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Risk Analysis and Control Factors Based on Excavation of a Large Underground Subway Station under Construction

Zhien Zhang [1,2,*], Mingli Huang [1,2] and Baohua Wu [3]

[1] School of Civil Engineering, Beijing Jiaotong University, Beijing 100044, China; mlhuang@bjtu.edu.cn
[2] Tunneling and Underground Engineering Research Center of Ministry of Education, Beijing 100044, China
[3] China Railway 16th Bureau Group Co., Ltd., Beijing 100018, China; 18121044@bjtu.edu.cn
* Correspondence: 19115053@bjtu.edu.cn; Tel.: +86-136-8311-4602

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Abstract: Considering the convenience of pedestrian transfer, reasonable structural stress and beautiful shape design, most subway stations adopt symmetrical design. At present, the new subway station is developing in the direction of a multidimensional space, as well as a large scale, and complex structure. Tunnel construction also presents unpredictability, coupling amplification and high risks. For example, a subway extension project involves construction, which would affect the normal use of the subway or damage its structure. Based on excavation of the largest underground subway station under construction in China, the Erligou station extension project (line 16 of Beijing Metro), and using theoretical analysis, numerical simulation, monitoring data, and other research methods, this paper quantitatively analyzes the risk of a large space station's construction process on the adjacent existing station structure and track, as well as highlights key, high-risk sub-projects, or construction steps, combined with specific engineering measures to ensure safety during construction of a new station. The general rules concerning large space subway station construction are further summarized to provide reference for similar projects.

Keywords: large space subway station; undercutting; extension construction; risk analysis; control measures

1. Introduction

Generally, subway stations are designed symmetrically. However, due to the increasing number of urban public transport trips, its construction also presents another trend: a multidimensional space, as well as a large scale, and complex structure. Its construction risk also presents unpredictability, coupling amplification and high risk [1,2]. A subway is usually built in the center of a densely populated city. Since a large number of subways, municipal bridges, roads, municipal pipelines, and high-rise buildings have been built in city centers, newly-built subways often pass through existing buildings and structures in a short distance. Table 1 lists some engineering cases at Beijing Metro crossing existing lines [3–17]. If the stratum deformation caused by engineering construction is too large, it will cause excessive subsidence, differential subsidence, cracking, and even collapse of adjacent existing projects, and then cause irreparable economic property loss and casualties [18,19]. For example, in July 2003, an accident occurred in the tunnel between Pudong South Road and Nanpu Bridge Station of Shanghai Metro Line 4, resulting in three buildings on the ground, the fracture of surrounding roads, fracture of the Pujiang levee due to excessive deformation, as well as river water flowing back into the tunnel. In November 2008, 17 people died and more than 50 people were injured due to the collapse of the subway foundation pit at Hangzhou Fengqing Avenue. In July 2010, the collapse of Xisanqi station (line 8 of Beijing Metro) caused the rupture of an underground natural gas pipeline, and gas leakage, which affected the gas consumption of tens of thousands of nearby households [20–22].

Subway extension constructions take place close to existing lines. Existing stations are built into new subway stations by means of close-up extensions, connections, and vertical increases. These kinds of newly-built subway stations are very close to existing stations, and are combined with a large scale of undercut sections and obvious spatial effects, which significantly increase construction risks. Construction risks in subway extension projects are mainly due to excessive deformation of existing station structures caused by close-distance construction, which affects normal use of the subway or causes structural failure. Some scholars have carried out research, combined with specific projects, to analyze the mechanical behaviors of subway construction close to existing lines.

Regarding Suzhou Street Station (line 16 of Beijing Metro), Jia Longfei [23] simulates the construction process of the new station by combining the stratum structure method and the load structure method, and analyzes the influence of the existing station on the stress deformation caused by the existing station. According to the deformation control standard of the existing structure of the urban rail transit, Jia Longfei [23] puts forward the deformation control value for the construction procedure of the new station, and gives engineering measures to control the deformation.

Wu Zhijian [24] used ANSYS finite element analysis software, combined with the actual monitoring data, and obtained the deformation law of the concrete structure and track geometry size of the new station, parallel, crossing the existing station, and proposed construction safety control measures.

According to the engineering characteristics of Xuanwumen Station (line 4 of Beijing Metro), passing under the existing station, Liu Lei et al. [25] put forward comprehensive construction technology of a large pipe shed and segmented backward curtain grouting for pre-reinforcement, tracking compensation grouting in the whole process of excavation and support, and block construction of secondary lining to ensure normal operation safety of existing lines.

In view of engineering problems (i.e., tunnels crossing existing lines and deformation control), Chen Mengqiao [26] and Yang Guangwu [27] proposed technology used for synchronous jacking. This involves dynamically adjusting the jack layout and jacking force distribution based on the deformation monitoring data of the existing line. The technology is based on the principle of "zoning, phased, grouping and grading". It was applied in the turn back line project of Dongzhimen Station at the Beijing Airport line after crossing line 13 of Dongzhimen Station.

Relying on the Gongzhufen station (line 10 of Beijing Metro) closely passing through the Gongzhufen station of line 1, Tao Lianjin et al. [28], through theoretical analysis and numerical calculation, concluded that the stress release of the tunnel face is the main factor causing the settlement of the existing station. However, timely closing the initial support, adding temporary jack column, and back-filling grouting can effectively control the settlement deformation of the existing structure.

Park, boo Seong et al. [29] introduced the design and construction method of the largest tunnel station in Seoul. The station is located 15 cm below the existing Metro Line 3, and an abandoned underground shopping center has been built in the highly congested area. In order to overcome the obstacles of adjacent construction, civil complaints, and traffic jams caused by site conditions, a construction method combining pipe shed method and honeycomb arch method is proposed and applied. The subway station has been successfully constructed without any damage to adjacent structures.

Through a variety of advanced monitoring instruments, including distributed optical fiber strain sensing (DFOS), photogrammetry, and strain gauge instrumented tunnel bolts, Gue, C.Y., etc. [30], studied the mechanical and deformation behavior of the existing royal post tunnel during the new passenger tunnel construction, and guided the design and construction of the tunnel according to data feedback.

Table 1. Engineering cases of Beijing Metro crossing existing railway.

Number	Overview of Crossing		Section Shape of New Station	Width * Height/(m * m)	Crossing Mode	Crossing Angle (°)	Minimum Spacing/m	Construction Method
	New Metro	Existing Metro						
1 [3,4]	Xuanwumen Station of line 4	Xuanwumen Station of line 2	Flat top vertical wall	9.85 * 9	Crossing below	90	1.9	CRD method
2 [5]	Pingguoyuan station of line 6	Pingguoyuan station of line 1	Flat top vertical wall	23.5 * 15	Crossing below	70	0	PBA method
3 [6]	Gongzhufen station of line 10	Gongzhufen station of line 1	Flat top vertical wall	14. * 9.32	Crossing below	90	0	PBA method
4	Jiaomen west station of line 10	Jiaomen west station of line 4	Horseshoe shape	10.1 * 9.3	Crossing below	90	0.15	PBA method
5 [7]	Suzhou Street Station of line 16	Suzhou Street Station of line 10	Flat top vertical wall	9.4 * 8.77	Crossing below	70	0	PBA method
6 [8]	Xidan station of line 4	Section of line 1	Horseshoe shape	9.9 * 9.17	Overhead crossing	90	0.5	CRD method
7 [9]	Dongdan station of line 5	Wangfujing Dongdan section of line 1	Single arch	23.7 * 7.17	Overhead crossing	90	0.6	Column hole method
8 [10]	Chongwenmen station of line 5	Chongwenmen Beijing station section of line 2	arch	24.2 * 11.4	Crossing below	90	1.98	Column hole method
9 [11]	Chaoyang Gate Dongdaqiao section of line 6	Chaoyang Gate Station of line 2	Flat top vertical wall	6.3 * 7.52	Crossing below	90	0	PBA method
10 [12]	Dongsi Chaoyang Gate section of line 6	Line 5 Dongsi station	Flat top vertical wall	7.1 * 8.7	Crossing below	90	0	PBA method
11 [13]	Chegongzhuang pinganli section of line 6	Chegongzhuang station of line 2	Horseshoe shape	6.6 * 6.9	Crossing below	90	2.47	Step method
12 [14]	Guang-double section of line 7	Double well station of line 10	Flat top vertical wall	6.2 * 6.5	Crossing below	90	0	Step method
13	Chongwenmen Ciqikou section of line 7	Ciqikou station of line 5	Horseshoe shape	6.2 * 6.5	Crossing below	90	0.7	Step method
14 [15]	Guomao Shuangjing section of line 10	Guomao Dawanglu section of line 1	Flat top vertical wall	6.1 * 7.84	Crossing below	90	1.08	PBA method
15 [16]	Jiulongshan Dawang road section of line 14	Dawang road Sihui section of line 1	Circular	6 * 6	Crossing below	90	2.15	Shield method
16 [17]	Futong Wangjing section of line 14	Wangjing to Wangjing west section of line 15	Circular	6 * 6	Crossing below	73	1.9	Shield method
17	National Library to Erligou section of line 16	National Library of line 9—Baishiqiao south section	Horseshoe shape	6.3 * 6.42	Crossing below	90	2.2	Step method
18	Xiyuan Wanquanhe section of line 16	Section of line 4	Circular	6.4 * 6.4	Crossing below	56	4	Shield method

Researchers mostly focus on the study of construction deformation, under a new subway crossing an existing line, while research on the construction risk of crossing existing lines, above, is relatively small, especially for subway extension projects involving large spaces and large sections. Using Erligou station (line 16 of Beijing Metro) as the engineering background, this paper analyzes the influence of construction processes of new stations (involving large spaces) and the resulting stress and deformation on adjacent structures, and track crossing existing lines, by using the research methods of theoretical analysis, numerical simulation, and monitoring data. The construction risk is quantified by force and deformation, and the key construction process sensitive to the deformation of existing structures, is discovered. Control measures are taken to ensure the normal use of existing stations in the construction process.

2. Overview of New Station Project

2.1. Project Overview

The new Erligou station (line 16 of Beijing Metro) is designed symmetrically, and it comprises of a total length of 303 m (including a 113.2 m undercut double-layer section at the north end, a 49.5 m single-layer undercut section at the middle, and a 140.3 m undercut double-layer section at the south side), with a clear span of 28 m and a clear height 16.3 m, the burial depth of the bottom plate is 27.255 m, and the total construction area is 39,000 m^2. It is currently the largest underground excavation extension subway station under construction in the country. The existing Erligou Station of line 6 is a single-layer underground excavation and separated platform station, with a total length of 174.2 m and a buried depth of 27.93 m of the station roof. The two stations are "crossing" transfer stations with a minimum distance of 0.675 m. The station is at a crossroads, with many surrounding buildings and underground pipelines, and the construction environment is very complicated. The plane position of the new Erligou station is shown in Figure 1.

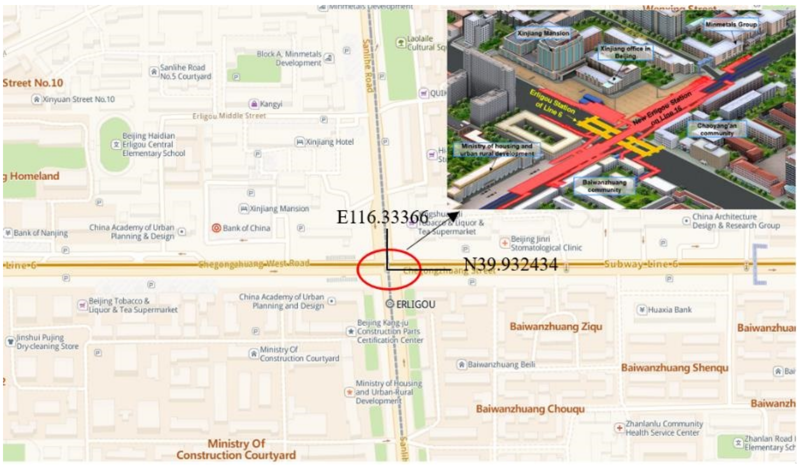
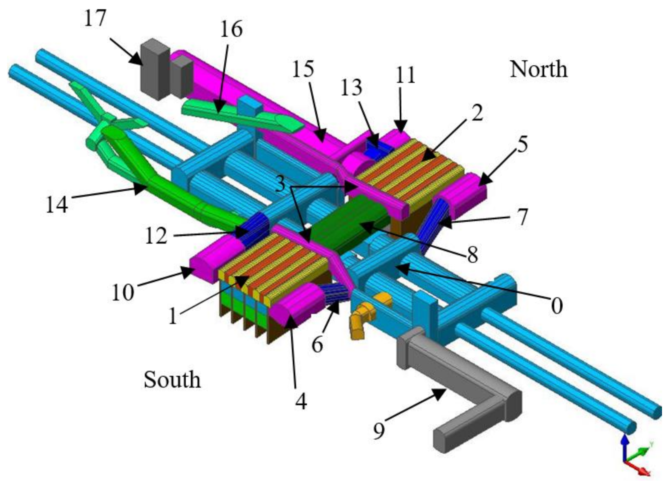


Figure 1. Plane position of new Erligou station.

The newly-built Erligou station is composed of three main structures at both ends (double-layer three column four span structure) and middle (single-layer and double span structure), as well as auxiliary structures, such as transfer channel, external hanging hall, and air duct, as shown in Figure 2.

The north and south ends of the station are constructed by the Pile-Beam Arch (PBA) Method. The height of the excavation section is 18.36 m, the width is 29.40 m, and the covering depth is 8.90 m, as shown in Figure 3. The middle section of the station crosses the existing Erligou Station (of line 6 above), which is constructed by the middle tunnel method. The excavation section is 19.8 m wide and 8.57–9.67 m high. The existing line 6, here, is a flat-topped, straight wall section ZB; the initial lining adopts a 350 mm thick C20 grid shotcrete structure, and the second lining adopts a C40 molded concrete, as shown in Figure 4.



Note: 0—existing station, 1—south PBA construction section, 2—north PBA construction section, 3—transverse passage, 4—east side no.3 hanging hall, 5—east side no.4 hanging hall, 6—east side no.2 access road, 7—east side no.3 access road, 8—the overpassing and concealed excavation section, 9—no.3 air duct, 10—west side no.2 hanging hall, 11—west side no.5 hanging hall, 12—west side no.1 access road, 13—west side no.4 access road, 14—southwest entrance, 15—external hanging hall 1, 16—northwest entrance and exit, 17—northwest new air shaft.

Figure 2. Structural layout of new station.

2.2. Geology

The maximum depth of the stratum revealed in this survey is 51 m. According to the drilling data and indoor geotechnical test results, the stratum is mainly composed of artificial fill, silty fine sand, silty clay, and sand pebble. The Erligou station, of the new line 16, is mainly located in pebble and silty clay layers. The geological profile is shown in Figure 5.

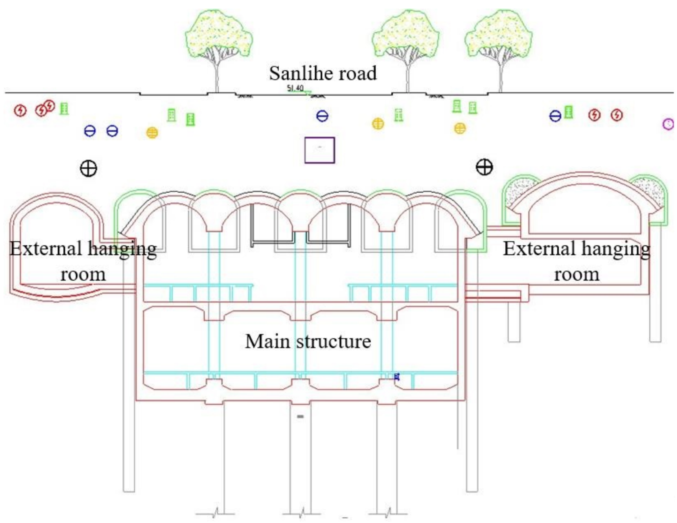


Figure 3. Cross section of main structure of the PBA section.

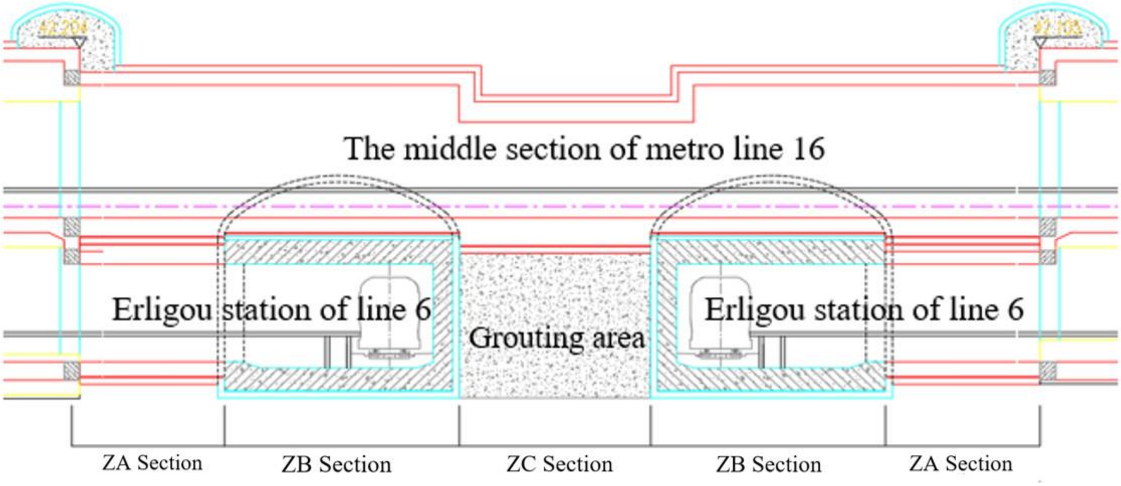


Figure 4. Longitudinal section of the overpassing and concealed excavation section.

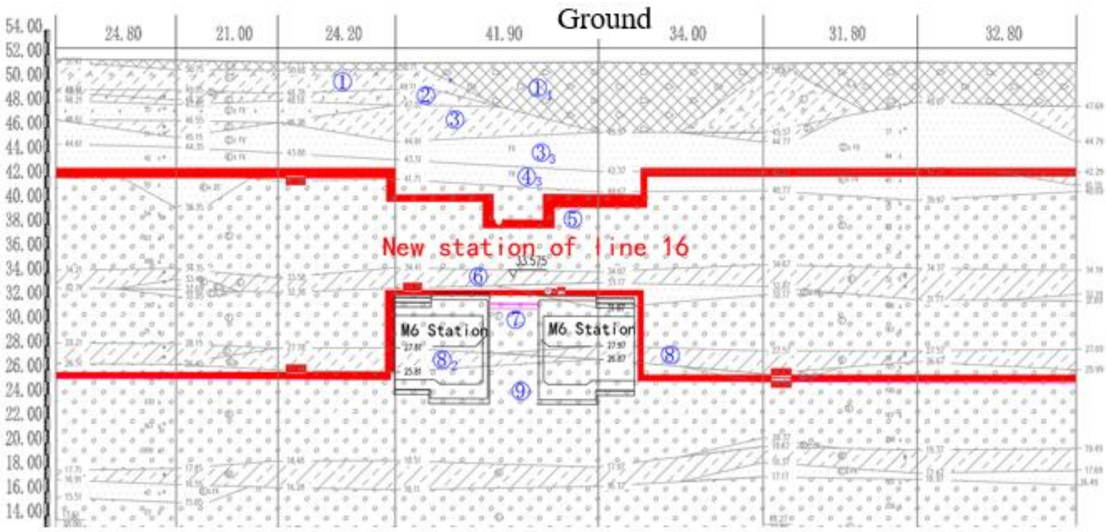


Figure 5. Geological section. Note: unit of number: m, ①—silt fill, ①$_1$—miscellaneous fill, ②—silt, ③—silt, ③$_3$—silty sand, ④$_3$—silty fine sand, ⑤—pebble, ⑥—silty clay, ⑦—pebble, ⑧—silty clay, ⑧$_2$ —silt, and 9 ⑨—pebble.

3. Analysis of the Station Construction on the Stress and Deformation of Existing Structure

3.1. Description of Calculation Model

(1) Calculation Assumption

In this paper, MIDAS/GTS finite element software is used to establish the stratum structure model, to analyze the influence of the construction stages of the newly-built M16 Erligou station on the station structure and track of line 6. The purpose of using the finite element software is, not to pay attention to the accuracy of the absolute value of the calculation results, but to find out the rules and trends by analyzing the relative values of deformation or stress.

The calculation assumes the following:

(1) During the construction of the new structure, the Erligou station of the existing metro line 6 only considers normal operational conditions, and does not consider earthquakes and civil air defense conditions.
(2) It is assumed that the soil layer is homogeneous and horizontally distributed.

(2) Mechanical Model and Calculation Parameters

The upper boundary of the numerical calculation model is the surface, which is 50 m in Z direction, 215 m in X direction, and 200 m in Y direction, as shown in Figure 6. Different constitutive models are used to simulate different materials, a linear elastic model is used for concrete, and the Mohr Coulomb (M–C) model is used for soil. The model is divided into 139,811 elements with 21,134 nodes. The ground overload is considered as 20 kPa. The values of physical and mechanical parameters of materials in the model are shown in Table 2.

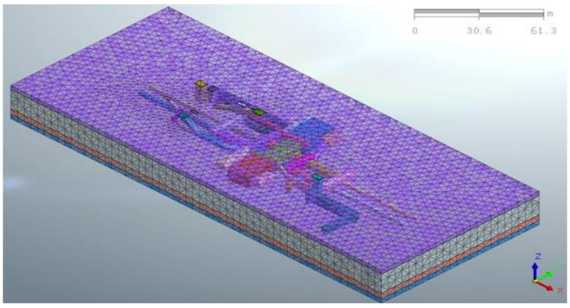


Figure 6. Computational model.

Table 2. Physical and mechanical parameters of materials.

Project	h/m	E/MPa	v	c/kPa	φ/°	γ (KN/m^3)	Constitutive Relation
1—Silt, Fill	2.5	9	0.3	23.5	28	19.5	M–C
2—Fine sand	4	25	0.33	0	33	21	M–C
3—Pebble layer 1	28.7	90	0.2	0	45	21	M–C
4—Pebble layer 2	8.3	120	0.2	0	45	21	M–C
5—Gravel layer	6.5	400	0.2	0	45	22	M–C
Initial support	Thick 0.3	25,500	0.2	/	/	25	Elastic
Second lining	Thick 0.5	32,500	0.2	/	/	25	Elastic

Note: h, E, v, c, φ and γ represent material thickness, elastic modulus, Poisson’s ratio, cohesion, internal friction angle and gravity, respectively.

3.2. Simulation of Construction Process

According to the construction process of Erligou station, on the new M16 line, the calculation is divided into 15 construction stages for simulation, as shown in Table 3.

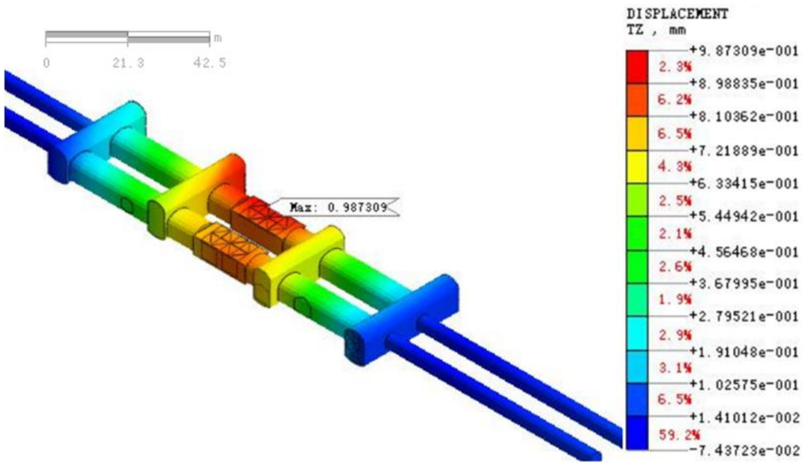
Table 3. Description of construction simulation process.

Construction Stage	Description
1	Initial stage
2	Construction cross passage and PBA section
3	Construction of no.3 and no.4 external hanging halls
4	Construction of no.2 and no.3 access roads
5	Integrated interface of construction southeast corner
6	Ground reinforcement by grouting in the overpassing and concealed excavation section
7	Construction of overpassing and concealed excavation section
8	Four connecting channels under the construction undercut section
9	Construction of no.3 air duct
10	Construction of no.2 and no.5 external hanging halls
11	Construction of no.1 and no.4 access roads
12	Southwest entrance and exit of construction
13	Construction of external hanging hall 1
14	Northwest entrance and exit of construction
15	Construction of northwest exhaust and fresh air shaft

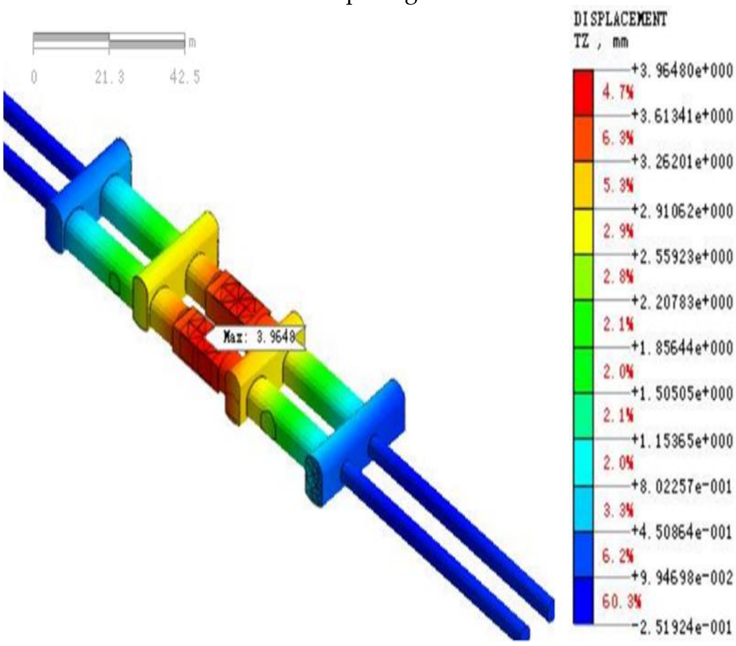
3.3. Stress and Deformation Analysis of Existing Station Structure

(1) Deformation Analysis

The newly-built station is located above the existing station of line 6; therefore, the deformation effect of the new station construction on the existing station structure is mainly (Z direction) vertical deformation, and only the vertical deformation can be analyzed. Since there are many simulated construction stages, only partial deformation diagrams are listed, as shown in Figure 7. The deformation results of each construction stage are shown in Table 4.



2 Construction cross passage and PBA section.



7 Construction of overpassing and concealed excavation sections.

Figure 7. Accumulated deformation diagram of Z direction of the existing station in partial construction stage.

Table 4. Statistics of vertical deformation of the existing line caused by each construction stage.

Construction Stage	Description	Maximum Cumulative Vertical Deformation of Existing Line/mm	Maximum Vertical Deformation of Existing Line/mm
1	Initial stage	0	0
2	Construction cross passage and PBA section	0.987	0.987
3	Construction of no.3 and no.4 external hanging Hall	1.072	0.085
4	Construction of no.2 and no.3 access roads	1.257	0.185
5	Integrated interface of construction southeast corner	1.404	0.147
6	Ground reinforcement by grouting in the overpassing and concealed excavation section	1.404	0
7	Construction of overpassing and concealed excavation section	3.965	2.561
8	Four connecting channels under the construction undercut section	4.142	0.177
9	Construction of no.3 air duct	4.218	0.076
10	Construction of no.2 and no.5 external hanging halls	4.303	0.085
11	Construction of no.1 and no.4 access roads	4.768	0.465
12	Southwest entrance and exit of construction	4.952	0.184
13	Construction of external hanging hall 1	4.831	−0.121
14	Northwest entrance and exit of construction	4.829	−0.002
15	Construction of northwest exhaust and fresh air shaft	4.819	−0.01

Note: positive value indicates upward floating and negative value indicates settlement, Maximum vertical deformation of existing line N = Maximum cumulative vertical deformation of existing line N—Maximum cumulative vertical deformation of existing line N-1.

The existing station is one of the risk sources in the construction environment of the new station. The construction of the new station will cause disturbance and deformation in the soil. The soil, as the transmission medium, will transfer the deformation to the existing station, causing the deformation of the existing station's concrete structure. If the deformation is too large, it will cause the concrete structure to crack. According to the cooperative deformation principle, the track will also produce excessive deformation, which will affect the normal operation of the subway. This is consistent with the principle of the tuning fork resonance test. Air, as a medium, transmits acoustic energy, which makes the non-contact tuning fork vibrate.

If the deformation is regarded as the direct factor causing the construction risk, the risk of adjacent construction can be quantitatively analyzed. It can be seen from Table 4 that the construction of the new Erligou station will cause the overall uplift of the existing station. The maximum uplift of the existing structure is 4.952 mm, which occurs in the construction of the southwest entrance and exit in phase 12. The construction of the PBA section of main structure and the overpassing and concealed excavation section has obvious influence on structural deformation of the existing railway. In the seventh construction stage, the distance between the overpassing and concealed excavation section and the existing line is the closest, which has the greatest impact on the structural deformation of the existing line 6 tunnel, with upward floating of 2.561 mm. Therefore, the overpassing and concealed excavation section is a key part of the project to control the structural deformation of the existing line. Secondly, the PBA section of the main structure causes the existing line to float 0.987 mm. Due to the close distance between the PBA construction section, the existing line, and the large scale of underground excavation space, the construction disturbance has great influence on the deformation of the existing line tunnel structure.

<The technical code for monitoring of Urban Rail Transit Engineering> (GB 500911-2013) stipulates that the floating deformation of the existing line shall be controlled within 5 mm. The safety factor of 5 mm is considered here. Even if the floating deformation of the existing line exceeds 5 mm, the structure may not be damaged, but the probability of structural failure risk will increase. From the perspective of safety, we assume that 5 mm is the value limit of deformation, and failure of the existing station structure, and the contribution degree of each construction stage to the structural failure risk of the existing line 6 tunnel can be given; P = deformation value D/limit value D_0 of existing station, as shown in Figure 8. It can be seen, from the figure, that the seventh stage of the construction of the overpassing and concealed excavation section has the largest contribution to the structural failure risk of the existing station, 50.38%, which is a key part of the project to control the risk.

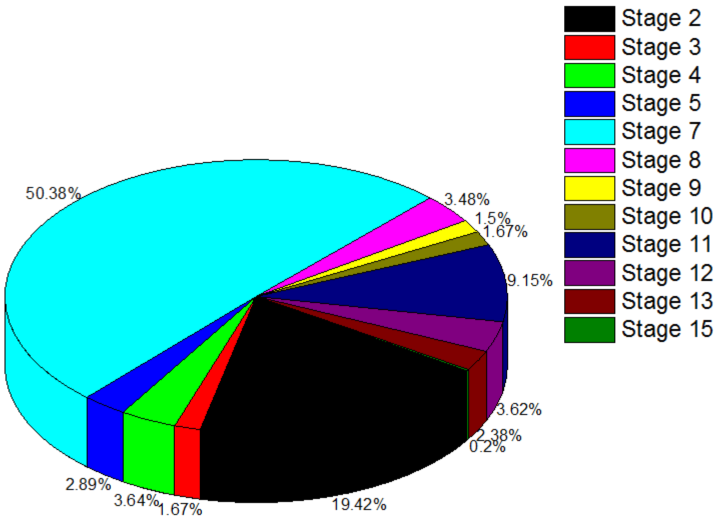


Figure 8. Contribution of each construction stage to the structural failure risk of the existing line 6 tunnel.

(2) Stress Analysis

The position with the largest structural deformation of the existing line tunnel is selected for stress analysis, as shown in Figure 9 and Table 5. Due to the large number of stress nephogram and little color difference between stress diagrams, Figure 9 only shows the partial stress F_{xx} before and after construction, at the place with the largest deformation of the existing structure, and the complete stress difference is shown in Table 5.

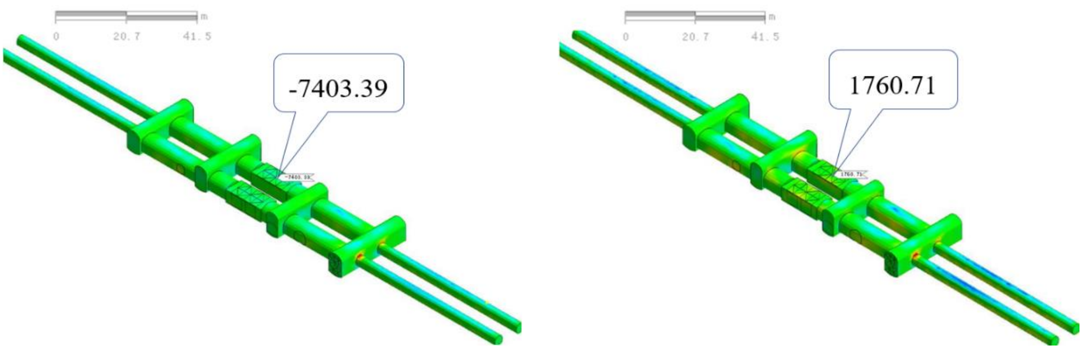


Figure 9. Cloud chart of internal force of existing station and section structure.

Table 5. Internal force value at the maximum displacement of Erligou station and section structure of existing line 6.

Direction	Initial Stage/kPa	Internal force Value at the Maximum Displacement/kPa
F_{xx}	−7403.39	1760.71
F_{yy}	−5861.64	4043.69
F_{xy}	−157.759	−154.326

It can be seen from Table 5 that during the whole construction process of Erligou station, of metro line 16, the maximum structural internal force of the Erligou station of the existing metro line 6, and the section with the largest structural deformation, is 4043.69 kPa; thus, it is necessary to check the bearing capacity of reinforced concrete structure, and focus on real-time monitoring of this part during the construction process to ensure the safety of the existing structure.

4. Analysis on Construction Risk of the Overpassing and Concealed Excavation Section Close to the Existing Station

4.1. Description of Calculation Model

Midas finite element software was used to establish the three-dimensional calculation model. The x, y, and z were 49.5 m × 90 m × 50 m, respectively. The main part of the station adopts a grid size of 1.0 m, and the external soil size gradually transits to 4 m. The model is divided into 98,975 nodes and 164,794 elements (Figure 10). The calculation assumption, constitutive model, and material physical and mechanical parameters are the same as those in Section 3.1.

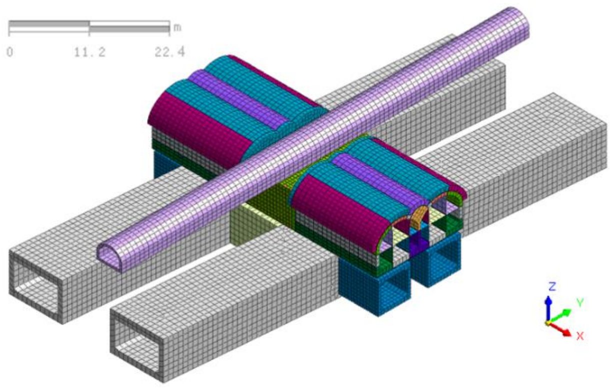


Figure 10. Model drawing of the overpassing and concealed excavation section.

4.2. Simulated Construction Sequence

According to the actual construction method of the sub-project, the simulation is divided into 16 construction stages, as shown in Figure 11 and Table 6.

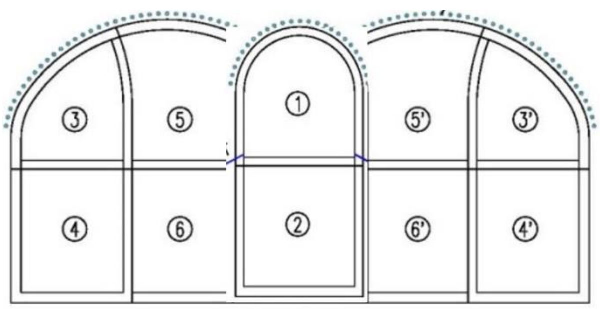


Figure 11. Construction sequence. Note: ① and ② are middle holes, ③ and ④ are side holes, and ⑤ and ⑥ are side holes.

Table 6. Simulation construction stage.

Construction Stage	Description
1	Initial stress
2	Excavation of existing station
3	Displacement clearing
4	Grouting reinforcement of soil mass of tunnels 1 and 2
5	Excavation of soil mass of tunnels 1 and 2
6	Initial support for tunnels 1 and 2
7	Construction of secondary lining of tunnels 1 and 2
8	Grouting reinforcement of soil mass of tunnels 3 and 4
9	Excavation of soil mass of tunnels 3 and 4
10	Initial support for tunnels 3 and 4
11	Grouting reinforcement of soil mass of tunnels 5 and 6
12	Excavation of soil mass of tunnels 5 and 6
13	Initial support for tunnels 5 and 6
14	Construction of base plate
15	Construction of secondary lining
16	Excavation of rectangular passage

4.3. Analysis of Stress and Deformation Characteristics of Track Bed Structure

(1) Deformation Analysis

According to the calculation assumption, the existing track and track bed structure deform harmoniously, so the track bed structure deformation is used to represent the track deformation, and the stress and deformation characteristics of the existing line in the construction process of the overpassing and concealed excavation section, using the middle hole method, are analyzed. The corresponding monitoring points are set on the existing station structure, as shown in Figure 12, to monitor the vertical displacement of the station in each construction stage.

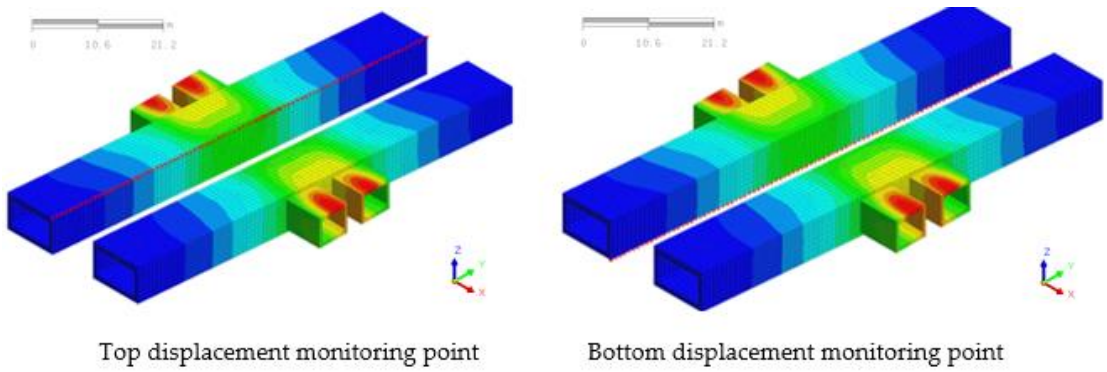


Figure 12. Selection of deformation measuring points of existing stations. Note: the red dots in the cloud image indicate the deformation monitoring points.

The vertical displacement of the main structure of the existing station is shown in Figures 13 and 14. It can be seen from the deformation curve that due to the excavation and unloading of the soil mass of the new station, the uplift deformation of the lower station occurs, and the uplift amount is positively correlated with the excavation progress. The overall uplift deformation presents a reverse peck curve. The construction of primary support and secondary lining forms the main structure of the new station, which is equivalent to loading above the existing station, which helps to reduce the uplift deformation of the existing station. Because the soil between the two stations is reinforced by grouting, the uplift of the middle part of the curve will be reduced, and the trend curve of the reverse double peck settlement tank will be formed finally. The influence of grouting reinforcement on the bottom of the existing station structure is small, and its general trend is consistent with that of the top, but there is only a single reverse peck settlement tank.

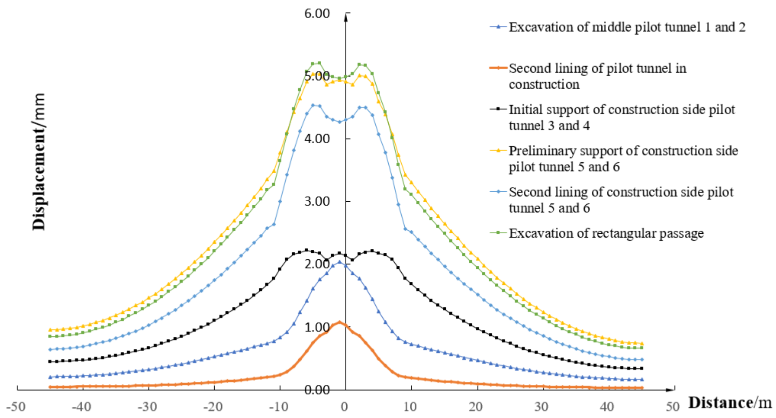


Figure 13. Z-direction displacement of the monitoring point at the top of the existing station.

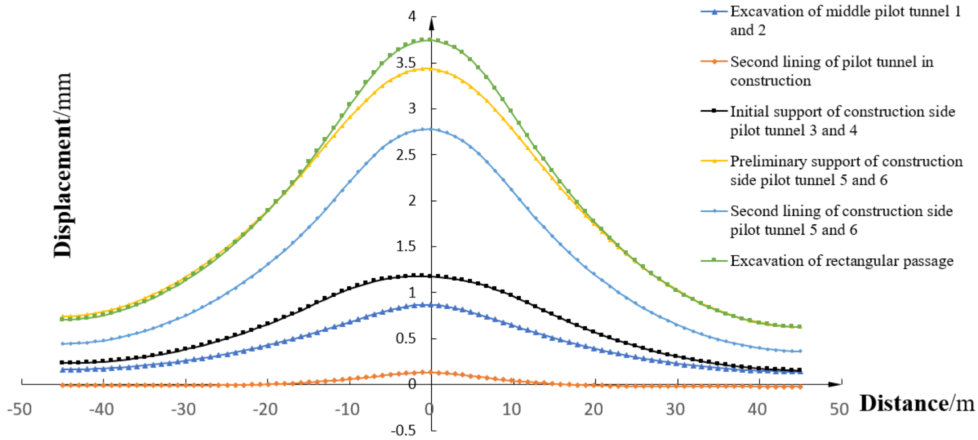


Figure 14. Z-direction displacement of the monitoring point at the bottom of the existing station.

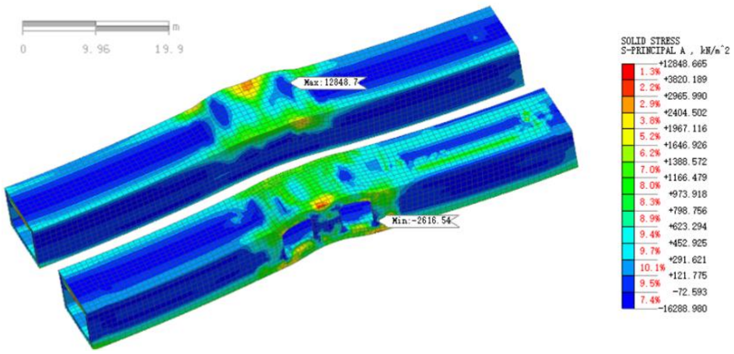
The vertical deformation of existing station structure in each construction sequence is shown in Table 7. It can be seen from the table that the accumulated maximum floating point of the existing station was 5.473 mm, which occurred in the 12th construction stage. The maximum floating value of the existing station in each construction stage was 3.3 mm, which also occurred in the 12th construction stage, accounting for 63.4% of the cumulative deformation of the existing station. Therefore, the soil excavation of the side tunnels, 5 and 6, is the stage with the greatest risk of causing excessive deformation of the existing station structure. In the actual construction process, the deformation monitoring during the construction stage should be strengthened and reinforcement measures should be taken in time.

(2) Stress Analysis

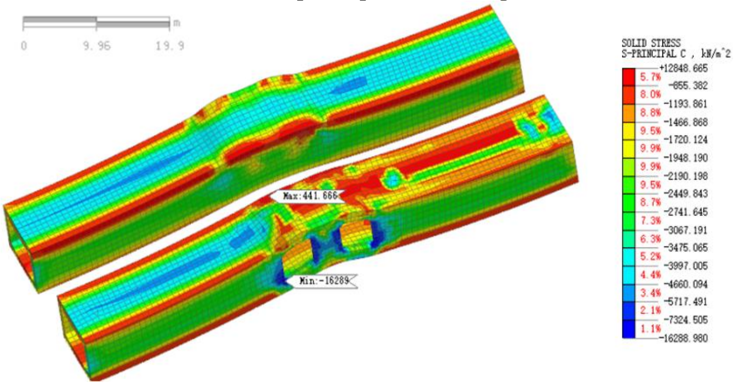
During the construction of the new station, the maximum and minimum principal stresses of the existing station structure are shown in Figure 15. The maximum principal stress occurs at the top plate of the left line, with the maximum value of 12.848 MPa, which is greater than the design value of C40 concrete axial tensile strength of 1.71 MPa, and there is a risk of concrete cracking. In addition, the maximum compressive strength of the reinforced concrete is 288.1 MPa, which is smaller than the design value of reinforced concrete.

Table 7. Vertical deformation of existing station structure.

Construction Stage	Description	Maximum Cumulative Vertical Deformation of Existing Station/mm	Maximum Vertical Deformation of Existing Station/mm
1	Initial stress	0.000	0.000
2	Excavation of existing station	9.163	9.163
3	Displacement clearing	0.000	0.000
4	Grouting reinforcement of soil mass of tunnels 1 and 2	−0.005	−0.005
5	Excavation of soil mass of tunnels 1 and 2	1.577	1.582
6	Initial support for tunnels 1 and 2	2.041	0.464
7	Construction of secondary lining of tunnels 1 and 2	1.084	−0.957
8	Grouting reinforcement of soil mass of tunnels 3 and 4	1.032	−0.052
9	Excavation of soil mass of tunnels 3 and 4	1.934	0.902
10	Initial support for tunnels 3 and 4	2.221	0.287
11	Grouting reinforcement of soil mass of tunnels 5 and 6	2.173	−0.048
12	Excavation of soil mass of tunnels 5 and 6	5.473	3.3
13	Initial support for tunnels 5 and 6	5.038	−0.435
14	Construction of base plate	4.293	−0.745
15	Construction of secondary lining	4.533	0.24
16	Excavation of rectangular passage	5.201	0.668



Maximum principal stress diagram



Minimum principal stress diagram

Figure 15. Stress analysis of existing station structure.

5. Risk Control of Construction Close to Existing Station

5.1. Deformation Control Measures for Construction Close to Existing Line

Deformation is the direct factor leading to the failure of the existing station concrete structure. In the construction process of the new station, it is necessary to control the deformation to ensure the normal use of the existing station. The deformation includes the structural deformation of the new station itself, the surrounding soil deformation, and the concrete structure deformation of the existing station. The construction of the new station is the source of deformation, and soil is the medium to transfer deformation/risk. Therefore, deformation can be effectively controlled from the source and propagation path.

The source: (1) changes the construction method, adopts a multi-pilot tunnel excavation to change the tunnel working face from a large section to a small section, reduces the space effect caused by construction, and then reduces the deformation (Figure 16). (2) Support measures, such as initial support, radial bolt, foot lock bolt, and advance small pipe are adopted to provide support resistance from outside, bear part of the surrounding rock pressure caused by excavation unloading, and restrain soil deformation around the tunnel excavation contour line.

Figure 16. Excavation of multiple pilot tunnels.

In the aspect of the transmission path: the cement slurry, or cement water glass double liquid slurry, is injected into the soil to improve the cohesion c and internal friction angle of the soil, to enhance the anti-deformation ability of the soil body itself, reduce the soil pressure exerted on the existing station structure due to the soil deformation, and control the deformation of the existing station structure.

5.2. Analysis on Deformation Monitoring of Existing Track Station

Whether the engineering measures adopted are effective, and whether the construction risks are controlled or not needs to be verified by the actual monitoring data. The vertical deformation of track structure in Erligou station, Baishiqiao south station—Erligou station section, and Erligou station Chegongzhuang West station section of the existing metro line 6 is monitored. The range is K5 + 009.000~K5 + 310.000 for the right line, 301 m for single track, K4 + 991.000~K5 + 310.000 for the left line, and 319 m for single track. Figures 17 and 18 show the monitoring range of the track's vertical deformation of the existing station and the data pictures taken by staff during field monitoring.

It can be seen from Figure 19 that, due to the influence of the construction of the new Erligou station, the existing line floats upward, and the deformation trend is high in the middle and low on both sides. The distance between the station and the upper undercutting section is closer than that of the sections on both sides, so the space–time effect caused by the construction is greater, and the floating degree is more obvious. The accumulated maximum uplift value of the left line is 1.34 mm, and that of the right line is 1.63 mm, which meets the requirements of the existing line structure and track deformation in the technical code for monitoring of Urban Rail Transit Engineering (GB 500911-2013) and the enterprise standard technical standard of Beijing Metro Operation Co., Ltd. guidelines for maintenance of public works (QB (J)/BDY (a) xl003-2009).

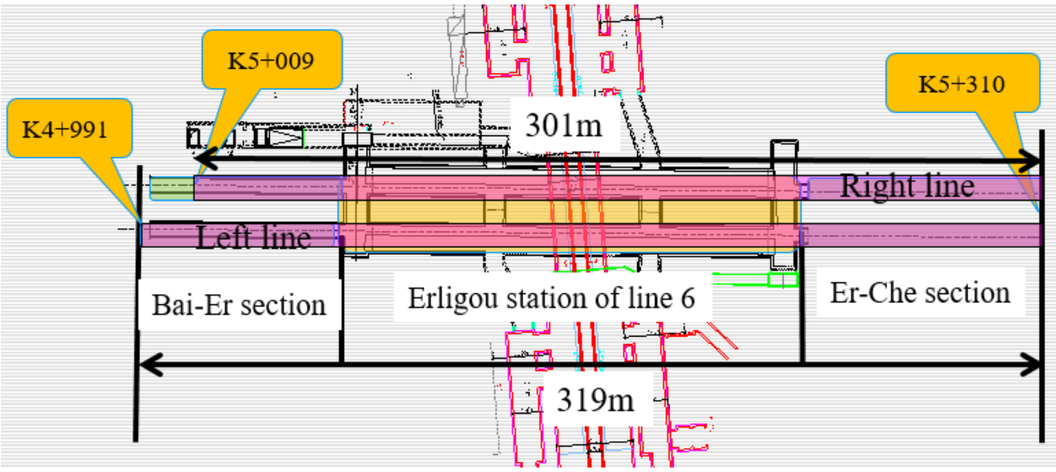


Figure 17. Monitoring range of track vertical deformation of the existing station.

Figure 18. On-site monitoring of track deformation of the existing station.

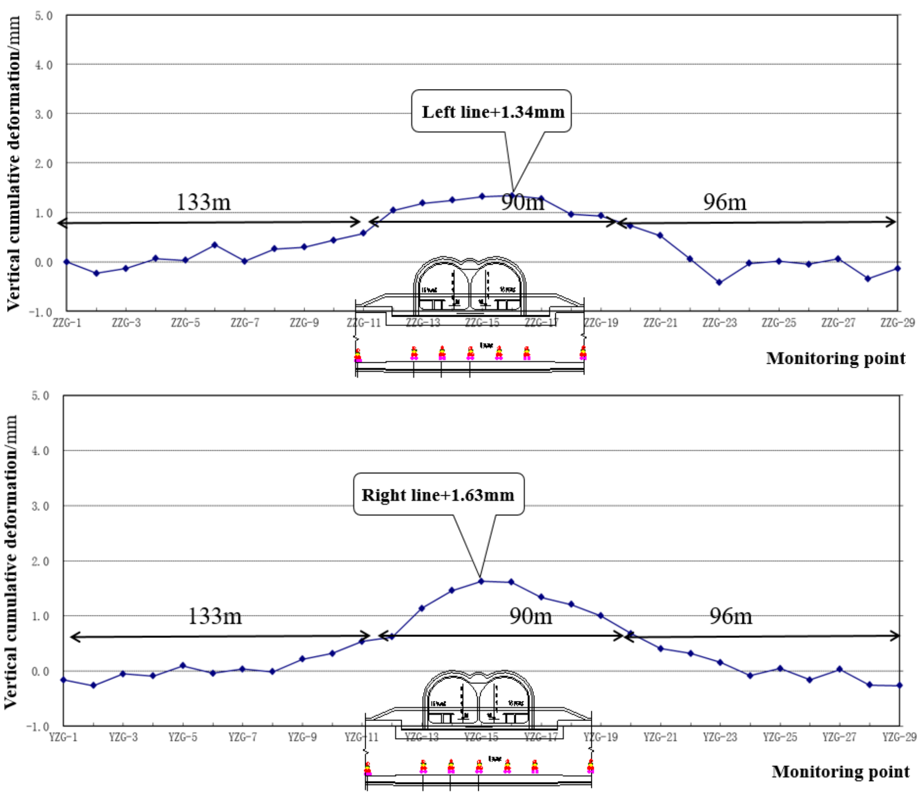


Figure 19. Monitoring data of track vertical deformation of the existing station.

6. Conclusions

Through the above research, we can draw the following conclusions:

(1) Construction risks may occur in metro extensions due to adjacent existing structures. The risk of underground excavation in large sections and large space subway stations has the following characteristics: classification, zoning, and time sharing.

(2) There are many types of tunnel construction risks. There are many types of tunnel construction risk. Different risk types have different quantitative evaluation indexes and different monitoring instruments. The analysis of construction risk must be specific to a certain risk event in order to be targeted. For example, the risk of structural failure of adjacent existing stations caused by the construction of new stations is studied.

(3) During the construction of subway stations, there are risk zones. The upper-pass and undercut sections are high-risk areas, which contribute 50.38% to the risk of structural failure of the existing station. It is necessary to strengthen monitoring and safety measures. The size of the construction space and the proximity distance are the two most important factors that affect risk zoning.

(4) The risk of a single sub-project during the construction process is dynamic and a function of time. In the construction process of the upper-crossing undercut section, the soil excavation of the side tunnels, 5 and 6, has the greatest impact on the deformation of the adjacent existing line, accounting for 63.4% of the cumulative deformation of the existing station. It is necessary to strengthen monitoring during the high-risk construction period. The best way to control risk is to "break the whole into parts" and prevent and control them step-by-step.

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