument, and two static levelling points are set at two ends of the underpinning beam (the corresponding displacement of the new pile). The main monitored parameters include absolute settlement and differential settlement at both ends of the joist beam.

Table 4. Field monitoring variables and corresponding alarming and controlling values.

No.	Monitoring Variables	Monitoring Instruments	Precision	Alarming Value	Controlling Value
1	Pier displacement	Hydrostatic level	0.1 mm	2.0 mm	3.0 mm
2	Pier inclination	Inclinometer	0.001°	0.06°	0.12°
3	New pile displacement	Hydrostatic level	0.1 mm	3.5 mm	5 mm
4	Underpinning displacement	Hydrostatic level	0.1 mm	3.5 mm	5 mm

5.2. Monitoring Data Analysis

During construction, the monitoring in the jacking process is the most critical stage of the project. The underpinning jacking adopts the graded loading, this process is divided into 10 stages, and the interval is 10% of the predetermined limit of loading. Each loading stage is held for 10 min until the tested displacement parameters are stable and meet the limit requirements (controlled by 0.1 mm/h), and then the next stage of loading can be carried out. After the static compression of the new pile is completed (reaching the design control value of the jacking force), the monitorization continues until the settlement is stable (consecutively controlled by 0.1 mm/h for 12 h). During the pile-cutting stage, the settlement of the pier and underpinning beam are continuously monitored (including the difference in settlement change), and sudden displacement of the underpinning structure is not allowed. At the same time, the pier settlement and underpinning beam settlement (including differential settlement changes) are continuously monitored, and sudden displacement of the underpinning structure is not allowed. In order to focus on the study of the deformation law of the main structure in the lower part of the bridge during the three important stages of jacking, unloading and pile cutting in the underpinning project, the change of the monitoring data of the key nodes of the C15 pile foundation construction was analyzed. As shown in Figure 10, the data of monitoring points are the same as that of the extraction points in the numerical simulation. Measuring points 6 and 7 are the new pile settlement monitoring points, and measuring points 8 and 9 are the underpinning beam settlement monitoring points. The inclinometer is placed on the top of the pier column (measurement point 10).

5.2.1. Jacking Stage of Underpinning Pile

As shown in Figure 11, during the jacking process of C15, both the pier and the underpinning beam experience upward displacement within the control range under the action of jacking force. When the jacking is completed, the change of displacement gradually becomes stable without significant fluctuation. The maximum change rate of the pier displacement is -0.25 mm/h, and the cumulative change is 0.23 mm. The maximum change rate of the underpinning beam displacement is 1.28 mm/h, and the cumulative change is 1.32 mm. The maximum change rate of the pier inclination is 0.006° /h, the cumulative change value is 0.016° . During the jacking process, the displacement and inclination of the piers are all within the normal range. Among them, the measured value of seven measuring points (new piles near the F ramp) exceeds the control value after the completion of the 7th level of loading, but after the completion of the 10th level of loading, the differential settlement of the new piles is 1.74 mm, and other monitoring items have no abnormality. According to the monitoring results after reaching the jacking design load for 30 h, it is shown that the monitoring data are gradually stable, the final differential settlement of the new pile is 1.66 mm, and the overall monitoring cumulative value and change rate are both small. In the jacking stage, although the settlement of the new pile exceeds the control value, the deformation of the superstructure is stable, which is also the same as the conclusion of the numerical simulation, indicating that the design of the jacking force is reasonable, and the construction plan is feasible.

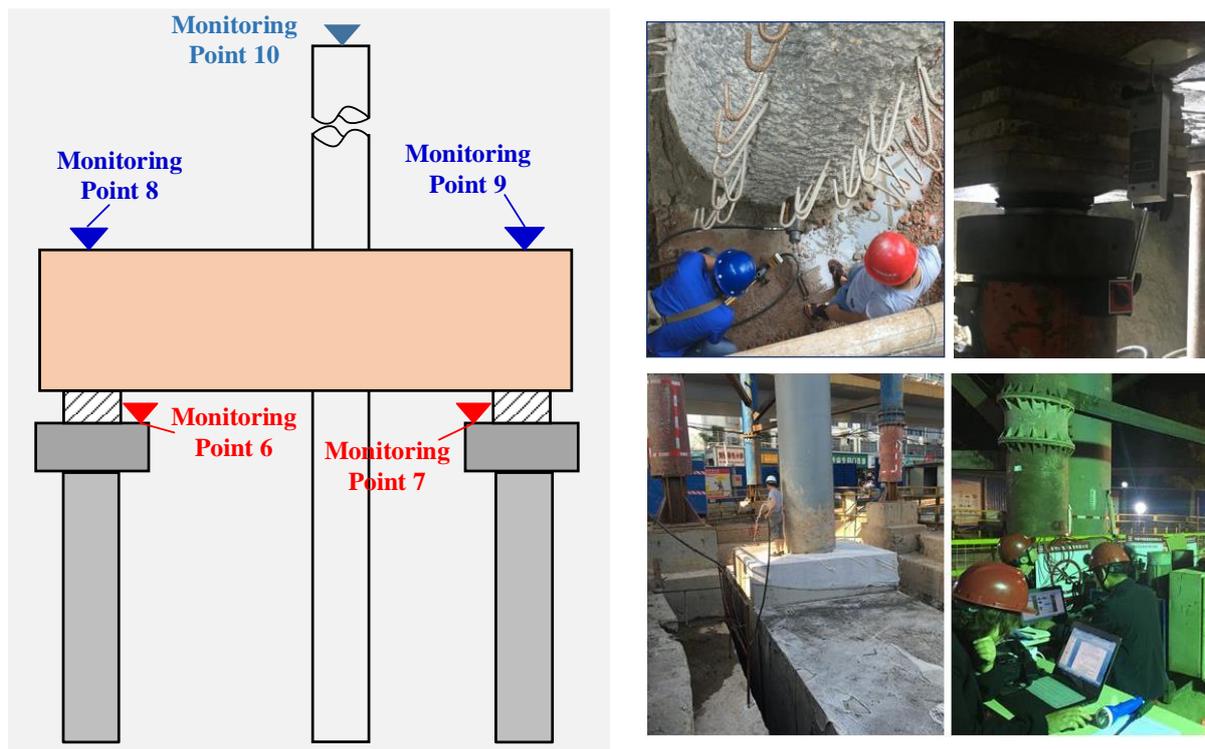


Figure 10. Layout of the monitoring points during underpinning construction (left) and the field monitoring (right).

5.2.2. Underpinning Pile Unloading Stage

As shown in Figure 12, during the unloading process of C15, the force from the jack becomes smaller, and the load transfer is gradually realized. The settlement of the bridge pier and the underpinning beam gradually increases, but the change of the displacement tends to be stable after the unloading of the jack is completed. There is no sudden change in displacement during the process, indicating that the construction plan is reasonable in the unloading stage. During this period, the maximum change rate of pier settlement is -0.01 mm/h, and the final cumulative maximum value is -0.04 mm. The maximum change rate of pier inclination angle is 0.003° /h, and the final cumulative maximum value is 0.007° . The maximum change rate of underpinning beam settlement is -0.04 mm/h and the final cumulative maximum value is -0.09 mm. The settlement and inclination of the bridge superstructure are within the safe range.

5.2.3. Underpinning Pile Cutting Stage

As shown in Figure 13, in the process of two piles cutting of C15, the maximum change rate of the bridge pier displacement is 0.06 mm/h, and the cumulative maximum value is 0.18 mm, showing an upward trend. This is because in the jacking stage, due to the existence of the old piles, the jacking force will generate prestress between the old piles and the bridge piers. When the old piles are truncated, the stress is gradually released, increasing the displacement of the bridge piers, but the displacement of the bridge piers tends to be stable at the end, and the magnitude of the change is also within a safe range. The maximum change rate of the pier inclination angle is 0.038° /h, and the cumulative maximum value is 0.046° . The maximum change rate of the displacement of the underpinning beam is -0.1 mm/h, and the cumulative maximum value is -0.42 mm, which are both within the safe range. Combined with the analysis results of numerical simulation and field measurement data, it can be seen that the active gantry type bridge pile foundation underpinning technology scheme is highly feasible, and it is worth popularizing

in pile foundation underpinning projects of single-column and single-pile bridges in similar narrow-space curved bridge sections.

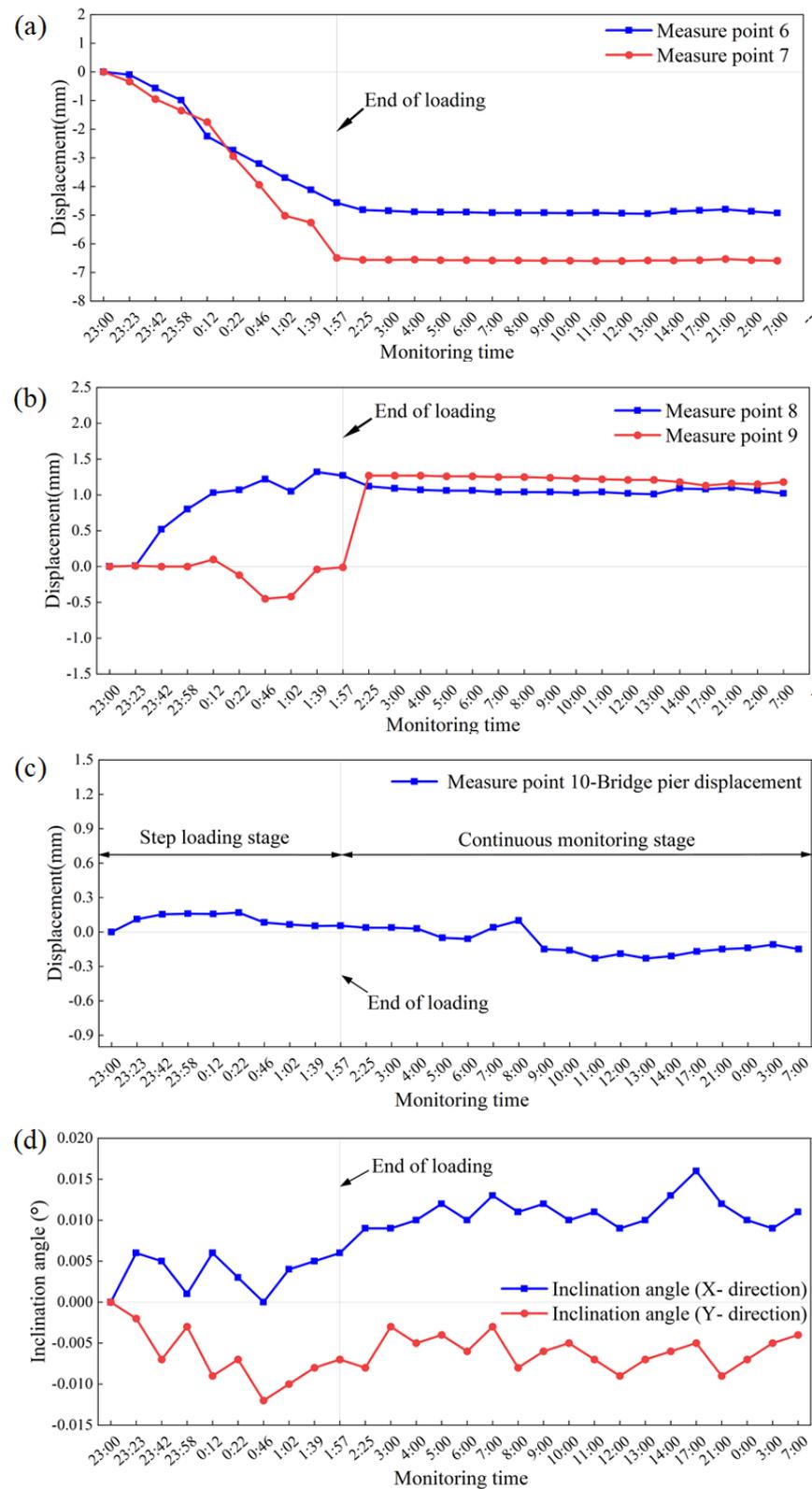


Figure 11. Displacement monitored during jacking-up stage: (a) displacement of new pile; (b) displacement of underpinning beam; (c) displacement of bridge pier; and (d) pier inclination.

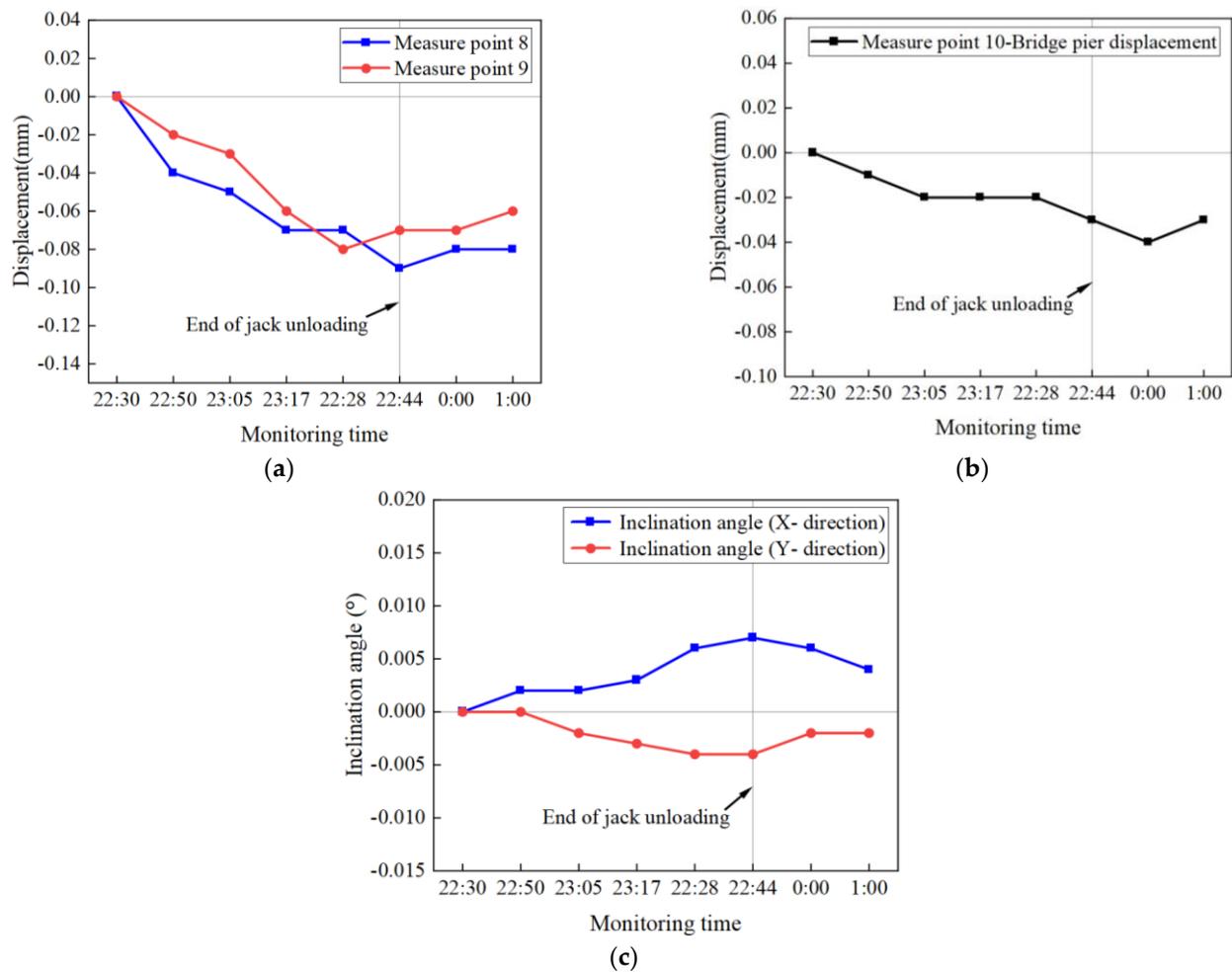


Figure 12. Displacement monitored during unloading stage: (a) displacement of underpinning beam; (b) displacement of bridge pier; and (c) pier inclination.

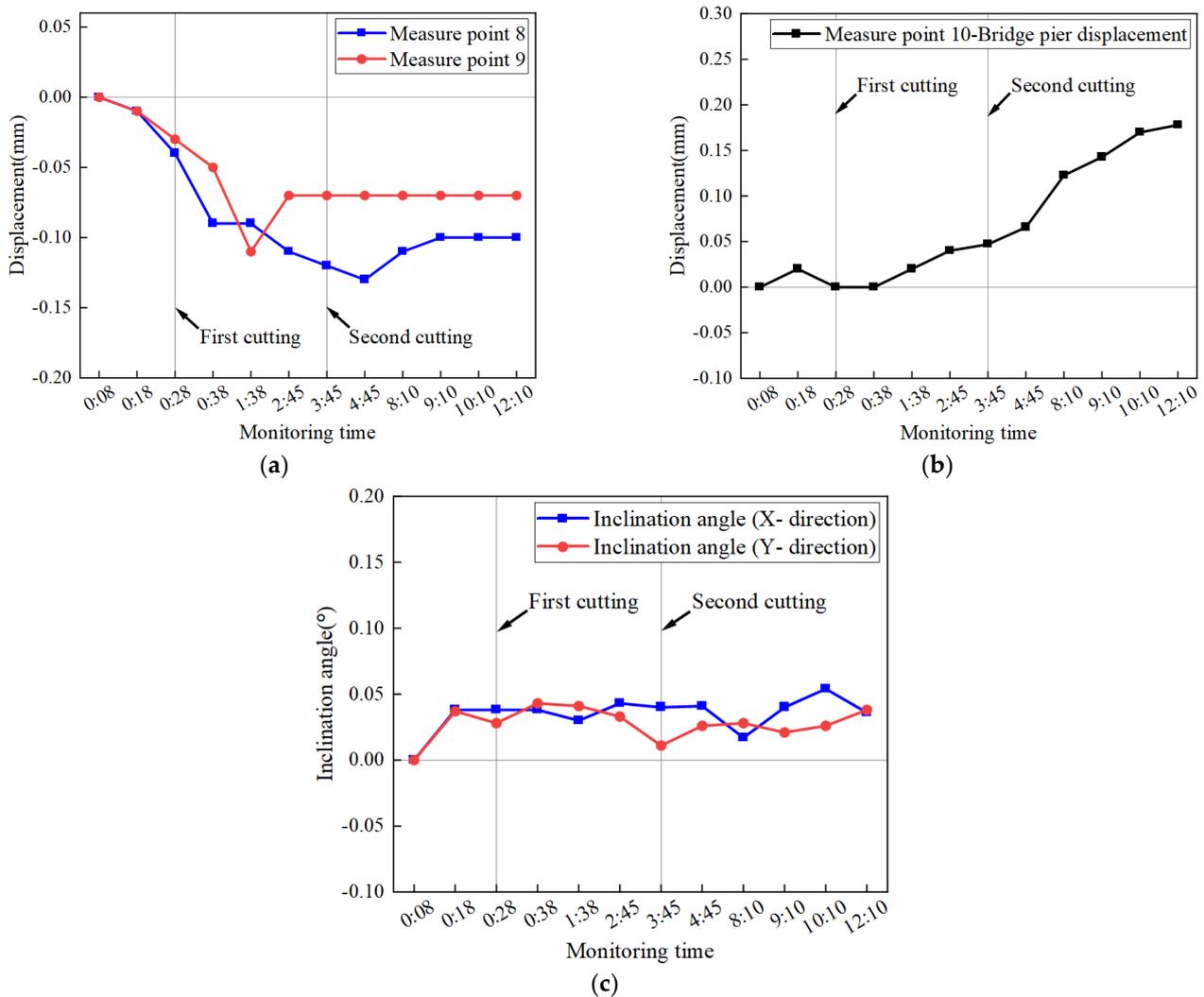


Figure 13. Displacement monitored during pile cutting stage: (a) displacement of underpinning beam; (b) displacement of bridge pier; and (c) pier inclination.

6. Conclusions

In this paper, the shield tunnel between Nanchang Metro No. 2 Hongguzhong Avenue Station and Yangming Park Station was taken as the engineering background, and an active gantry-type bridge pile foundation underpinning technology and its specific construction sequence were developed based on the technology comparison and analysis of in-situ engineering conditions. On this basis, for the C15 pile foundation with the most complex working conditions, ABAQUS finite element software was used to simulate the pile foundation's jacking, unloading and pile cutting process, and the displacement variation law of the bridge pier, underpinning beam and new pile during the whole construction process were analyzed. The application of this newly proposed technology was verified through the analysis of the practical construction process on-site monitoring data, and the following main conclusions were drawn:

- (1) It can be seen from the changing trend of the displacement of the new piles through numerical simulation that were the same as the bridge pier and the underpinning beam, that there is a relatively stable growth of the displacement in the first five times of jacking, and after the 6th jacking, especially at the new pile near the old pile side, the settlement value in the last jacking was increased by 40% compared with the previous one. The maximum settlement value of the new pile on the side away from the old pile was 2.12 mm, while the maximum settlement value of the new pile was

- 3.48 mm, which reached the early warning value during monitoring, but did not reach the control value; thus, the focus should be on monitoring the settlement changes of the new piles near the old piles during the jacking process of the jack underpinning the pile foundation;
- (2) When the jack was unloaded in the numerical simulation, the piers, underpinning beams and new piles had relatively stable displacement changes. In the actual monitoring data, the same displacement change was within the safe range. When the old piles were cut off, there was no sudden change in the displacement of the bridge piers, underpinning beams and new piles, which proved that the pile foundation underpinning construction scheme is reasonable and feasible. In the actual monitoring of the pile cutting stage, there was no displacement exceeding the early warning value in the two cutting-off old piles;
 - (3) In the monitoring of the two piles, the displacement of the bridge piers had an upward trend. This is because in the jacking stage, due to the existence of the old piles, the jacking force will generate prestress between the old piles and the bridge piers. When the old piles are cut off, the stress is gradually released, resulting in an increase in the displacement of the bridge piers. The displacement tends to be stable, and the magnitude of the change is also within a safe range. The above phenomena indicate more attention should be paid to the monitoring of the substructure of the bridge during the pile-cutting stage;
 - (4) According to the analysis of the monitoring results of the bridge piers, underpinning beams and new piles, the data calculated by the finite element software were roughly the same as the monitoring trend. The main structure of the lower part of the bridge did not have a large displacement, indicating that the finite element calculation results are credible.

However, it should be noted that the above conclusions are case-based findings, which are directly related to the engineering conditions. The shield tunnelling parameters and the underpinning schemes should be evaluated and optimized according to the actual engineering conditions of certain cases when the proposed active gantry bridge pile foundation underpinning technology is adopted.

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References

1. Xiao, C.; Yang, Y.; Chi, G. Subway development and obesity: Evidence from China. *J. Transp. Health* **2021**, *21*, 101065. [[CrossRef](#)]
2. Ding, L.; Jie, X.U. A review of metro construction in China: Organization, market, cost, safety and schedule. *Front. Eng. Manag.* **2017**, *16*, 4–19. [[CrossRef](#)]
3. Wang, T.; Tan, L.; Xie, S.; Ma, B. Development and applications of common utility tunnels in China. *Tunn. Undergr. Space Technol.* **2018**, *76*, 92–106. [[CrossRef](#)]
4. Chang, X.S. Underground Tunnel Development Survey of Shield Tunnelling Machine. *Adv. Mater. Res.* **2011**, 299–300, 1111–1114. [[CrossRef](#)]
5. Koyama, Y. Present status and technology of shield tunneling method in Japan. *Tunn. Undergr. Space Technol.* **2003**, *18*, 145–159. [[CrossRef](#)]

6. Mao, J.-H.; Yuan, D.-J.; Jin, D.-L.; Zeng, J.-F. Optimization and application of backfill grouting material for submarine tunnel. *Constr. Build. Mater.* **2020**, *265*, 120281. [[CrossRef](#)]
7. Cao, L.; Kalinski, M. Risk Analysis of Subway Shield Tunneling. In *Geo-Risk 2017*; The American Society of Civil Engineers: Reston, VA, USA, 2017; pp. 309–319.
8. Liu, C.; Li, J.; Zhang, Z.; Li, P.; Cui, J.; Liu, H.; Yang, Y. Model tests on tail-grouting process during URUP shield tunneling in soft soil. *Tunn. Undergr. Space Technol.* **2020**, *103*, 103451. [[CrossRef](#)]
9. Hajjar, M.; Hayati, A.N.; Ahmadi, M.M.; Sadrnejad, S.A. Longitudinal Settlement Profile in Shallow Tunnels in Drained Conditions. *Int. J. Geomech.* **2015**, *15*, 04014097. [[CrossRef](#)]
10. Fagnoli, V.; Boldini, D.; Amorosi, A. TBM tunnelling-induced settlements in coarse-grained soils: The case of the new Milan underground line 5. *Tunn. Undergr. Space Technol.* **2013**, *38*, 336–347. [[CrossRef](#)]
11. Loganathan, N.; Poulos, H.G.; Stewart, D.P. Centrifuge model testing of tunnelling-induced ground and pile deformations. *Géotechnique* **2000**, *50*, 283–294. [[CrossRef](#)]
12. Wu, C.; Zhu, Z. Analytical Method for Evaluating the Ground Surface Settlement Caused by Tail Void Grouting Pressure in Shield Tunnel Construction. *Adv. Civ. Eng.* **2018**, *2018*, 3729143. [[CrossRef](#)]
13. Xie, X.; Yang, Y.; Ji, M. Analysis of ground surface settlement induced by the construction of a large-diameter shield-driven tunnel in Shanghai, China. *Tunn. Undergr. Space Technol.* **2016**, *51*, 120–132. [[CrossRef](#)]
14. Li, X.-G.; Chen, X.-S. Using Grouting of Shield Tunneling to Reduce Settlements of Overlying Tunnels: Case Study in Shenzhen Metro Construction. *J. Constr. Eng. Manag.* **2012**, *138*, 574–584. [[CrossRef](#)]
15. Mirhabibi, A.; Soroush, A. Effects of surface buildings on twin tunnelling-induced ground settlements. *Tunn. Undergr. Space Technol.* **2012**, *29*, 40–51. [[CrossRef](#)]
16. Li, Z.; Chen, Z.; Wang, L.; Zeng, Z.; Gu, D. Numerical simulation and analysis of the pile underpinning technology used in shield tunnel crossings on bridge pile foundations. *Undergr. Space* **2021**, *6*, 396–408. [[CrossRef](#)]
17. Zhang, K.; Chavez Torres, J.L.; Zang, Z. Numerical Analysis of Pipelines Settlement Induced by Tunneling. *Adv. Civ. Eng.* **2019**, *2019*, 4761904. [[CrossRef](#)]
18. Lin, C.-G.; Zhang, Z.-M.; Wu, S.-M.; Yu, F. Key techniques and important issues for slurry shield under-passing embankments: A case study of Hangzhou Qiantang River Tunnel. *Tunn. Undergr. Space Technol.* **2013**, *38*, 306–325. [[CrossRef](#)]
19. Wang, N.; Jiang, Y.; Geng, D.; Huang, Z.; Ding, H. Numerical Investigation of the Combined Influence of Shield Tunneling and Pile Cutting on Underpinning Piles. *Front. Earth Sci.* **2022**, *10*, 896634. [[CrossRef](#)]
20. Zumsteg, R.; Langmaack, L. Mechanized Tunneling in Soft Soils: Choice of Excavation Mode and Application of Soil-Conditioning Additives in Glacial Deposits. *Engineering* **2017**, *3*, 863–870. [[CrossRef](#)]
21. Soomro, M.A.; Ng, C.W.W.; Liu, K.; Memon, N.A. Pile responses to side-by-side twin tunnelling in stiff clay: Effects of different tunnel depths relative to pile. *Comput. Geotech.* **2017**, *84*, 101–116. [[CrossRef](#)]
22. Xu, Q.; Zhu, H.; Ma, X.; Ma, Z.; Li, X.; Tang, Z.; Zhuo, K. A case history of shield tunnel crossing through group pile foundation of a road bridge with pile underpinning technologies in Shanghai. *Tunn. Undergr. Space Technol.* **2015**, *45*, 20–33. [[CrossRef](#)]
23. Yan, L.; Wang, G.; Chen, M.; Yue, K.; Li, Q. Experimental and Application Study on Underpinning Engineering of Bridge Pile Foundation. *Adv. Civ. Eng.* **2018**, *2018*, 5758325. [[CrossRef](#)]
24. Liu, C.; Zhang, Z.; Regueiro, R.A. Pile and pile group response to tunnelling using a large diameter slurry shield—Case study in Shanghai. *Comput. Geotech.* **2014**, *59*, 21–43. [[CrossRef](#)]
25. Stulgis, R.P.; Barry, B.E.; Francis, S.; Harvey, J. Foundation Underpinning with Mini-Piles: “A First” in Guyana, South America. In Proceedings of the GeoSupport Conference 2004, Orlando, FL, USA, 29–31 December 2004; pp. 700–711.
26. Ma, L.; Wang, J. Technology of Pile Foundation Underpinning in Shield Tunnel of Xi’an Subway. *Appl. Mech. Mater.* **2012**, *204–208*, 1445–1448. [[CrossRef](#)]
27. Yao, A.; Yang, X.; Dong, L. Numerical Analysis of the Influence of Isolation Piles in Metro Tunnel Construction of Adjacent Buildings. *Procedia Earth Planet. Sci.* **2012**, *5*, 150–154. [[CrossRef](#)]
28. Park, Y.-H.; Kim, J.-P.; Cho, K.-H. Stability analysis of subway box structure supported by modified underpinning method. *Tunn. Undergr. Space Technol.* **2015**, *50*, 199–208. [[CrossRef](#)]
29. Wang, F.; Yuan, D.; Cai, R.; Mu, Y.; Wang, M. Field Test Study on Cutting Obstacle Piles Directly by Shield Cutters. *Appl. Mech. Mater.* **2013**, *353–356*, 1433–1439. [[CrossRef](#)]
30. Peng, F.; Ma, S.; Li, M.; Fu, K. Stress Performance Evaluation of Shield Machine Cutter Head during Cutting Piles under Masonry Structures. *Adv. Civ. Eng.* **2022**, *2022*, 4111637. [[CrossRef](#)]
31. Fu, D.-M. Model Test on Concrete Cutting Directly by Shield and Pile Foundation Cutting Technology. *Tunn. Constr.* **2014**, *34*, 472–477.
32. Chen, H.-F.; Yuan, D.-J.; Wang, F.; Wang, M.-S. Study on shield cutting parameters when cutting big diameter piles. *China Civ. Eng. J.* **2016**, *49*, 103–109. (In Chinese)

33. Yuan, D.-J.; Wang, F.; Dong, C.-W.; Han, B.; Wang, M.-S. Study on New-style Cutter for Shield Cutting Large-diameter Reinforced Concrete Pile. *China J. Highw. Transp.* **2016**, *29*, 89–97.
34. Institute CHPaD. *General Code for Design of Highway Bridges and Culverts*; People's Transportation Press; China Communications Press: Beijing, China, 2015.

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