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Research Article

Bridge Responses Induced by Adjacent Subway Station Construction Using Shallow Tunneling Method

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This paper presents a case of subway station construction under an existing prestressed concrete bridge with a three-span continuous beam located at the intersection of the 3rd Ring Road, Beijing. The Huayuan Subway Station of line 6, constructed crossing between #7 and the #8 piers of the bridge by the shallow tunneling method, is approximately perpendicular to the existing Huayuan Bridge. The minimum horizontal distance between the pile foundation and the subway station is only 0.08 m. The "Pile-Beam-Arc" construction sequence was used to ensure the safety of both the subway station and the bridge. Moreover, a series of reinforcement measures were adopted to safeguard the project, including deep grouting reinforcement surrounding the pile foundation from ground surface, temporary inverted arch in the middle of No. 5 drift, and the lateral steel support. Even though some cracks were observed on the bridge deck surface by the on-site deformation monitoring, the results were still within the proposed control standard. To prevent the further development of the cracks, jacking protection measure and bonded steel constructed under the box girder were performed. The related measures proposed in this research can provide useful references for future similar projects.

1. Introduction

With the development of public transportation in congested urban areas, more subway stations and tunnels are constructed adjacent to existing infrastructures. Especially in big cities, a large number of municipal bridges are inevitably influenced by adjacent subway construction. One of the big issues of this kind of project is to ensure the safety of the existing bridge and the new underground structure.

Ground movements and loss of pile bearing capacity may happen when tunneling adjacent to piles and also due to the results of deformations of adjacent pile foundations and more damages. Therefore, attentions should be paid to tunneling adjacent to existing pile foundations. The pile or pile groups' responses caused by adjacent tunneling have been extensively studied by theoretical analysis, physical modelling, numerical modelling, and field observation in recent years. The physical modelling tests (Morton and King [1]; Bezuijen and Schrier [2]; Lognathan et al. [3], Yu et al. [4], and Zhu et al. [5]) and three-dimensional numerical analysis (Poulos and Davis [6]; Chow et al. [7]; Loganathan et al. [8]; Cheng et al. [9]; Emilios and Spyridoula [10]; Lee and Ng [11]; Lee and Jacobsz [12]; Soomro et al. [13]; Li and Shao [14]; Xiang et al. [15], Luo et al. [16], and Ma et al. [17]) were conducted to investigate the effects of the tunnel excavation on the different types of pile foundations which can conclude the presence of an existing pile settlement and horizontal displacement, owing to its stiffness and stability which are further influenced by its frictional resistance at the soil-pile interface. Furthermore, Cheng et al. [9], Su [18], and Zhou and Su [19] presented the influence area partition of pile due to the different spatial positional relationship, which has been utilized in many projects.

Recently, several existing structures crossed by tunneling were researched, including buildings, bridges, and pipelines,

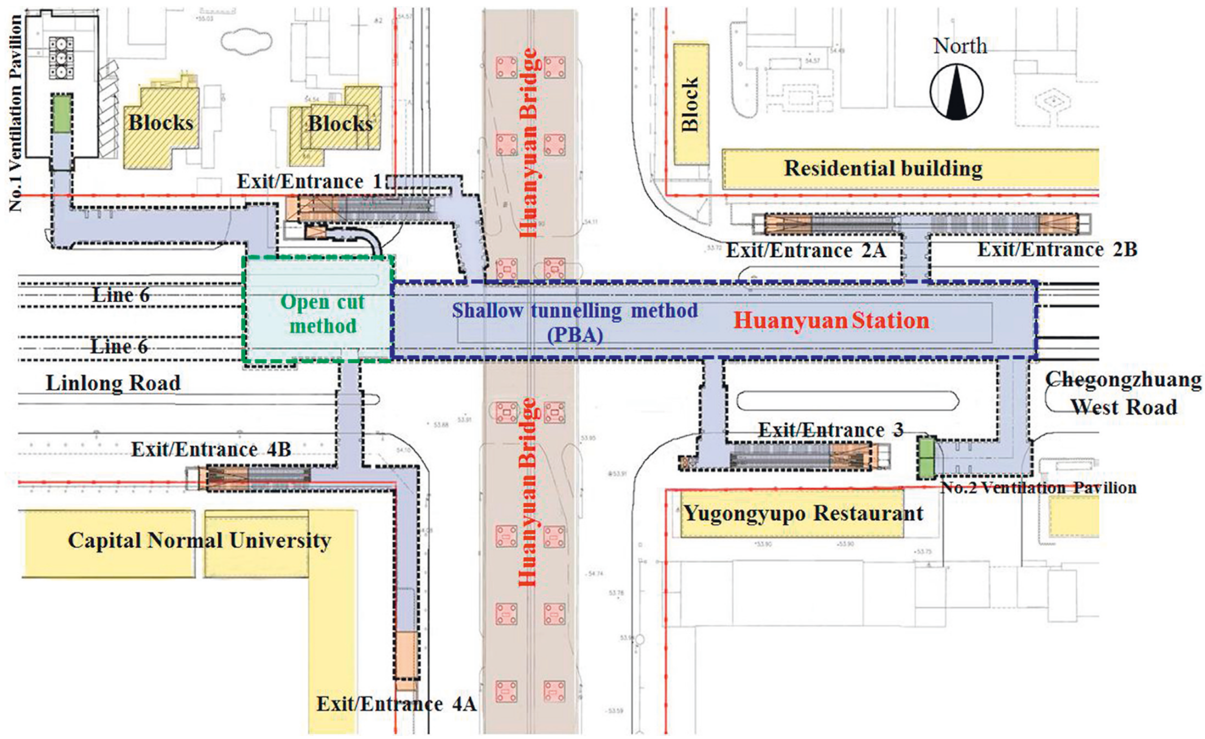


Figure 1: Plan view.

and all of them have similar deformation mechanism. Fu et al. [20] reported the ground and existing building response due to the construction of a sprayed concrete lining (SCL) subway twin tunnel in Shenzhen. Liu et al. [21] investigated the disturbance to piles and pile groups caused by multiple nearby drives of a large diameter slurry shield-driven tunneling machine in Shanghai. Zhang [22] described a systematic approach for existing building safety adjacent to twin tunnel excavation. Hou et al. [23] analyzed the pipeline damage during shallow tunneling. Qian et al. [24–26] studied the effects of existing tunnel due to new tunnel excavation. Besides, some specific reinforcement measures to reduce the impact of existing structures, especially existing bridges due to adjacent tunneling, have been developed, such as underpinning (Deb [27] and Xu et al. [28]), composite bolt pile (Lv and Liu [29]), and grouting reinforcement (Li et al. [30] and Qiu et al. [31]) during underground infrastructures construction. These papers illustrated the causes and influence degree for existing structures, even the control measures.

The previous literatures reveal that valuable insight could be gained from both numerical and physical modelling. The shield method or small cross-sectional excavation was used mostly in previous researches to document the response and control on tunnel excavation adjacent to existing structures. Moreover, all of the reinforcement measures mentioned above were the existing common measures. However, the jacking application for protection of the existing bridge was seldom reported.

This paper investigated the response and safety control schemes of an existing bridge due to nearby subway station construction. The main procedures are listed as following. Firstly, the existing bridge and subway construction method and geology and hydrogeology conditions are described and demonstrated. After the control index and standard value determination, FLAC3D numerical analysis of the tunneling-soil-pile interaction was utilized to expound the effect of the reinforcement measures in line with the real project. Due to the uncertainties of the underground engineering and the complexities of the urban underground environment, the monitoring and feedback in combination with reasonable control measures were described during construction. In particular, the active jacking was used as emergency plan to protect the bridge safety for the first time in this project. Finally, this project of subway station construction crossing to existing bridge in urban are successful and representative. The safety control schemes as used in this case are widely used in similar projects in China and have been viewed as an effective solution to protect the safety of existing structures during tunnel construction. In addition, some suggestions are provided for engineers.

2. Project Overview

A plan view and a cross-sectional view of the relationship between the Huayuan Subway Station and the existing bridge are shown in Figures 1 and 2, respectively. The Huanyuan Subway Station with the total length of 233.6 m is located under the Linlong Road and the Chegongzhuang West Road on Line 6 of the Beijing subway. The west part of the station, with the length of 43.6 m, was excavated by the open cut method. The shallow tunneling method (Qian et al. [24]) using the "pile-beam-arch" approach was used

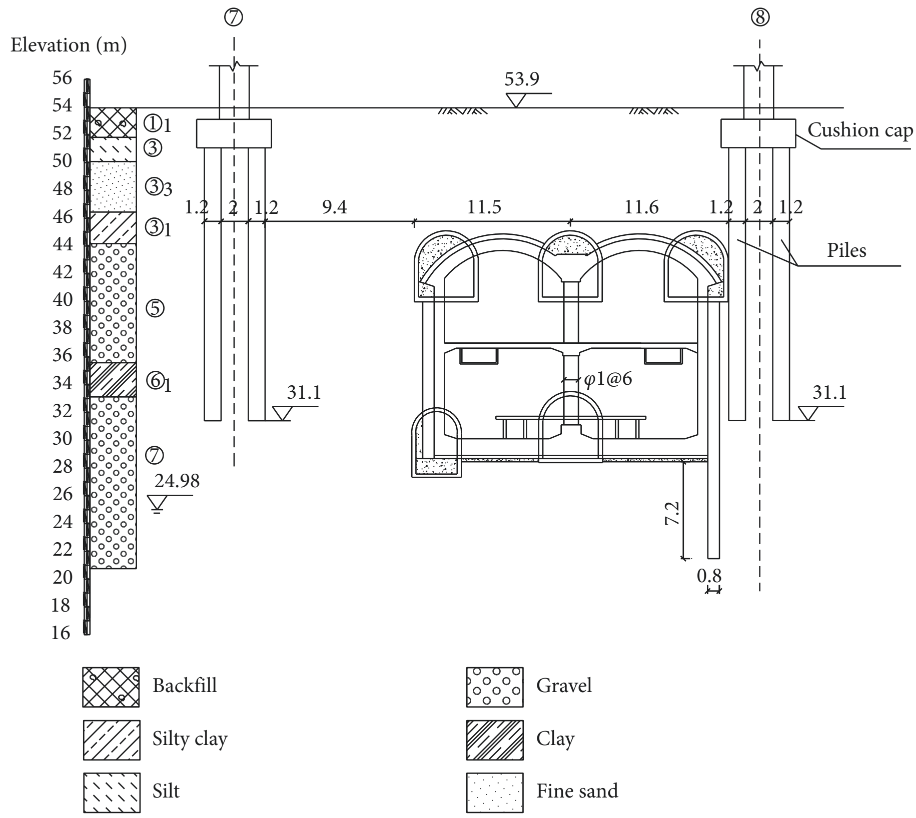
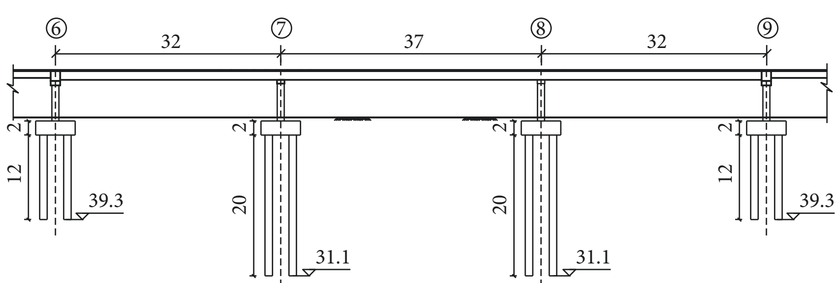
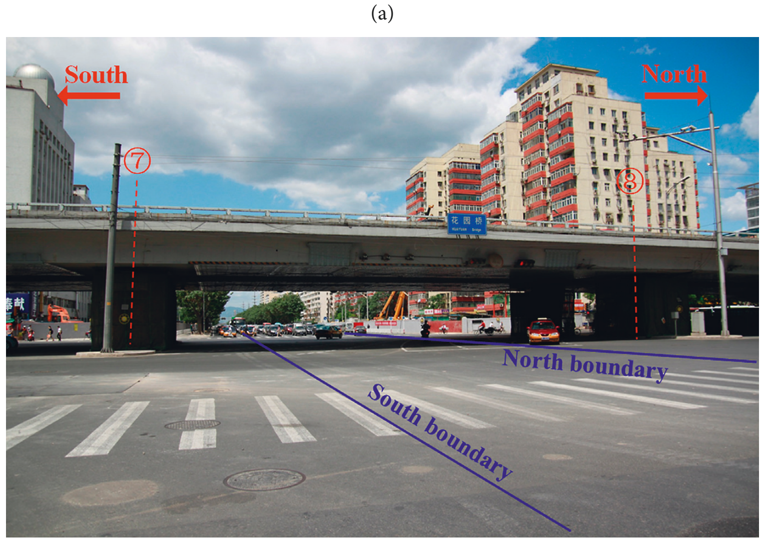


Figure 2: Cross-sectional view (unit: m).

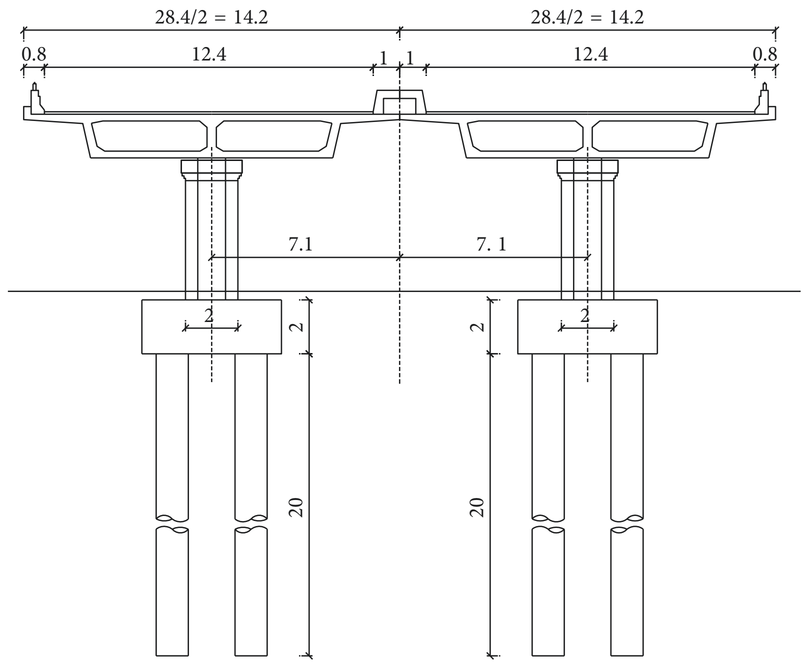


(a)



(b)

Figure 3: Continued.



(c)

Figure 3: Huayuan Bridge. (a) Side view (unit: m). (b) Photograph. (c) Cross section (unit: m).

Table 1: Physical and mechanical properties of soil.

	Bulk density (kg/m^3)	Coefficient of earth pressure	Cohesion (kPa)	Friction angle (°)	Compression modulus (MPa)
Backfill	1600		15	10	5.65
Silt	1890	0.43	11.67	15.5	8.78
Fine sand	2000	0.38	0	32	23
Silt clay	1990	0.49	25.75	13.38	6.49
Gravel	2150	0.25	0	46	65
Clay	1910	0.5	32	14.7	10.82
Gravel	2150	0.23	0	46	

for the excavation for the rest part of the subway station. The subway station, constructed between the 7th and the 8th piers of the bridge, is perpendicular to the existing Huayuan Bridge in the plan. The minimum horizontal clearance between the station and the bridge pier is only 0.08 m. And the overburden depth of the subway station centerline is about 8.7 m. As usual, the composite lining includes primary lining and the secondary lining, and the waterproof sandwiched between them was used in this project.

The Huayuan main bridge, constructed in 1994, is located at a busy transport hub (interchange of the 3rd Ring Road and Chegongzhuang West Road). As shown in Figure 3, the superstructure of the bridge is prestressed concrete of continuous single box and double-cell box girder with three spans (32 m + 37 m + 32 m). The transverse of the full bridge, which is 28.3 m width, is divided into two widths. The substructure of the bridge is a single pier with four 1.2 m diameter and 20 m long piles spaced at 3.2 m for #7 pier and #8 pier.

A typical geological profile of the project is shown in Figure 2. The overburden soil of the subway station is amalgamation of backfill, silt, fine sand, and silt clay. The arch top of main station structure is mainly located at silt clay. The middle and bottom part are located at gravel, clay, and gravel, respectively. The profile reveals that the new subway station is mainly located in gravel. The corresponding soil physical and mechanical properties are shown in Table 1.

At the beginning, the main subway structure construction was far away from the existing bridge, and the six-drift mining method was used in this period. However, when the subway station entered into the bridge area, the mining method had been changed to five-drift plus isolation pile. The brief construction steps are shown in Figure 4. The construction timeline is shown in Table 2. The lower drifts were excavated prior to the upper drifts. Then, side piles, which were closed to the #8 pier, were stretched under the pile tip up to 7.2 m. After king-pile construction, the earthworks of the station hall and the platform including

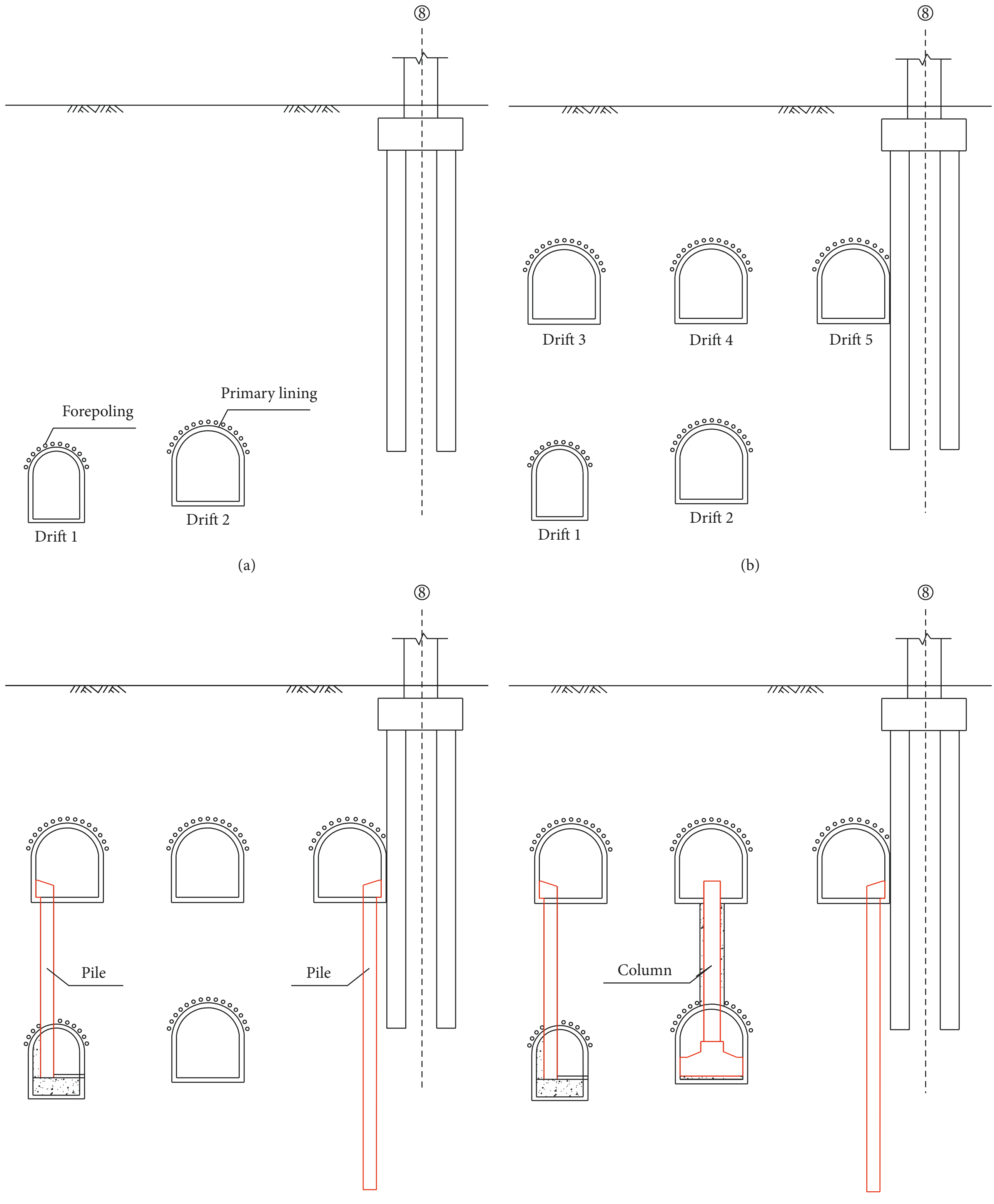


FIGURE 4: Continued.

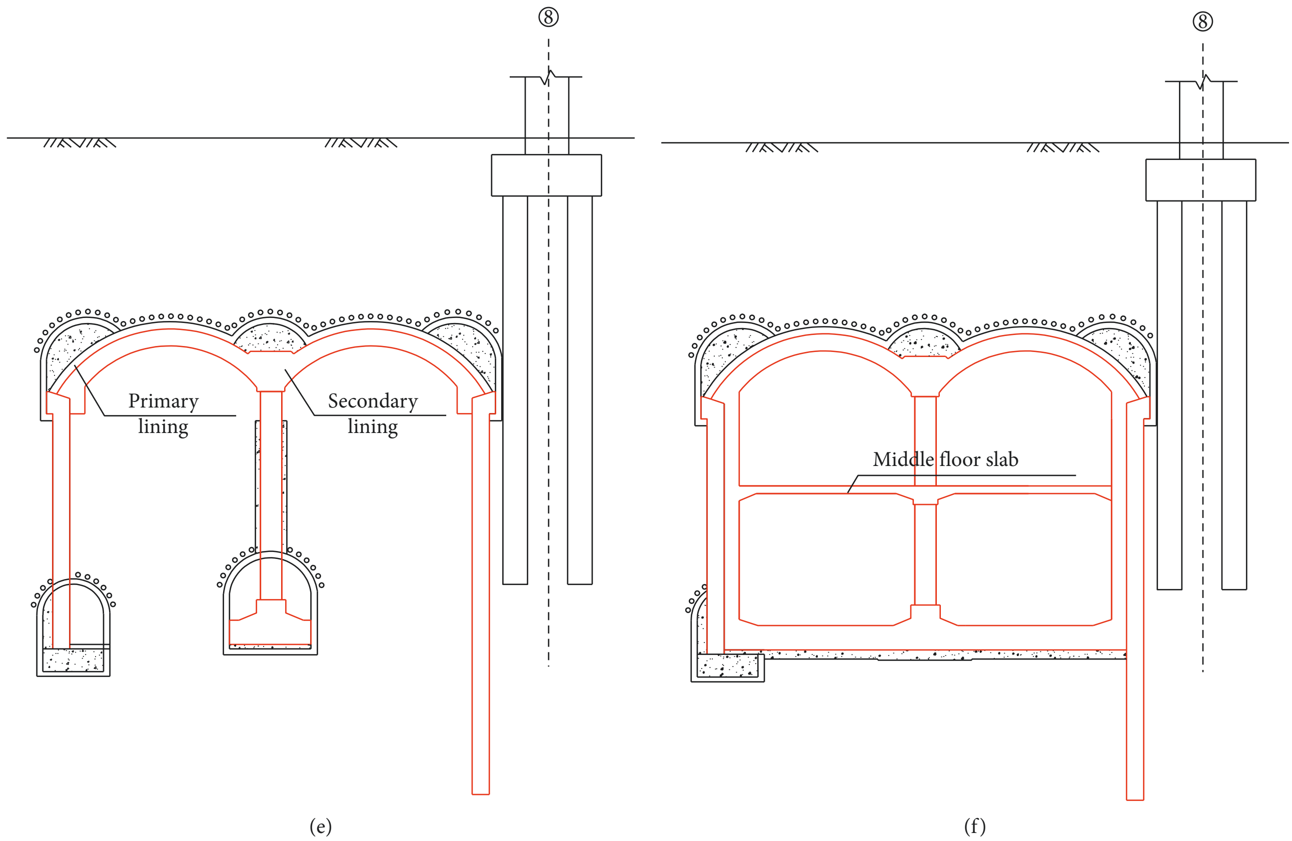


Figure 4: Construction process. (a) Step 1. (b) Step 2. (c) Step 3. (d) Step 4. (e) Step 6. (f) Step 6.

Table 2: Construction timeline.

Construction stage	Start date–end date
Nos. 1 and 2 drift cross bridge	2010.10.17–2010.11.20
Nos. 3 and 4 drift cross bridge	2010.11.17–2010.12.20
Construction suspended	2010.12.21–2011.7.3
Jacking for the first time	2011.7.4
Jacking for the second time	2011.7.17
No. 5 drift cross bridge	2011.7.18–2011.8.9
Arch construction	2011.8.9–2011.9.14
Station concourse completion	2011.9.10–2011.11.21
Station platform completion	2011.11.23–2012.1.6

primary lining and the secondary lining was excavated and constructed one after another.

3. Bridge Safety Criteria

The subway station excavation might cause differential settlement and horizontal displacement for bridge, which were of a great influence on the bridge security.

Considering the Huayuan Bridge is a statically indeterminate structure, additional internal forces would be applied to the bridge superstructure when the differential settlement of the pier occurs. Due to the superposition of internal forces and additional internal forces, the internal forces in a cross section may exceed the bridge bearing capacity structure and cause damage. In addition, due to single pier structure, the bridge structure may be overturning in the lateral to cause box girder damage. Therefore, the differential settlement and horizontal displacement of the caps and pier are the main control indexes for existing bridges. Besides, the soil is the deformation transfer carrier, so the excessive stratum settlement is not allowed. For all of the existing structures, the stratum settlement is another important control index.

Based on the detection results and the *Technical Code of Maintenance for City Bridge* (CJJ99-2003) [32], the safety grade of the bridge was B. It means that the bridge with some defects on the surface was virtually in good condition before construction. According to the design documents, the vertical differential settlement control value should be less than 5 mm, while the horizontal displacement of the pile foundation should be less than 4 mm in both directions. Besides, according to the *Technical Code for Monitoring Measurement of Subway Engineering* (DB11 490-2007) [33], the stratum settlement value is less than 60 mm. When the monitoring value reaches 60% of the controlling standard, monitoring frequency should be increased. When the monitoring value reaches 60%–80% of the controlling standard, the corresponding reinforcement measures should be adopted. When the monitoring value reaches 80% of the controlling standard, the constructing project should be stopped to take the emergency plan. However, some pipelines before station construction had been constructed. The

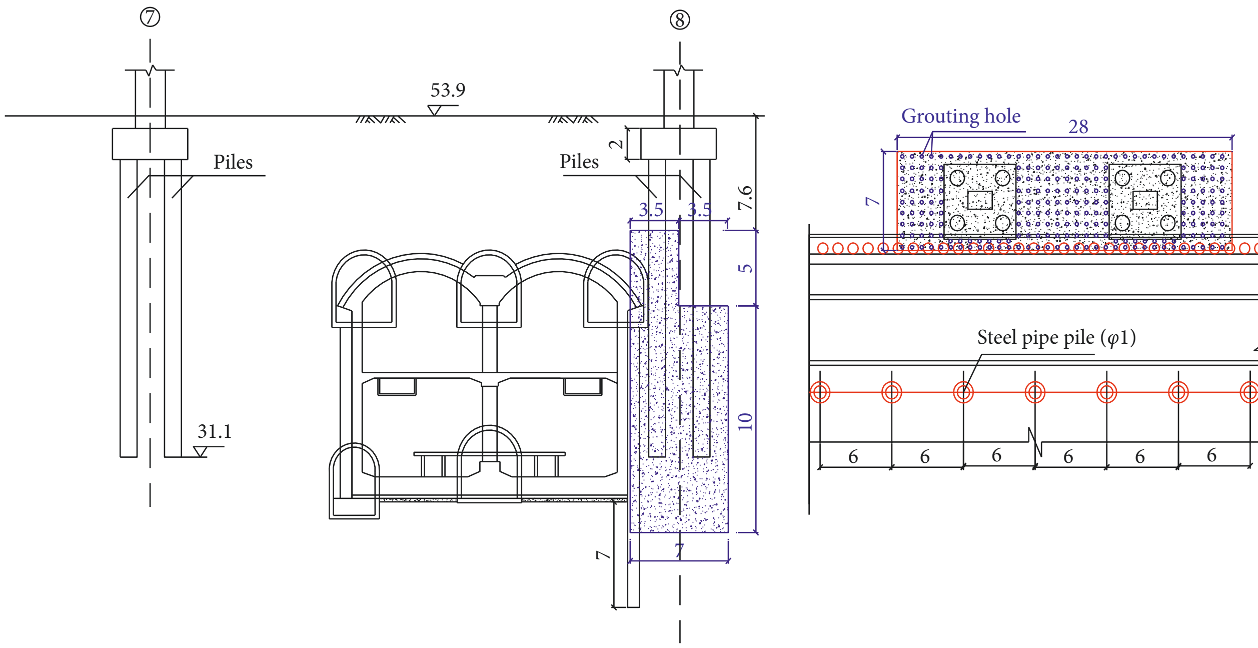


Figure 5: Grouting reinforcement measure (unit: m).

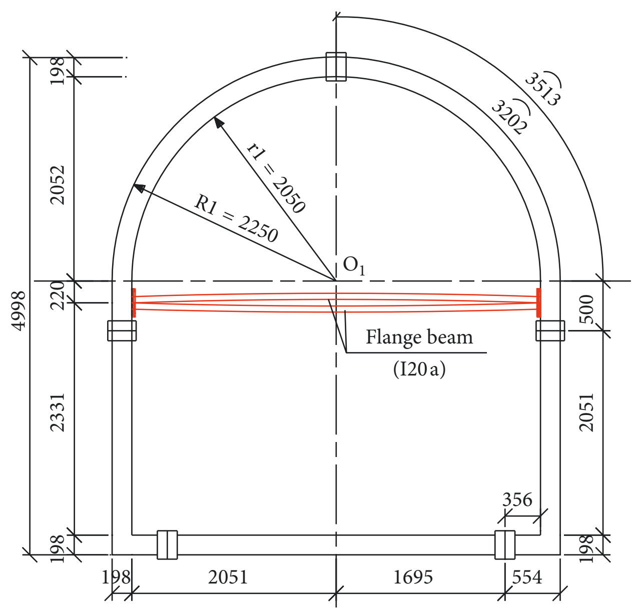


Figure 6: Temporary invert (unit: mm).

extracumulative settlement for the bridge structure should be paid attention.

4. Reinforcement Measures and Their Effectiveness

There were a series of common measurements, including the reasonable construction sequence, decreasing the excavation length, shorten the distance between two side piles, and deep grouting reinforcement surrounding the pile foundation from ground surface (Figure 5) during the construction. Besides, there was a temporary inverted arch in the middle of No. 5 drift to reduce the transverse displacement of the pile foundation (Figure 6). Meanwhile, the pile in No. 5 drift was extended below the station structure to form an isolation protection (Figure 7). And the lateral steel bracing was set in time during the main structures entered into the bridge area. The mechanical properties of the soils are shown in Table 1.

The FLAC3D (Fast Lagrangian Analysis of Continua in 3 Dimensions) numerical software was used to perform the numerical analysis. The FLAC3D can be operated in small or large strain mode. The large strain mode is adopted when the grid point (mesh) coordinates are updated at each

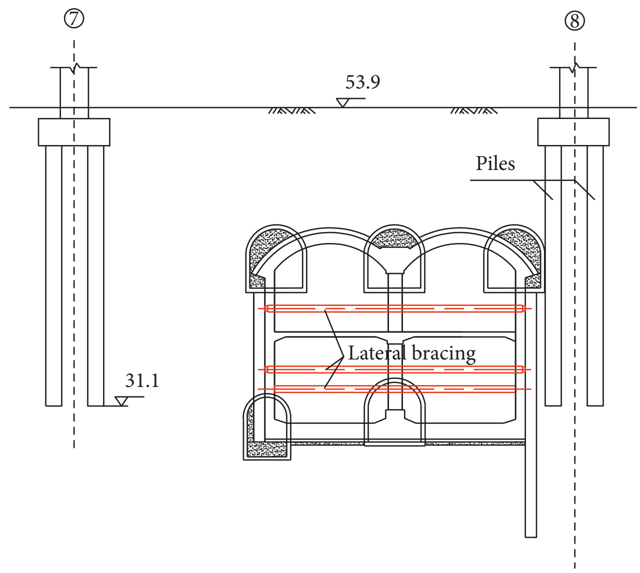


Figure 7: Lateral bracing and isolation pile (unit: m).

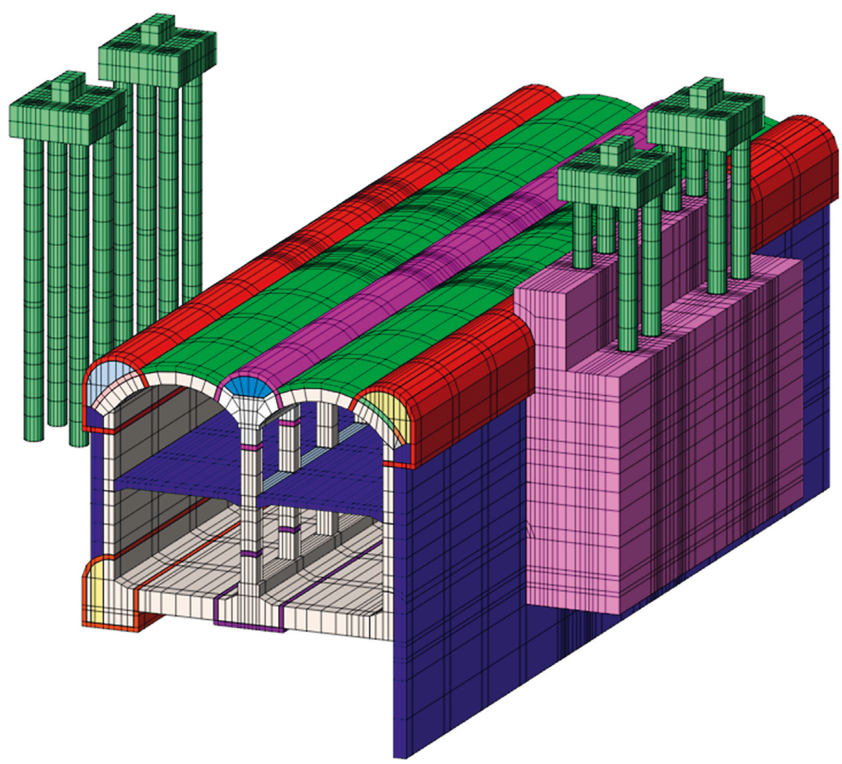


Figure 8: Numerical model.

strain or movement increment, according to the computed displacement. This is particularly important to the present study involving large soil movements. The model size is 100 × 80 × 60 m ($L \times W \times H$). The normal velocities of the grid points along the bottom, vertical, lateral, front, and back boundary planes are fixed to be zero. The actual geometry of subway station, reinforcement body, and pile foundation is modelled in the simulation (Figure 8). The mesh comprises of 18740 elements with 28747 nodes or grid points. The interface is used to simulate the soil-structure interaction. The superstructure weight and external load are applied on top of each cap. After the gravitational equilibrium is reached, the subway station excavation is carried out by removing the specific grid geometry.

The numerical simulation results of different construction stages are show in Figure 9. Notwithstanding the foregoing, due to the unpredictability and complexity of the construction, the bridge deformation may be beyond the

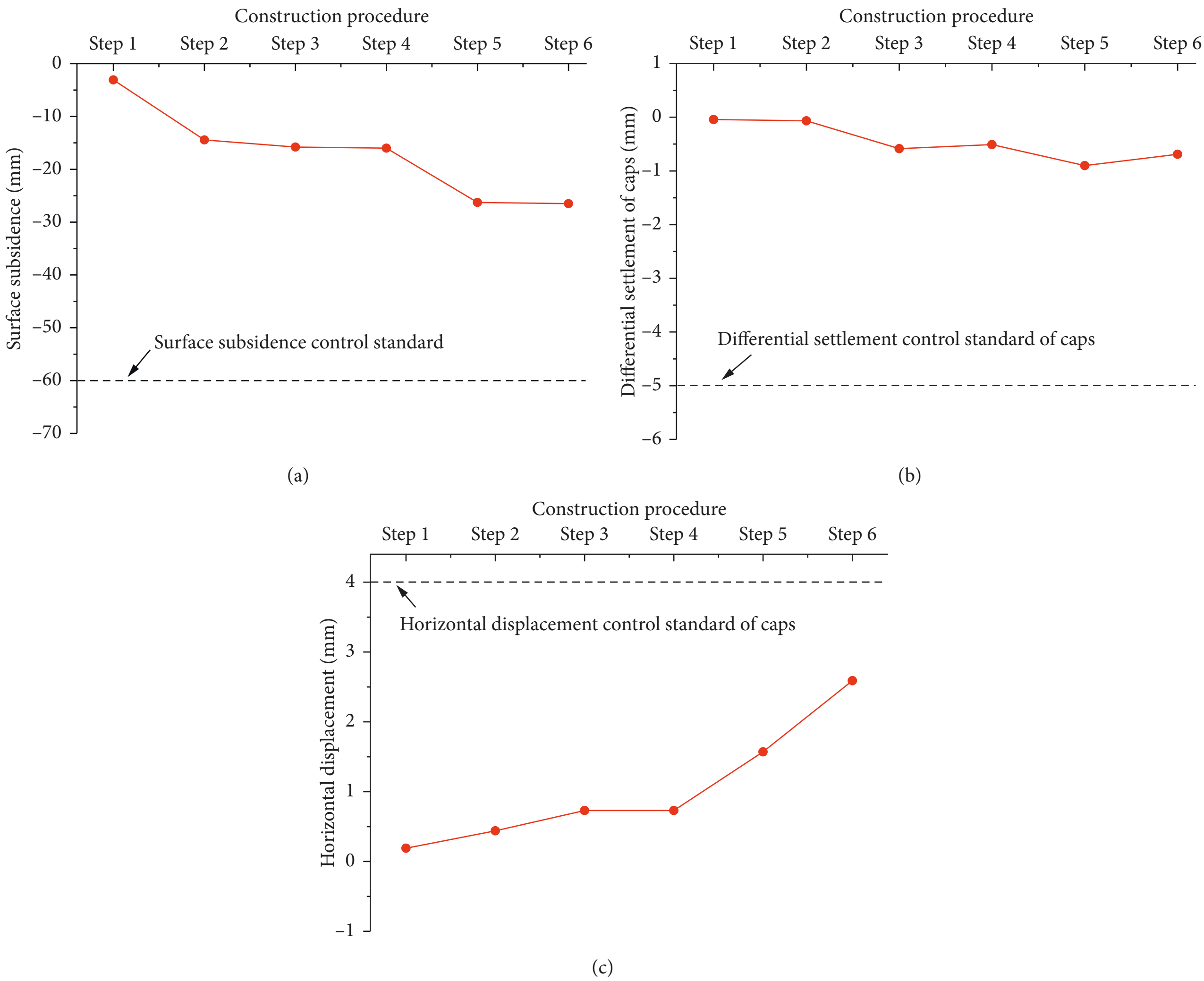


FIGURE 9: Calculation results. (a) Ground surface settlement. (b) Differential settlement of caps. (c) Horizontal displacement of cap.

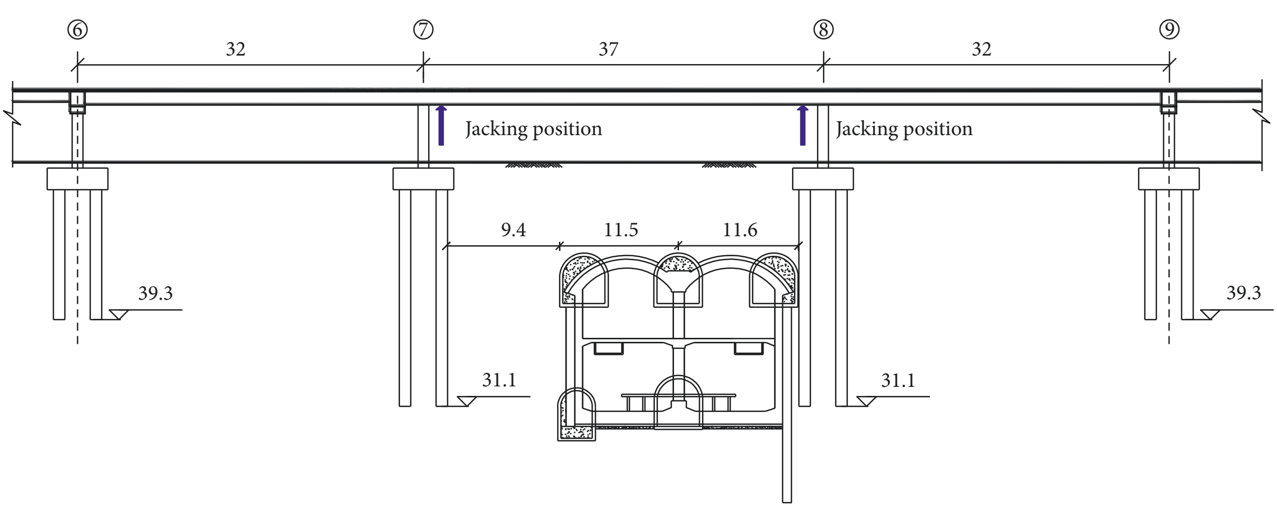


FIGURE 10: Jacking position schematic diagram (unit: m).

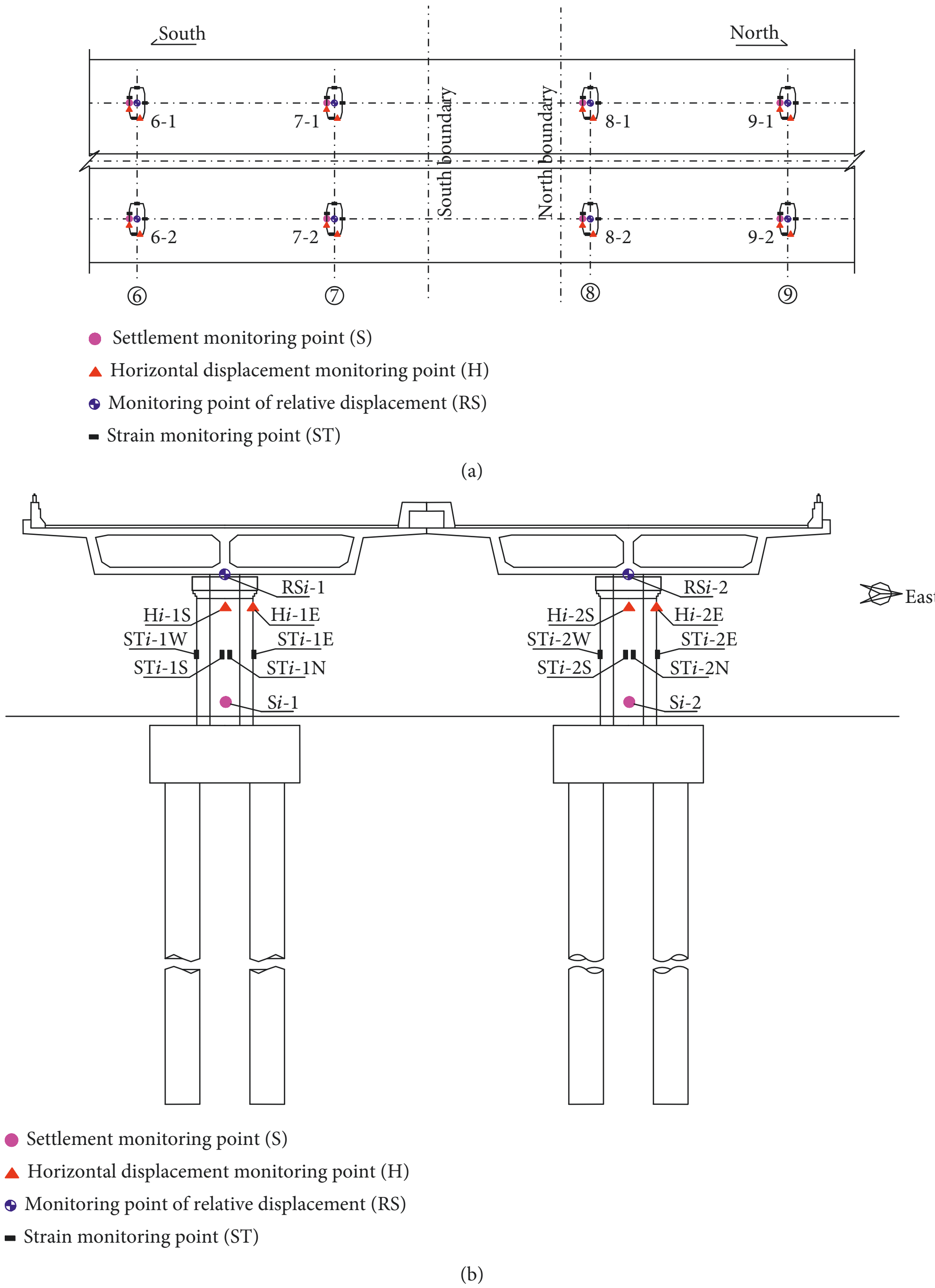


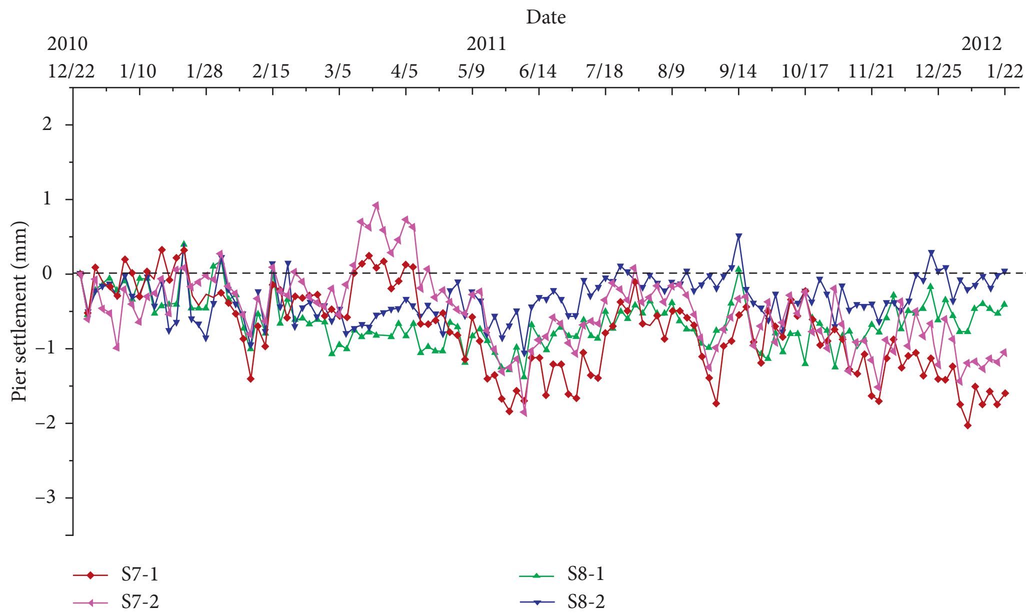
Figure 11: Layout of monitoring points. (a) Plan of monitoring points. (b) Monitoring points on piers (*i* stands for the axis ID).

standard. Therefore, the real-time data analysis and feedback under construction is important to figure out the problems and deal with them in time. The emergency plan can be carried out if needed.

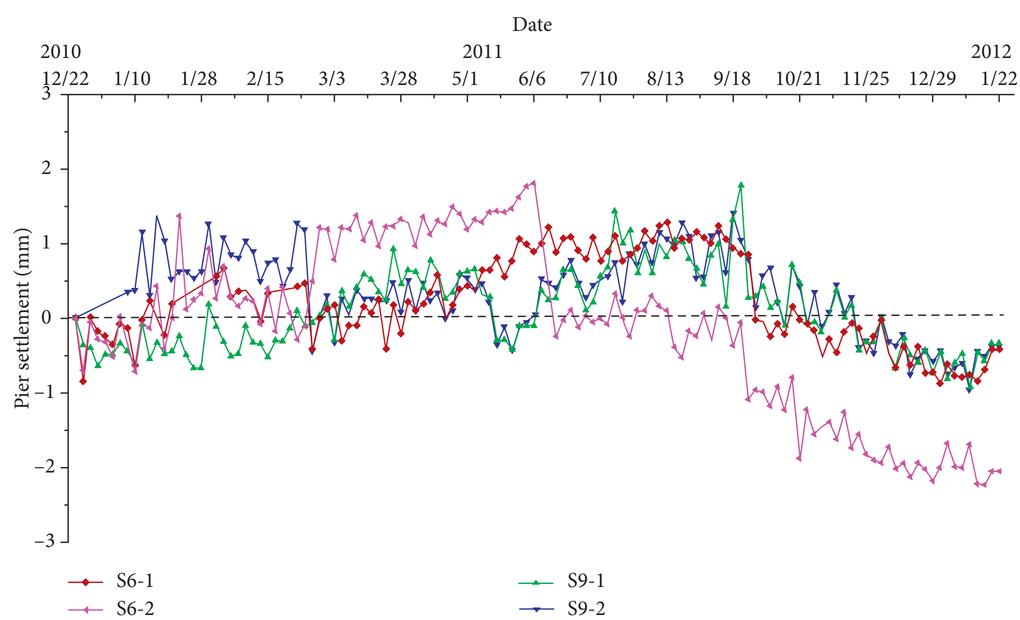
For Huayuan Bridge, the superstructure of the bridge is a prestressed concrete structure, so the crack development does not occur. When this risk occurs, the jacking method should be used to compensate the settlement and provide safety reserve. The jacking position of Huayuan Bridge is shown in Figure 10.

5. On-Site Monitoring

5.1. Layout of Monitoring Points. During the subway station construction, the common monitoring items including the pier settlement/tilt, the strain of the control section, and the crack development were monitored. During the bridge jacking process, the relative displacement between the bottom of the beam and the top of the pier was increased. All of the monitoring content is shown in Figure 11: (a) the layout of the monitoring points along #6~#9; (b) the



(a)



(b)

Figure 12: Settlement curve of pier: (a) S7 and S8; (b) S6 and S9.

monitoring points on the #8 cross section; and (c) the monitoring points of relative displacement. The crack open degree is done by manual observation. The first letters "S," "H," "T," and "ST" are settlement, horizontal displacement, tilt, and strain, respectively. And the first letter "W" or "E" of the monitoring point label indicated the monitoring point located at the west or east of the pier. The settlement and horizontal displacement were monitored with level and total station, respectively.

5.2. Monitoring Results of Bridge. The monitoring results (Figures 12 and 13) show that the deformation of the existing bridge did not exceed the control standard, when the drifts far away from #8 pier were excavated completely before the subway station entered into the existing bridge area. The maximum settlement was −0.97 mm at S8-1 pier. The maximum horizontal displacement was 0.6 mm. The maximum tilt was 0.37‰. The monitoring results were under the local standard value. Moreover, the numerical simulation can well reflect the mechanical responses associated with subway station excavation.

However, many transverse cracks (Figure 14) were found on the bridge deck which may be caused by axial tensile stress along the longitudinal direction. Therefore, the

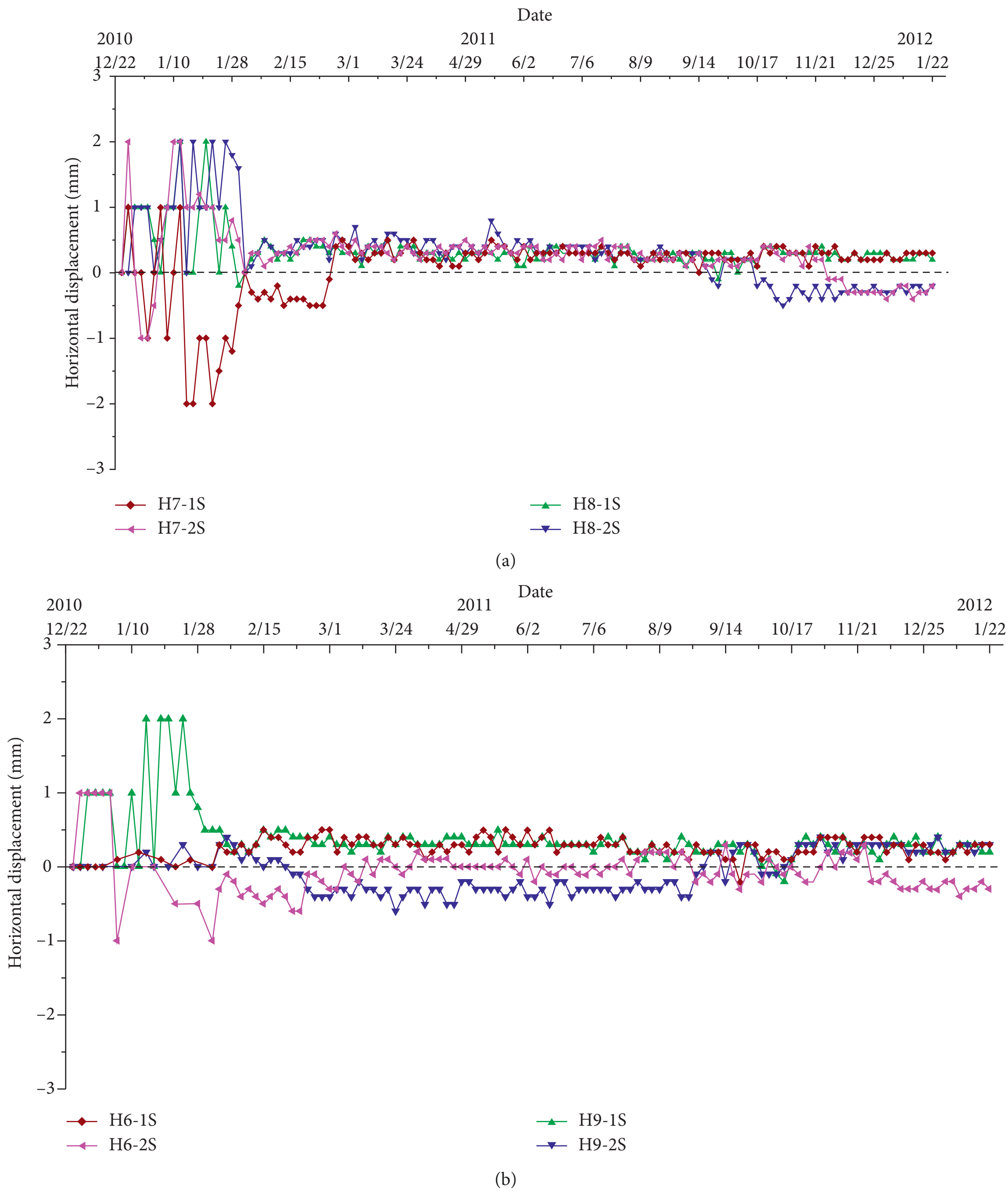


Figure 13: Horizontal displacement curve of pier: (a) S7 and S8; (b) S6 and S9.

positive jacking should be employed to prevent the development of cracks.

Although the reinforcement measures grouting and isolation, as well as the maximum settlement of the pier which is still in reasonable range, a small amount of cracks appeared. This phenomenon is representative during Beijing subway crossing overpass construction. It can be explained with severe reasons, listed as follows. (1) Because of heavy traffic, there was a long-term operation impact on the bridge. In addition, during the construction, the bridge was open to traffic. (2) The early cumulative value was not estimated accurately.

6. Jacking Measures

For the reasons above, the new emergency measure named as the bridge active jacking was proposed and used in this project (Figure 15). In this method, the superstructure and substructure are considered as two independent parts. (Based on control goal and the guarantee of the automated monitoring system, superstructure settlement was adjusted using hydraulic jacks controlled by the computer system to ensure structure safety in the whole jacking operation.) In this case, based on the elevation difference of the box girder

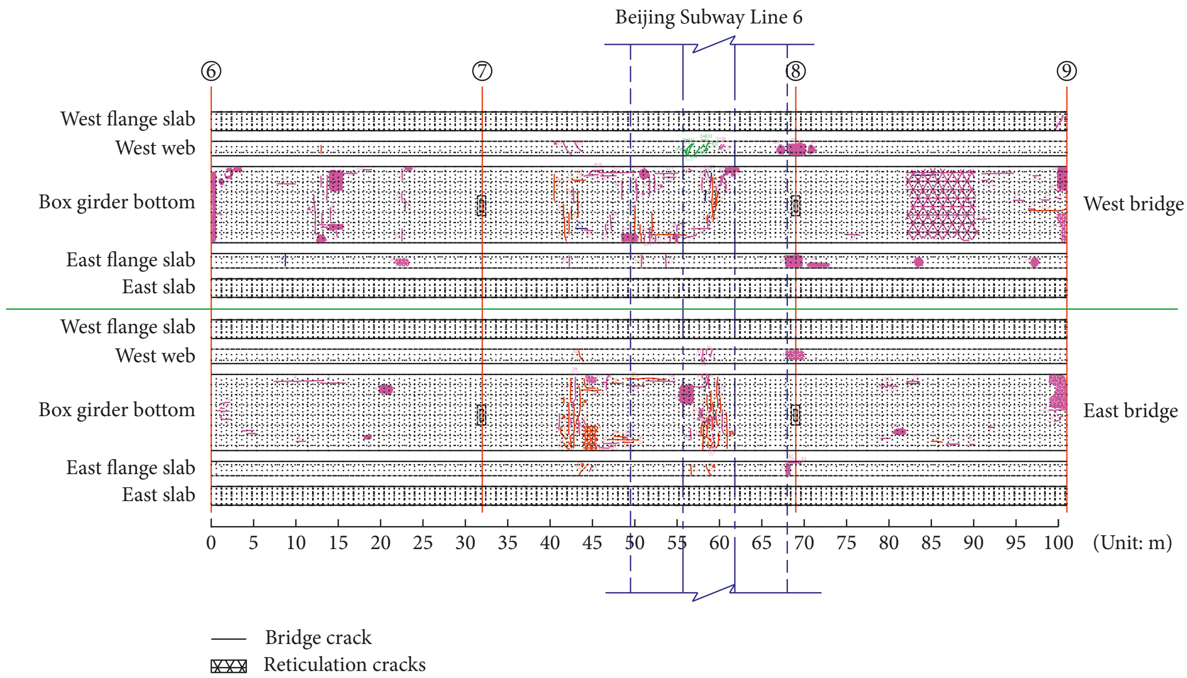


Figure 14: Distribution diagram of cracks.

(a) (b)

(c) (d)

Figure 15: Field photograph. (a) Jack layout. (b) Insert steel plate. (c) Monitoring and measurement. (d) Bridge reinforcement.

bottom, No. 8 pier should be raised up to 5 mm. However, due to the uncertainty, the jacking method should be applied twice. The first one is to check the functionality of the equipment and ensure the jacking effectiveness. The latter one is the formal jacking in order to reach the final goal (Tables 3 and 4). The whole process was divided into four loading steps and one unloading step gradually. For #8-1 pier, the average absolute height of the box girder had been jacked up to 5.64 mm. Similarly, the average absolute height had been jacked up to 4.7 mm for #8-2 pier. According to the

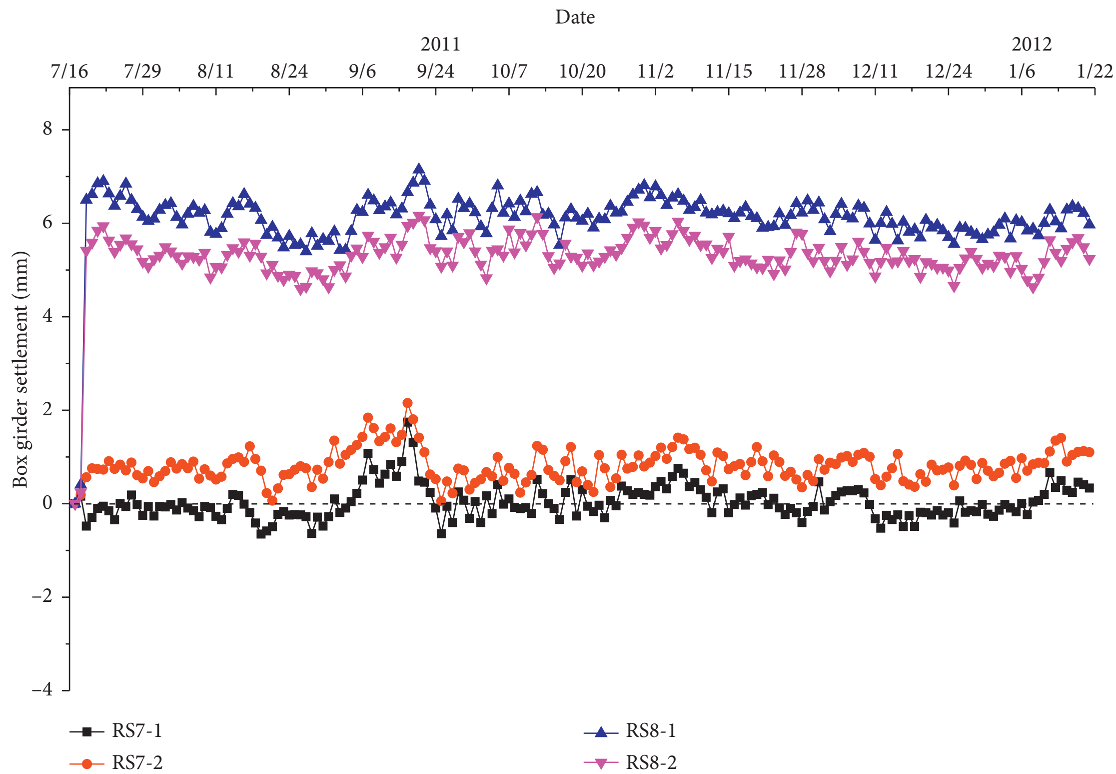


Figure 16: Differential displacement duration.

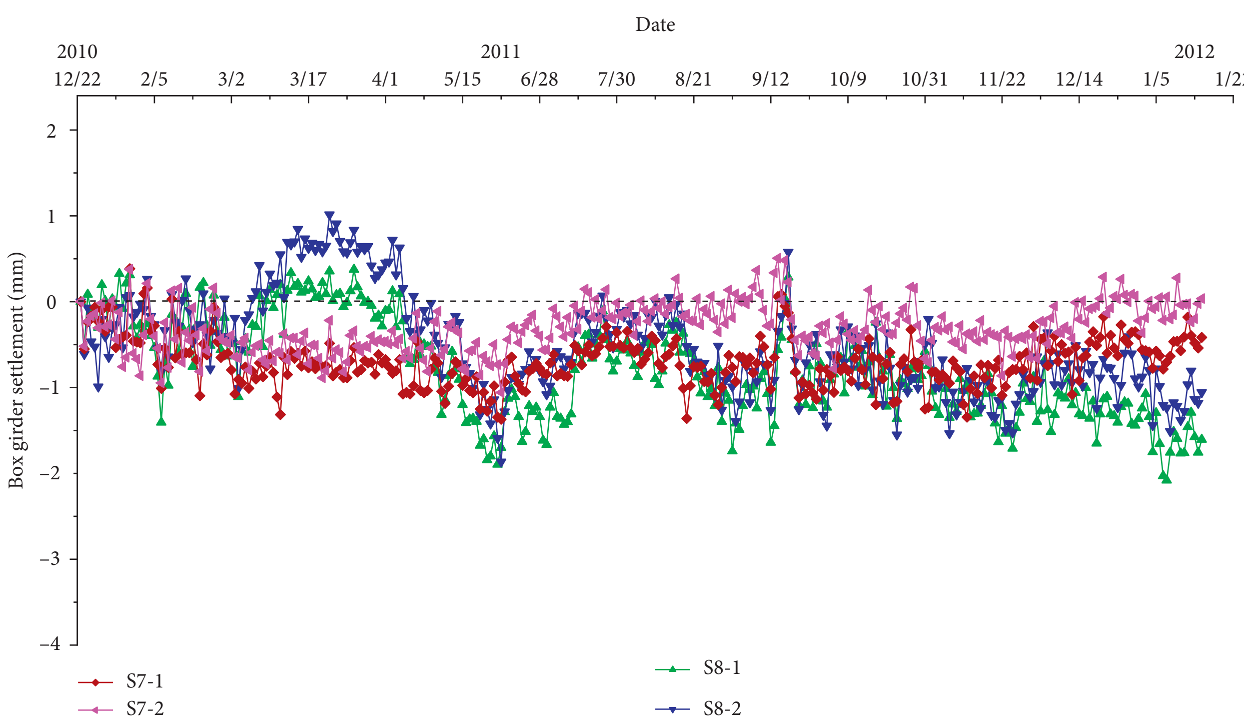


Figure 17: Settlements of pier after jacking.

inspection of the cracks and the absolute height value of the pier top (Table 4), the influence on the substructure due to jacking can be ignored.

After the jacking ended, the bonded steel was used to minimize the cracks on the #6–#9 box girder in order to increase the ultimate bearing capacity and shear capacity of

Table 3: Absolute height value of the bottom of the box girder (unit: m).

Monitoring items	1st loading	2nd loading	3rd loading	4th loading	Unloading
#8-1	1.47	4.15	10.03	11.54	5.62
#8-2	1.36	4.07	9.19	10.34	4.74

Table 4: Absolute height value of the pier top (unit: m).

Monitoring items	1st loading	2nd loading	3rd loading	4th loading	Unloading
#8-1	0.32	0.49	0.41	0.50	0.47
#8-2	0.25	0.42	0.30	0.32	0.41

the bridge. In the next year construction, the absolute height of the box girder and the settlement of the piers were stabilized according to the data shown in Figures 16 and 17. Furthermore, the evidence shows that the protection method in this project was successful.

7. Conclusions

This paper presents a case of the Huayuan Subway Station construction under the existing Huayuan Bridge. In order to protect the safety of both existing bridge and new station, some measurements are taken before and during the new station construction, such as deep grouting reinforcement surrounding the pile foundation from the ground surface, temporary inverted arch, and isolation protection, and lateral steel bracing. During the construction process, formation of new cracks and the growth of existing cracks were observed from the bottom of the box girder. Once cracks appeared, superstructure settlement would be adjusted using hydraulic jacks controlled by the computer system with the guarantee of the automated monitoring system.

As the results show, the jacking method is an effective way in compensating the bridge piers settlement due to tunneling. It can be concluded that real-time jacking is a valid approach to ensure that the existing bridge stays in the best situation before new subway construction entering into the bridge area.

The jacking height should be determined according to the detailed investigations and assessment, and jacking operation should be divided into several steps which should be raised synchronously to ensure bridge safety. In addition, the initiation of cracks on the box girder is an important indication to evaluate the safety of the bridge.

The jacking method has been used in many similar projects in Beijing, including the Shuangjing running tunnels of Line 7 constructed nearby Shuangjing Bridge, and the Guangqumen running tunnels of Line 7 constructed nearby Guangqumen Bridge.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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References

[1] J. D. Morton and K. H. King, "Effects of tunnelling on the bearing capacity and settlement of piled foundations, Tunnelling'79," in *Proceedings of 2nd International Symposium*, pp. 57–68, London, UK, March 1979.

[2] A. Bezuijen and J. Schrier, "The influence of a bored tunnel on pile foundations," *Tunnelling. A Decade of Progress. GeoDelft 1995-2005*, pp. 127–132, 2006.

[3] N. Loganathan, H. G. Poulos, and D. P. Stewart, "Centrifuge model testing of tunneling induced ground and pile deformation," *Geotechnique*, vol. 50, no. 3, pp. 283–294, 2000.

[4] H. T. Yu, X. Yan, A. Bobet, Y. Yuan, G. P. Xu, and Q. K. Su, "Multi-point shaking table test of a long tunnel subjected to non-uniform seismic loadings," *Bulletin of Earthquake Engineering*, vol. 16, no. 2, pp. 1041–1059, 2018.

[5] W. J. Zhu, J. G. Dai, and C. S. Poon, "Prediction of the bond strength between non-uniformly corroded steel reinforcement and deteriorated concrete," *Construction and Building Materials*, vol. 187, pp. 1267–1276, 2018.

[6] H. G. Poulos and E. H. Davis, *Pile Foundation Analysis and Design*, Wiley, New York City, NY, USA, 1980.

[7] Y. K. Chow, C. H. Lim, and G. P. K. Karunaratne, "Numerical modelling of negative skin friction on pile groups," *Computers and Geotechnics*, vol. 18, no. 3, pp. 201–224, 1996.

[8] N. Loganathan, H. G. Poulos, and K. J. Xu, "Ground and pile-ground respond due to tunneling," *Soils and Foundations*, vol. 41, no. 1, pp. 57–67, 2001.

[9] C. Y. Cheng, G. R. Dasari, C. F. Leung, K. ChowY, and H. B. Rosser, "3D numerical study of tunnel soil pile interaction," *Tunnelling and Underground Space Technology*, vol. 19, no. 4-5, pp. 381-382, 2004.

[10] M. C. Emilios and V. B. Spyridoula, "Evaluation of negative skin friction effects in pile foundations using 3D nonlinear analysis," *Computers and Geotechnics*, vol. 32, no. 3, pp. 210–221, 2005.

[11] G. T. K. Lee and C. W. W. Ng, "Effects of advancing open face tunneling on an existing loaded pile," *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 131, no. 2, pp. 193–201, 2005.

[12] C. J. Lee and S. W. Jacobsz, "The influence of tunnelling on adjacent piled foundations," *Tunnelling and Underground Space Technology*, vol. 21, no. 3-4, p. 430, 2006.

[13] M. A. Soomro, Y. Hong, C. W. W. Ng, H. Lu, and S. Y. Peng, "Load transfer mechanism in pile group due to single tunnel advancement in stiff clay," *Tunnelling and Underground Space Technology*, vol. 45, pp. 63–72, 2015.

[14] P. F. Li and Y. Zhao, "Performance of a multi-face tunnel excavated in loess ground based on field monitoring and

numerical modelling," *Arabian Journal of Geosciences*, vol. 9, no. 14, p. 640, 2016.

[15] Y. Z. Xiang, H. L. Liu, W. G. Zhang, J. Chu, D. Zhou, and Y. Xiao, "Application of transparent soil model test and DEM simulation in study of tunnel failure mechanism," *Tunnelling and Underground Space Technology*, vol. 74, pp. 178–184, 2018.

[16] Y. B. Luo, J. X. Chen, Y. Chen, P. S. Diao, and X. Qiao, "Longitudinal deformation profile of a tunnel in weak rock mass by using the back analysis method," *Tunnelling and Underground Space Technology*, vol. 71, pp. 478–493, 2018.

[17] C. Ma, D. C. Lu, and X. L. Du, "Seismic performance upgrading for underground structures by introducing sliding isolation bearings," *Tunnelling and Underground Space Technology*, vol. 74, pp. 1–9, 2018.

[18] J. Su, *Effect and Control of Neighboring Pile with Shallow Tunnel Construction*, Beijing Jiaotong University, Beijing, China, 2009, in Chinese.

[19] Z. Y. Zhou and J. Su, "Risk control crossing the existing bridge with shallow tunnel construction," *Journal of Beijing Jiaotong University*, vol. 6, no. 3, pp. 12–18, 2012, in Chinese.

[20] J. Y. Fu, J. S. Yang, X. M. Zhang, H. Klapperich, and S. M. Abbas, "Response of the ground and adjacent buildings due to tunnelling in completely weathered granitic soil," *Tunnelling and Underground Space Technology*, vol. 43, pp. 377–388, 2014.

[21] C. Liu, Z. X. Zhang, and R. A. Regueiro, "Pile and pile group response to tunnelling using a large diameter slurry shield—case study in Shanghai," *Computers and Geotechnics*, vol. 59, pp. 21–43, 2014.

[22] L. M. Zhang, X. G. Wu, Q. Q. Chen, M. J. Skibniewski, and S. C. Hsu, "Towards a safety management approach for adjacent buildings in tunneling environments: case study in China," *Building and Environment*, vol. 75, pp. 222–235, 2014.

[23] Y. J. Hou, Q. Fang, D. L. Zhang, and L. N. Y. Wong, "Excavation failure due to pipeline damage during shallow tunneling in soft ground," *Tunnelling and Underground Space Technology*, vol. 46, pp. 76–84, 2015.

[24] F. Qian, D. Zhang, Q. Li, and L. N. Y. Wong, "Effects of twin tunnels construction beneath existing shield-driven twin tunnels," *Tunnelling and Underground Space Technology*, vol. 45, pp. 128–137, 2015.

[25] X. Liu, F. Qian, and D. Zhang, "Mechanical responses of existing tunnel due to new tunnelling below without clearance," *Tunnelling and Underground Space Technology*, vol. 80, pp. 44–52, 2018.

[26] C. Zhang, X. Zhang, and F. Qian, "Behaviors of existing twin subway tunnels due to new subway station excavation below in close vicinity," *Tunnelling and Underground Space Technology*, vol. 81, pp. 121–128, 2018.

[27] S. Deb, "Basics of underpinning system its application and benefits," *Masterbuilder*, vol. 6, pp. 112–120, 2012.

[28] Q. W. Xu, H. H. Zhu, X. F. Ma et al., "A case history of shield tunnel crossing through group pile foundation of a road bridge with pile underpinning technologies in Shanghai," *Tunnelling and Underground Space Technology*, vol. 45, pp. 20–33, 2015.

[29] G. F. Lv and D. G. Liu, "Analysis on the reinforcement strategies for bridge piles foundation using composite bolt piles," *Urban Rapid Rail Transit*, vol. 26, no. 5, pp. 79–82, 2013.

[30] P. F. Li, F. Wang, and Q. Fang, "Undrained analysis of ground reaction curves for deep tunnels in saturated ground considering the effect of ground reinforcement," *Tunnelling and Underground Space Technology*, vol. 71, pp. 579–590, 2018.

[31] J. L. Qiu, H. Q. Liu, J. X. Lai, H. P. Lai, J. X. Chen, and K. Wang, "Investigating the long-term settlement of a tunnel built over improved loessial foundation soil using jet grouting technique," *Journal of Performance of Constructed Facilities*, vol. 32, no. 5, article 04018066, 2018.

[32] CJJ99-2003, *Technical Code of Maintenance for City Bridge*, Professional Standards Compilation Group of People's Republic of China, Beijing, China, 2003, in Chinese.

[33] DB11 490-2007, *Technical Code for Monitoring Measurement of Subway Engineering*, Professional Standards Compilation Group of People's Republic of China, Beijing, China, 2007, in Chinese.

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