water

Article

Risk Reduction Measures and Monitoring Analysis of Deep Foundation Pit with Water in a Metro Station in Hefei

Dengqun Wang [1], Shuaihua Ye [2,*] and Jun Zhang [2]

[1] HFUT Design Institute (Group) Co., Ltd., Hefei 230051, China
[2] School of Civil Engineering, Lanzhou University of Technology, Lanzhou 730050, China
* Correspondence: yeshuaihua@163.com

Abstract: The construction of an urban metro will inevitably involve deep excavation. Risk assessment before deep excavation, risk reduction measures, and real-time monitoring during excavation can effectively ensure the safety of deep excavation. Taking the deep excavation pit of Lingbi Road Station of Hefei Rail Transit Line 8 as the research object, this paper first analyses and evaluates the self-risk, groundwater risk, and surrounding environmental risk of the deep excavation pit, and gives the corresponding measures to reduce the risk of the deep excavation pit. Then, the monitoring content of the excavation process is determined according to the environment of the excavation, the hydrogeological conditions, and the type of supporting structure, and the monitoring scheme is designed. Finally, the entire excavation process is monitored in real time. By analyzing the monitoring data of 13 projects, such as horizontal displacement of the wall top, axial support force, groundwater level, etc., it is found that the monitoring values of 13 projects do not exceed the control value. This proves that the composite internal bracing structure of the underground diaphragm wall is suitable for deep foundation pit support in the Hefei area, as the selection of the water-bearing deep foundation pit support structure, the value of the support structure parameters, and the design of the foundation pit dewatering scheme are all reasonable. The study of this paper also serves as a case reference for the support design of water-bearing deep excavation of subway station in Hefei area.

Keywords: subway station; water-bearing deep foundation pit; composite internal bracing of diaphragm wall; risk reduction measures; monitoring and analysis

check for updates

Citation: Wang, D.; Ye, S.; Zhang, J. Risk Reduction Measures and Monitoring Analysis of Deep Foundation Pit with Water in a Metro Station in Hefei. *Water* **2023**, *15*, 3007. https://doi.org/10.3390/w15163007

Academic Editor: Chin H Wu

Received: 19 July 2023
Revised: 8 August 2023
Accepted: 16 August 2023
Published: 21 August 2023

1. Introduction

In the last few years, China's accelerating urbanization has led to a massive increase in the urban population, which leads to the shortage of urban land and great pressure on traffic. To this end, many cities began to vigorously develop underground space, and use underground space to build garages, commercial streets, and subways [1,2]. On the one hand, the construction of underground garages, commercial streets, and subways can greatly alleviate the pressure of urban land use. On the other hand, the construction of underground garages, commercial streets, and subways can promote the development of a city [3–5]. When building an underground car park, a shopping street or a metro, it is inevitable that you will come across a foundation pit. The excavation depth of underground station foundation pits tends to be relatively large and the environment relatively complex, which makes the design of underground station foundation pit support more difficult than the design of general foundation pit support.

At present, the support structure forms of foundation pits in different cities are also different due to the different geological conditions, hydrogeological conditions, and environment of foundation pits in different cities [6–9]. The research on the excavation process of foundation pit can clarify the change law between the displacement of support structure, groundwater level and surface settlement, and the excavation depth of foundation pit. Sun et al. [10] investigated the deep horizontal displacement and deformation of the pile body during the excavation of the deep foundation pit of the subway transfer station by means of field monitoring in combination with finite element simulation. Yang et al. [11] used the finite element software Midas GTS NX to simulate the construction of deep foundation pits in the vicinity of subway stations in areas with soft soil. The effect of constructing deep foundation pits on the structural deformation and stress of the subway station is investigated, and the influence of the pit supporting structure on the station is analyzed, based on geotechnical investigation, building information modeling, and multi-source sensor technology. Hong et al. [12] proposed an integrated intelligent method for the monitoring and management of deep foundation pits in subway stations. And real-time and high-precision monitoring of the foundation pit can be achieved using this method. Yang et al. [13] collected the monitoring data of deep foundation excavations in soft soil of six railway lines in Fuzhou, and obtained the deformation law of large and deep foundation excavations in Fuzhou's soft soil layers through comparison with the research results of similar projects in domestic and foreign countries. Wang et al. [14] proposed a method suitable for deep foundation pit support of swampy metro stations by analyzing and optimizing the parameters of grouting reinforcement, which can significantly reduce the amount of grouting. Liu et al. [15] used field observation combined with numerical simulation to study the stress and deformation of the support structure of the deep excavation of an underground railway, and made some proposals on the monitoring and construction of the deep excavation of the underground railway according to the analysis results. Based on 3D FEA software, Zhang et al. [16] conducted a deep excavating and drainage simulation for a T-shaped metro station, and analyzed deformation characteristics during excavating. Relying on a metro station in Xiamen, Zhao et al. [17] investigated the deformation response of an underground foundation pit with diaphragm wall composite internal reinforcement using the method of field observation combined with numerical simulation. Risk assessment of the trench before it is excavated can predict the potential safety hazards of the trench and reduce the likelihood of accidents. Wu et al. [18] established a risk assessment index system on the basis of the support structure, the asymmetric earth pressure of the subway station, the foundation pit condition, the surroundings, and the safety and security management on construction sites. And the system can reasonably and effectively evaluate the asymmetric risk of building a deep foundation for a metro station. Ye et al. [19] used PLAXIS 3D FES to model the excavation of foundation pits adjacent to subway tunnels. The influence of the excavation of the foundation pit due to the deformation of the adjacent tunnel is analyzed, and the supporting structure of the excavation is optimized in accordance with the numerical simulation results to keep the excavations. Shen et al. [20] established a three-level fuzzy comprehensive assessment model on the premise of analyzing the factors involved in building subway stations. And this model can comprehensively assess the risk involved in constructing subway station excavations. Zhou et al. [21] established an intelligent model based on the machine learning model for risk prediction of deep foundation excavations in metro stations. And the importance assessment function of this model can help site engineers determine the cause of safety risks.

From the above research, it can be found that the current research on the deep foundation pit of the subway station is mainly focused on the safety of the foundation pit itself and its impact on the surrounding buildings, and there is little research on the potential risk assessment of the foundation pit before the foundation pit excavation. In particular, there is almost no risk assessment and monitoring of the excavation of the foundation pit for the Hefei metro station. This paper first analyzes and assesses the self-risk, the ground-water risk, and the surrounding environmental risk of the deep excavation of the Lingbi Road Station of Hefei Railway No. 8, and then provides the corresponding measures to reduce the risk of the deep excavation. Then, the entire excavation process is monitored in real time, and the safety of the excavation process and the rationality of the choice of support structure and parameters are revealed by analyzing the monitoring data from 13 projects. The study of this paper can provide a case reference for the support design of water-bearing deep foundation pit of subway station in Hefei area.

2. Project Overview

2.1. Site Profile

Lingbi Road Station is the second station of the first phase of Rail Transit Line 8 in Hefei City, Anhui Province, China. The station is located at the intersection of Fuyang North Road and Lingbi Road, and is built along Fuyang North Road. The station is an open-cut underground three-story double-column and three-span island station. The east side of the station is Fuyang North Road viaduct. The northeast quadrant of the station is the dormitory of Hefei Prospecting Machinery Factory. The southeast quadrant of the station is Anhui Survey and Design Institute. The southwest quadrant of the station is the second dormitory of the Municipal Public Security Bureau. The northwest quadrant of the station is the warehouse of Hefei Prospecting Machinery Factory. The red line width of Fuyang North Road in this site is 60 m, which is the main road of the city. The viaduct of Fuyang North Road is laid along the road, and the deck width of the standard section of the viaduct is 25.5 m. The red line of Lingbi Road is 24 m wide and is a side road of the city. The surrounding plan of the foundation pit is shown in Figure 1.

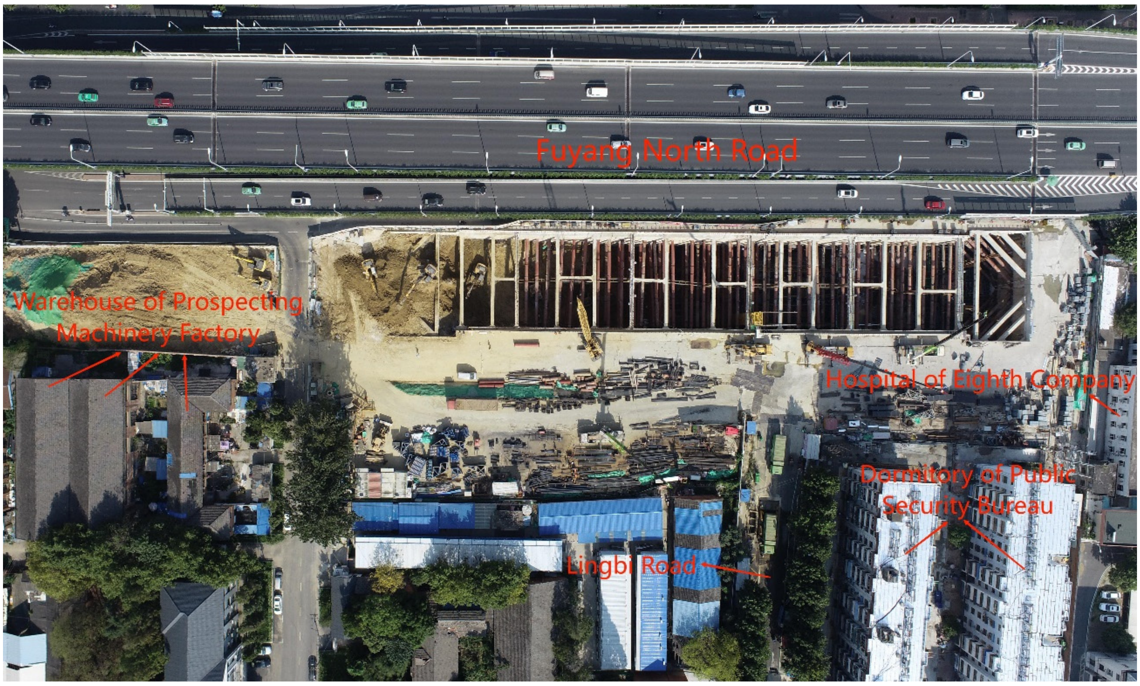


Figure 1. Surrounding environment plan of foundation pit.

There are two groups of wind pavilions, four entrances and exits, and two safety exits at Lingbi Road Station. The standard section excavation depth is approximately from 22.8 m to 23.6 m, the small mile end shaft excavation depth is approximately 24.1 m, and the large mile end shaft excavation depth is approximately 25.1 m. The total standard section width is 21.9 meters, the effective platform width is 13 meters, and the total station length is 155 meters. The two ends of the station are built using the shielding technique, with the small mileage end of the station equipped with a shielded launch pad and the large mileage end equipped with a shielded receiving pad. The station's main body is constructed by the open-cut method.

2.2. Engineering Geology Overview

The landform unit of Lingbi Road Station is a first-class terrace, the site is flat and open, with a natural slope of about 3–5° and an elevation of 23–27 m. The site is mainly the main road of urban traffic and residential area. Due to the long-term construction, most of the original landform has been changed. Table 1 shows the physical and mechanical parameters of the soil layer at Lingbi Road Station.

Table 1. The physical and mechanical parameters of each soil layer in Lingbi Road Station.

Soil code	Name of soil layer	Status	Floor level (m)	Natural Heavy $\gamma/(kN/m^3)$	Cohesion c/(kPa)
1	Fill soil	Loose to slightly dense	20.28~26.29	18	5
2-1	Clay soil	Malleable	12.28~21.29	19.4	35
2-2	Clay soil	Hard plastic	5.25~10.50	19.7	40
3-1	Silt	Medium secret	0.19~4.08	20.1	20
3-2	Silty sand	Medium secret	−1.91~1.28	20.1	1
4	Fully weathered argillaceous sandstone	The core is in the form of an earth column	−4.34~−1.11	20	30
5	Strongly weathered argillaceous sandstone	The core is massive	−8.34~−3.24	21	90
6	Moderately weathered argillaceous sandstone	The core is columnar	Not penetrated	23	140
Soil code	**Name of soil layer**	**Internal friction Angle $\varphi/(°)$**	**Permeability coefficient (m/d)**	**Standard value of limit resistance of soil on the side of pile (kPa)**	**Standard value of limit resistance of soil at the end of pile (kPa)**
1	Fill soil	7	0.1~5	—	—
2-1	Clay soil	17.4	0.0035	60	—
2-2	Clay soil	17	0.0024	85	—
3-1	Silt	23.1	0.1~0.5	45	—
3-2	Silty sand	24	1~2	45	—
4	Fully weathered argillaceous sandstone	16.2	0.1~0.2	85	1300
5	Strongly weathered argillaceous sandstone	22	0.1	160	1800
6	Moderately weathered argillaceous sandstone	28	0.05	200	2800

2.3. Hydrogeological Conditions

There are no rivers, reservoirs, and other water bodies in the proposed project area. The groundwater in the proposed project area is mainly perched water, micro-confined water, bedrock pore water, and fissure water. The perched water mainly occurs in the artificial fill, the water quantity is poor, the distribution is discontinuous, and the buried depth of the water level is 2.4~5.2 m. The confined water mainly occurs in silt (3-1) and silty sand (3-2). The buried depth at the top of silt (3-1) is 15.7–20.6 m, and the elevation of the top is 5.25–9.97 m. The buried depth at the top of silty sand (3-2) is 21.4~25.5 m, and the elevation of the top of the layer is 1.5~4.1 m. Silt (3-1) layer and silty sand (3-2) layer are generally rich in water, and the amount of groundwater gushing is small and has micro-pressure bearing property. The pore water of bedrock mainly occurs in fully weathered argillaceous sandstone (4), which is rich in water and weak in permeability. Bedrock fissure water mainly occurs in strongly weathered argillaceous sandstone (5) and moderately weathered argillaceous sandstone (6), which is rich in water and weak in permeability. In this survey section, the corrosion grade of groundwater to concrete structure is micro, and the corrosion grade of steel bar in concrete structure is micro. The corrosion grade of surface water to concrete structure is micro, and the corrosion grade of steel bar in concrete structure is micro.

3. Risk Characteristics and Countermeasures of Foundation Pit Engineering

There are various risks involved in the excavation of the foundation pit at Lingbi Road Subway Station. In order to reduce the likelihood of excavation accidents, it is necessary to evaluate the various risks of the excavation project and formulate countermeasures before excavating the foundation pit.

3.1. Own Risks and Countermeasures

3.1.1. Risk Situation

The excavation depth of the station standard section is 22.8~23.6 m, and the excavation width is 21.9 m. The excavation depth of the small mileage end well foundation pit is about 23.8 m, the excavation depth of the long mileage end well foundation pit is about 24.8 m, and the excavation width of the final pit is approximately 26.45 m. The excavation method of the foundation pit is the open-cut method, and the surrounding environment is normal. Soils within the pit excavation include clay (2-1), clay (2-2), and silt (3-1), and there is micro-confined water in silt (3-1) and silt (3-2). After a comprehensive evaluation, the risk level of the foundation pit itself is level one.

3.1.2. Countermeasures

(1) The ground in a certain area around the foundation pit is hardened to cut off the recharge of surface water and atmospheric precipitation to groundwater, and at the same time, the drain water on the ground and in the pit in time. (2) During the construction of foundation pit, it is necessary to ensure layered excavation, timely installation of bracing, strict prohibition of over excavation, and the steel bracing has anti-loosening and pre-stressing additional measures. (3) Monitoring of the foundation pit and observation and treatment of the diving level during construction. (4) To formulate emergency measures to deal with unfavorable weather, such as sudden heavy rainfall and instantaneous rainstorm, during construction. The foundation pit's own residual risk level after the countermeasures is level three.

3.2. Risks of Foundation Pit Dewatering and Its Countermeasures

3.2.1. Risk Situation

Confined water mainly occurs in silt (3-1) and silt (3-2). According to the on-site exploration, the water-rich situation of this layer is general, the amount of groundwater gushing is small, and it has micro-pressure bearing property. The risk level of foundation pit dewatering is level two.

3.2.2. Countermeasures

(1) The foundation pit adopts an underground diaphragm wall with a thickness of 1000 mm, and the bottom of the wall enters the moderately weathered rock layer to isolate the confined water layer. (2) Pressure-relief wells and water-collecting open drains are installed in the foundation pit. The type of pressure-relief wells is tube well with a diameter of 600 mm, and the pipe well is 6 m deeper than the bottom of foundation pit. Observation wells and emergency backup wells are installed outside the foundation pit. The risk level of foundation pit dewatering after the countermeasures is level three.

3.3. Environmental Risks and Countermeasures

3.3.1. Risk Situation of Underground Pipeline

(1) The DN1000 rainwater pipe is buried at a depth of about 2.0 m, which is arranged along Lingbi Road and is located on the west side of the main body of the station. (2) The DN700 sewage pipe is buried at a depth of about 1.5 m and is located on the west and south sides of the main foundation pit. (3) The D200 gas pipe is buried at a depth of about 1.4 m and is located on the west and south sides of the main foundation pit. (4) The DN700 heat pipe is buried at a depth of about 2.1 m and is located on the east side of the main foundation pit. The foundation pit risk level caused by underground pipelines is level two.

3.3.2. Countermeasures

(1) Before the construction of the main foundation pit, prepare a special emergency plan for risk events, such as excessive pipeline deformation and pipeline leakage. (2) The relocation distance of the pipeline meets the requirements of the code, and at the same time, it is analyzed that the deformation caused by the excavation of the foundation pit must meet the deformation protection requirements. (3) Strengthen the monitoring and protection of the pipeline. After the pipeline is relocated, direct measuring points should be arranged and the formation deformation at the location of the pipeline after the relocation should be monitored. Once the alarm value is exceeded, take the corresponding control measures, such as grouting and reinforcement. The residual risk level of the underground pipeline after the countermeasures is level three.

3.3.3. Risk Situation of Fuyang North Road Viaduct and Buildings around the Foundation Pit

Fuyang Road viaduct (see Figure 2), the main bridge of Fuyang Road viaduct, is laid along the north-south direction of Fuyang North Road, and is located on the east side of the main body of the station. The bridge adopts pile foundation + cap foundation, the pile diameter is 1.5 m, the pile length is 39~41 m, and the bridge deck width is 25.5 m. The bridge piles of the main bridge are about 20.66 m closest to the main foundation pit of the station. The on-ramp bridge is laid along the north-south direction of Fuyang North Road and is located on the east side of the main body of the station. The ramp bridge adopts pile foundation + cap foundation, the pile diameter is 1.2 m, the pile length is 32~35 m, and the bridge deck width is 8.5 m. The nearest distance between the ramp bridge pile and the main foundation pit of the station is about 4.31 m. There is an abandoned civil air defense passage at the north end of the station and near the entrance and exit on the east side of the station, running east-west and north-south. The connecting channel is a brick arch structure with a buried depth of about 10 m, a width of about 2 m, and a height of about 2.5 m. The risk level of the foundation pit caused by the Fuyang North Road viaduct is level one.

Figure 2. Fuyang Road viaduct and buildings around the foundation pit.

The buildings around the foundation pit are shown in Figure 2. (1) The guard room of the factory building of Hefei Prospecting Machinery Factory is a brick structure on the first floor, about 25 m away from the main foundation pit of the station. (2) The private house is a one-story brick structure, about 43 m away from the main foundation pit of the station. (3) The factory building of Hefei Prospecting Plant is a one-story brick structure, about 39 m away from the main foundation pit of the station. (4) The No. 1 residential building in the second living area of Hefei Public Security Bureau is a seven-story concrete structure, and the closest distance to the main foundation pit of the station is about 32 m. (5) The No. 5 residential building in the second living area of the Hefei Public Security Bureau is a six-story concrete structure, and the closest distance to the main foundation pit of the station is about 29 m. (6) The outpatient building is a four-story concrete structure, about 14 m away from the main foundation pit of the station. The risk level of the foundation pit caused by the surrounding buildings is level two.

3.3.4. Countermeasures

(1) The foundation pit support adopts underground diaphragm wall + internal bracing system, the thickness of the ground connection wall is 1000 mm, the first bracing adopts concrete support, and the second, third, and fourth bracing positions are steel bracings. The length of the underground continuous wall is 31.10~34.39 m, and the embedded depth is 10.36~10.49 m. The section size of the first reinforced concrete bracing is 1000 mm $\times$ 1000 mm, the diameter of second and third steel bracings is 800 mm, and the wall thickness is 20 mm. The diameter of fourth steel bracing is 800 mm and the wall thickness is 16 mm. The axial force servo system is added within the influence range of the viaduct piles, and the deformation of the foundation pit and the surrounding environment is controlled by strengthening the rigidity of the support structure. The section view of the support structure is shown in Figure 3. (2) Before construction, the third party shall evaluate the current quality and allowable deformation of the building, and propose the limit deformation value, warning value, and early warning value of the foundation allowed by the current building. The early warning value is 70% of the ultimate deformation value of the foundation, and the warning value is 80% of the ultimate deformation value of the foundation. (3) During the construction of the foundation pit, strengthen the monitoring of viaduct pile foundations and other buildings. According to the monitoring results, the construction plan and method can be dynamically adjusted in a timely manner, and the grouting can be tracked in real time. The residual risk level of the surrounding environment after the countermeasures is level three.

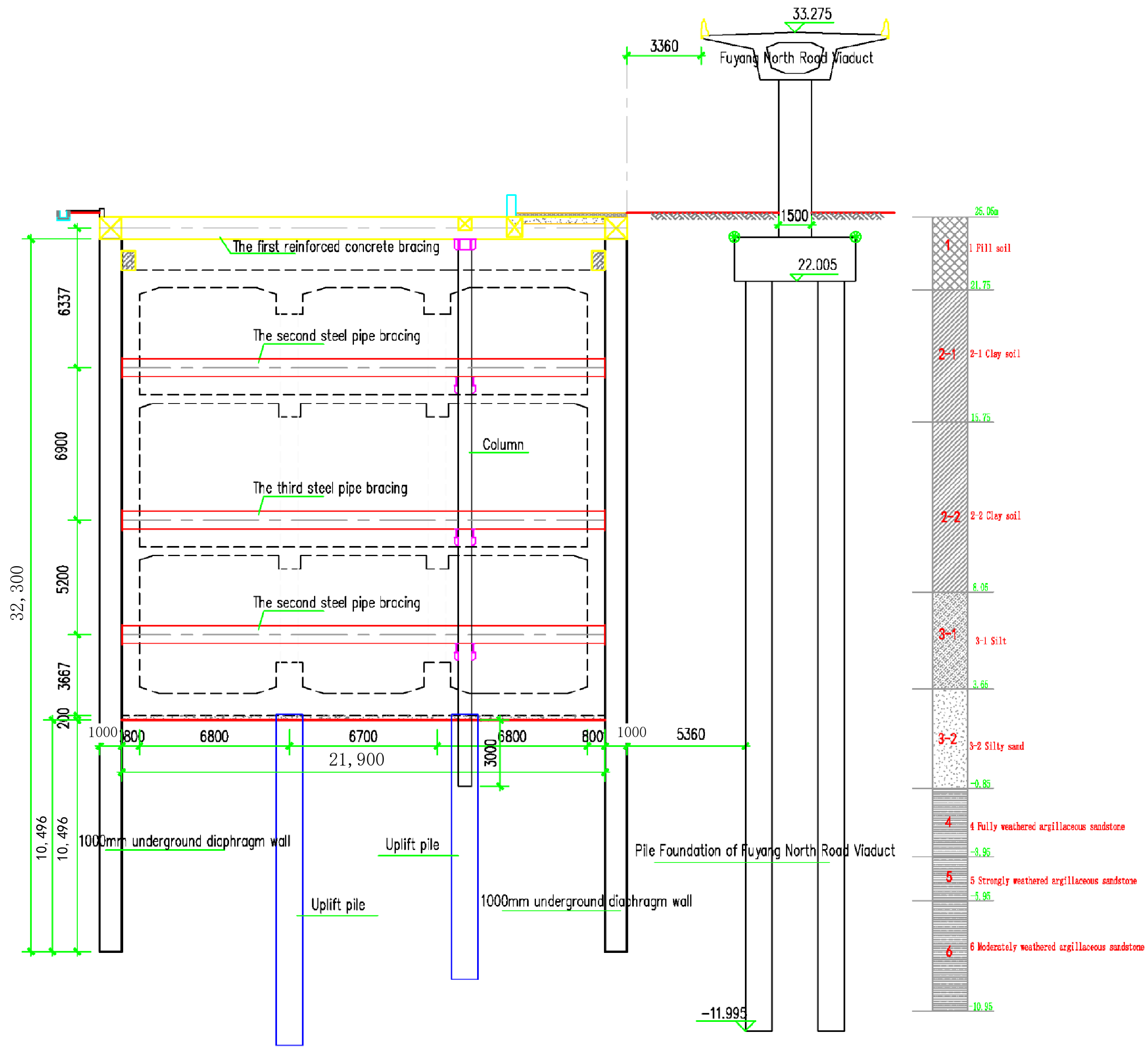


Figure 3. The section view of the support structure. Field monitoring and data analysis.

4. Field Monitoring and Data

According to the surrounding environment, hydrogeological conditions, and supporting structure types of the foundation pit of Lingbi Road Station, the monitoring objects of this project mainly include open-cut foundation pit, cover-excavated roof, surrounding important buildings, surrounding ground roads, surrounding important underground pipelines, and surrounding rocks and soils. For the above monitoring objects, the specific monitoring items of this foundation pit project mainly include horizontal displacement at the top of wall, vertical displacement at the top of wall, horizontal displacement in the deep layer of wall, axial force of the internal bracing, settlement of the columns, horizontal displacement of the columns, settlement of the building, groundwater level, surface settlement, pipeline settlement, settlement of the bridge abutment, horizontal displacement of the bridge abutment, and tilt of the bridge abutment. Figure 4 shows the plan view of the monitoring points in foundation pit, and the number of monitoring points are shown in Table 2.

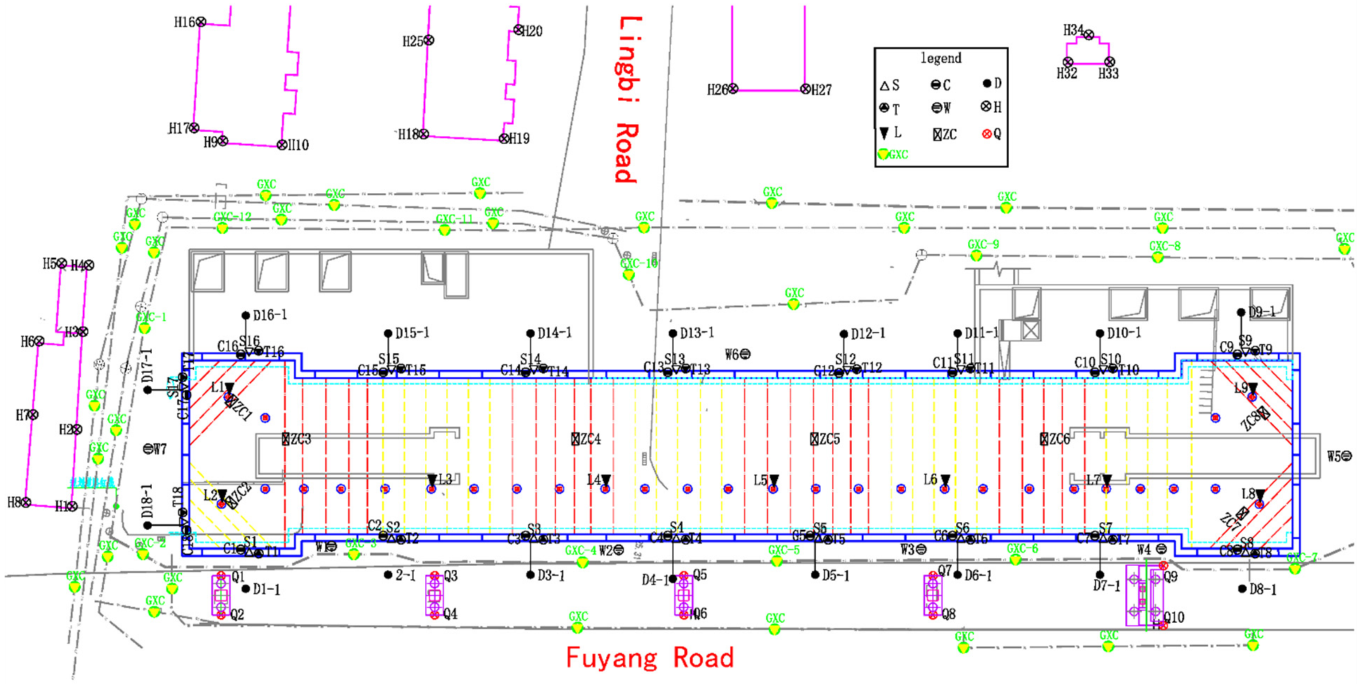


Figure 4. Plan view of monitoring points in foundation pit.

Table 2. Number of monitoring points.

Monitoring Project	Number of Monitoring Points
Horizontal displacement at the top of wall	18
Vertical displacement at the top of wall	18
Horizontal displacement in the deep layer of wall	18
Axial force of the internal bracing	32
Settlement of the columns	9
Horizontal displacement of the columns	9
Settlement of the building	37
Groundwater level	7
Surface settlement	74
Pipeline settlement	35
Settlement of the bridge abutment	60
Horizontal displacement of the bridge abutment	60
Tilt of the bridge abutment	60

4.1. Horizontal Displacement at the Top of Wall

The construction process of the underground diaphragm wall is shown in Figure 5. The horizontal displacement monitoring points at the top of the retaining wall are arranged in an array-like pattern along the perimeter of the foundation pit, with one measurement point every 20 to 40 m. It is advisable to place the monitors in the middle of each side of the trench, at the sun angles and near the shelter, and to place two monitors at each end-well on either side of the station. A total of 18 monitoring points are in place, with numbers from S1 to S18. The instrument used to monitor the horizontal displacement at the top of the wall is a Leica TS09 total station, and the monitoring map of the field is shown in Figure 6. Figure 7 shows the results of monitoring the horizontal displacement at the top of the wall.

Figure 5. Construction picture of underground diaphragm wall.

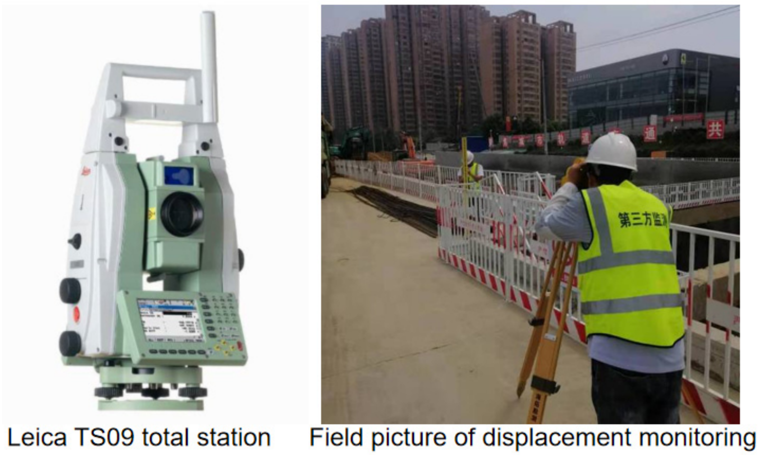


Figure 6. Field monitoring map of horizontal displacement at the top of wall.

As shown in Figure 7, before 1 August 2021, the horizontal cumulative displacement of each monitoring point is gradually increasing, and after 1 August 2021, the cumulative horizontal displacement of each monitoring point decreases sharply. This is due to the fact that before 1 August 2021, the excavation of the foundation pit begins after the construction of the diaphragm wall and the first reinforced concrete bracing is completed, and the cumulative value of the horizontal displacement at the top of the wall increases with the increase in the excavation depth. After 1 August 2021, the second steel pipe bracing was constructed, and the second steel pipe bracing played a certain role in controlling the deformation of the foundation pit; therefore, the cumulative value of horizontal displacement at the top of the wall decreased sharply. After 15 November 2021, each monitoring point's cumulative horizontal displacement remains basically unchanged. This is due to the fact that the foundation pit has been excavated to the bottom of the pit on 15 November 2021, after which the foundation construction and the construction of the main structure of the subway station begin. When the depth of the foundation pit no longer changes, the horizontal displacement at the top of the wall changes a little. It can also be seen from Figure 7 that the horizontal cumulative displacement value of S14 monitoring point is the largest, and the displacement value is 2.34 mm. In the whole process of foundation pit excavation, the monitoring values of the horizontal displacement monitoring points at the top of the wall did not exceed the control value (15 mm) set by the code [22], which meets the design requirements.

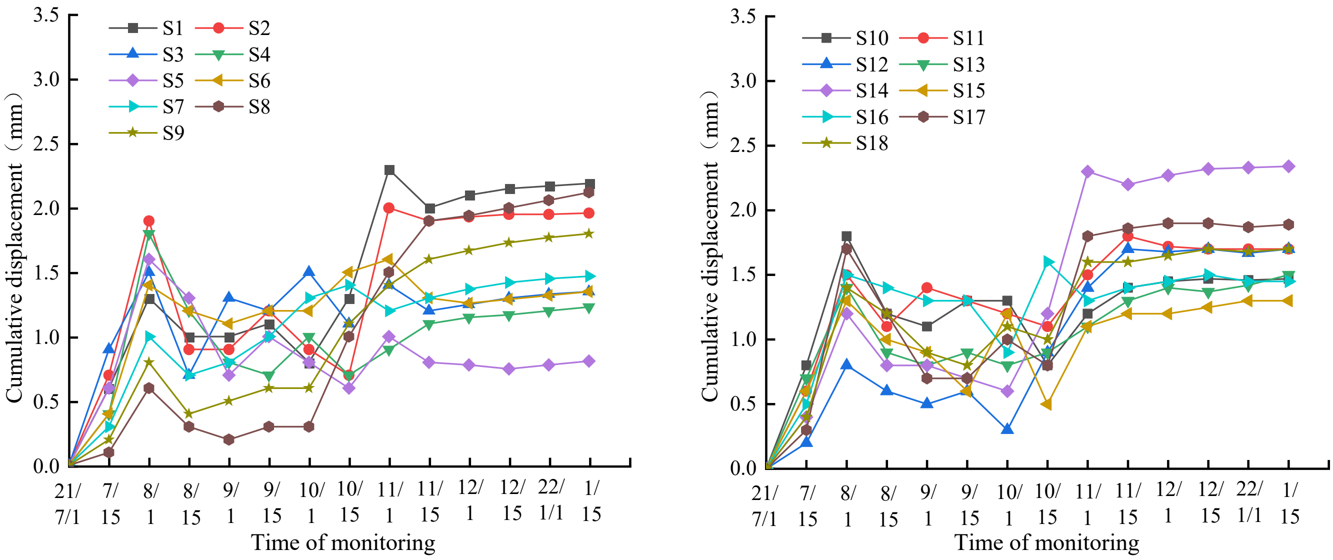


Figure 7. Time history curve of horizontal displacement at the top of wall.

4.2. Vertical Displacement at the Top of Wall

The vertical displacement monitoring point at the top of the enclosure wall and the horizontal displacement monitoring point at the top of enclosure wall are common points. The vertical displacement monitoring instrument at the top of wall is Trimble DINI03 electronic level, and the field monitoring map is shown in Figure 8. The horizontal displacement monitoring results at the top of wall are shown in Figure 9.

Figure 8. Field monitoring map of vertical displacement at the top of wall.

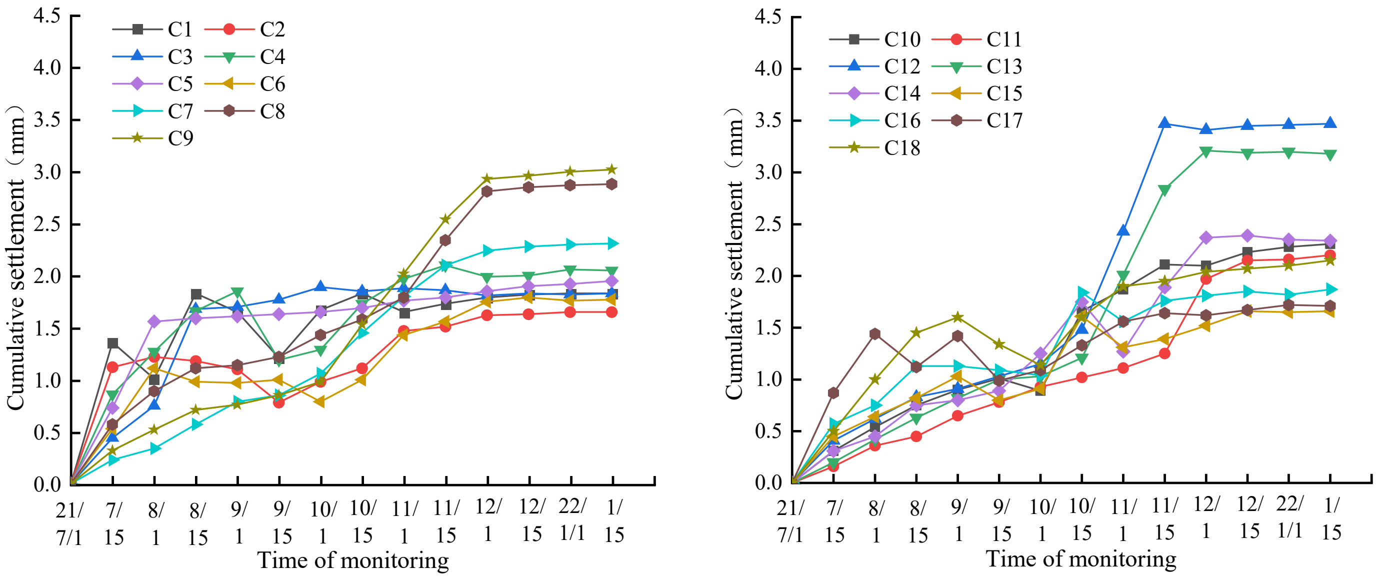


Figure 9. Time history curve of vertical displacement at the top of wall.

As shown in Figure 9, before 1 December 2021, the cumulative settlement of each monitoring point showed an overall increasing trend, but the cumulative settlement of some monitoring points showed a decreasing trend within the range of the small area. After 1 December 2021, the cumulative settlement of each monitoring point has changed very little. It can also be seen from Figure 5 that the cumulative settlement of the C12 monitoring point is the largest, with a settlement of 3.47 mm, and the cumulative settlement of the C2 monitoring point is the smallest, with a settlement of 1.65 mm. During the entire excavation process of the foundation pit, the monitoring values of each vertical displacement monitoring points at the top of the wall did not exceed the control value (10 mm) stipulated in the code [22], which meets the design requirements.

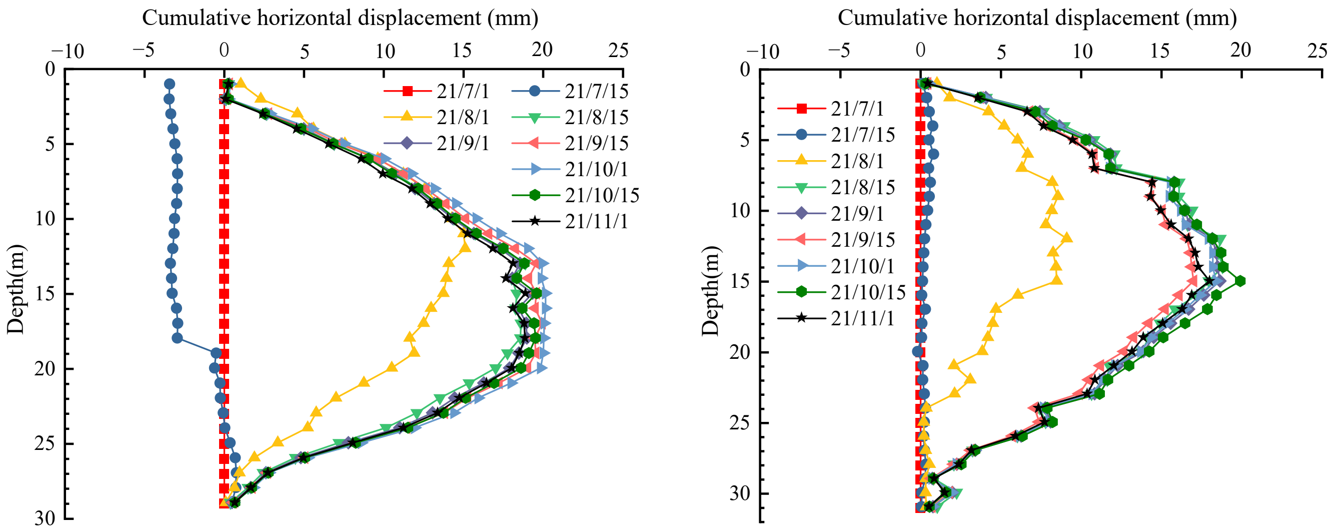
4.3. Horizontal Displacement in the Deep Layer of Wall

The layout of the monitoring points for the deep horizontal displacement of the enclosure wall is the same as that of the horizontal displacement monitoring points for the top of the enclosure wall. The inclinometer pipe is fixed on the steel cage of the wall by direct binding, and after the steel cage is put into the groove, concrete is poured, as shown in Figure 10. A total of 18 monitoring points are in place, with numbers from T1 to T18. The deep horizontal displacement monitoring instrument of the wall is the CX-3C foundation pit inclinometer, and the field monitoring map of horizontal displacement in the deep layer of wall (see Figure 11). According to the importance of the location of the monitoring points, the monitoring results of the deep horizontal displacement of the four monitoring points T2, T4, T6, and T12 with the largest displacement are shown in Figure 12.

Figure 10. The actual picture of the laying of the inclinometer pipe.

CX-3C inclinometer for foundation pit Field picture of displacement monitoring

Figure 11. Field monitoring map of horizontal displacement in the deep layer of wall.



(**a**) (**b**)

Figure 12. *Cont.*

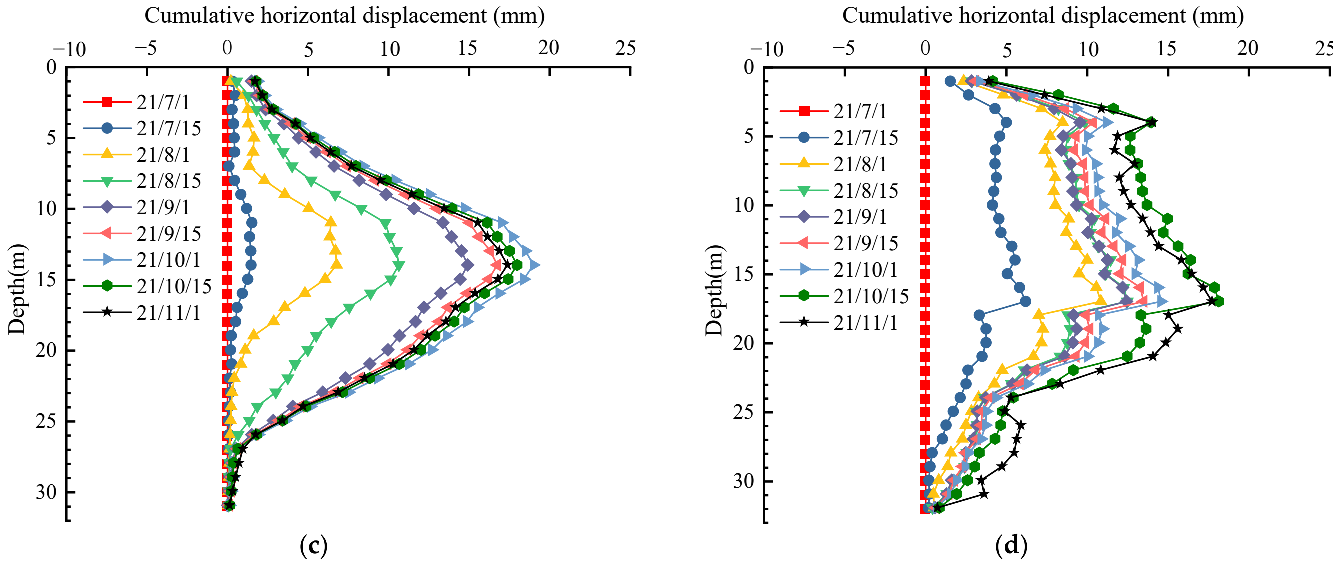


Figure 12. Time history curve of horizontal displacement in the deep layer of wall. (**a**) Time history curve of horizontal displacement in the deep layer of T2. (**b**) Time history curve of horizontal displacement in the deep layer of T4. (**c**) Time history curve of horizontal displacement in the deep layer of T6. (**d**) Time history curve of horizontal displacement in the deep layer of T12.

As shown in Figure 12, except for 1 July and 15 July 2021, the deep horizontal displacements of T2, T4, T6, and T12 monitoring points all showed a trend that is large in the middle and small at the ends for the rest of the time. The above rules also fully demonstrate that in the design of foundation pit support, the middle and lower parts of the foundation pit are the focus of the design. From Figure 12a, it can be seen that the maximum displacement of T2 monitoring point occurred at the buried depths of 15 m and 16 m on 1 October 2021, and the maximum displacement was 20.20 mm. From Figure 12b, it can be seen that the maximum displacement of T4 monitoring point occurred at a buried depth of 15 m on 15 October 2021, and the maximum displacement was 19.98 mm. From Figure 12c, it can be seen that the maximum displacement of T6 monitoring point occurred at the buried depth of 14 m on 1 October 2021, and the maximum displacement was 19.06 mm. From Figure 12d, it can be seen that the maximum displacement of T12 monitoring point occurred at a buried depth of 17 m on 15 October 2021, and the maximum displacement was 18.2 mm. Throughout the excavation of the foundation pit, the monitoring values of the deep horizontal displacement monitoring points of each wall did not exceed the control value (30 mm) specified in the code [22], which meets the design requirements.

4.4. Axial Force of the Internal Bracing

The construction process of the first reinforced concrete internal bracing is shown in Figure 13. The number of monitoring points for each layer of bracing is not less than 10% of the number of each layer of bracing, and not less than three. Eight monitoring points are arranged for the first reinforced concrete bracing, numbered from ZC1 to ZC8. Eight monitoring points are arranged for the second steel bracing, numbered from ZC2-1 to ZC2-8, and the axial force meter of bracing is shown in Figure 14. The bracing axial force monitoring instrument is CTY-202 vibrating wire frequency reading instrument, and the field picture of bracing axial force (see Figure 15). Considering the importance of the bracing position, only the monitoring data of the first bracing and the second bracing are analyzed. Due to the damage of the second bracing monitoring point during the construction process, there are only four monitoring points that can obtain monitoring data. The monitoring results of the bracing axial force are shown in Figure 16.

Figure 13. Construction process of the first reinforced concrete internal bracing.

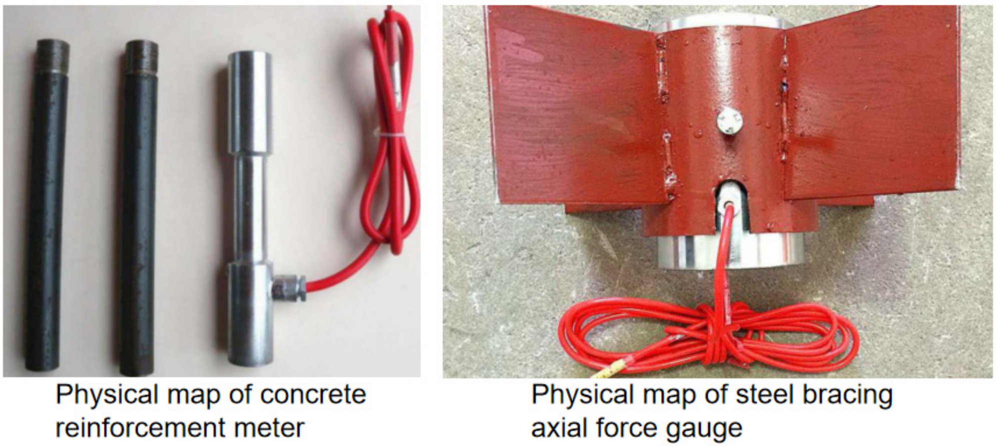


Figure 14. The axial force meter of bracing.

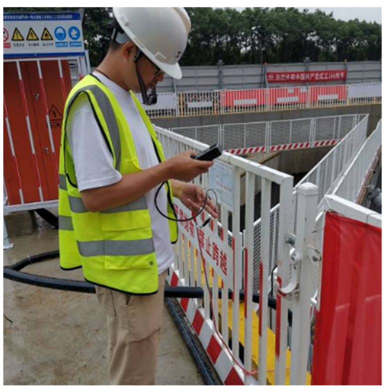


Figure 15. Field picture of bracing axial force.

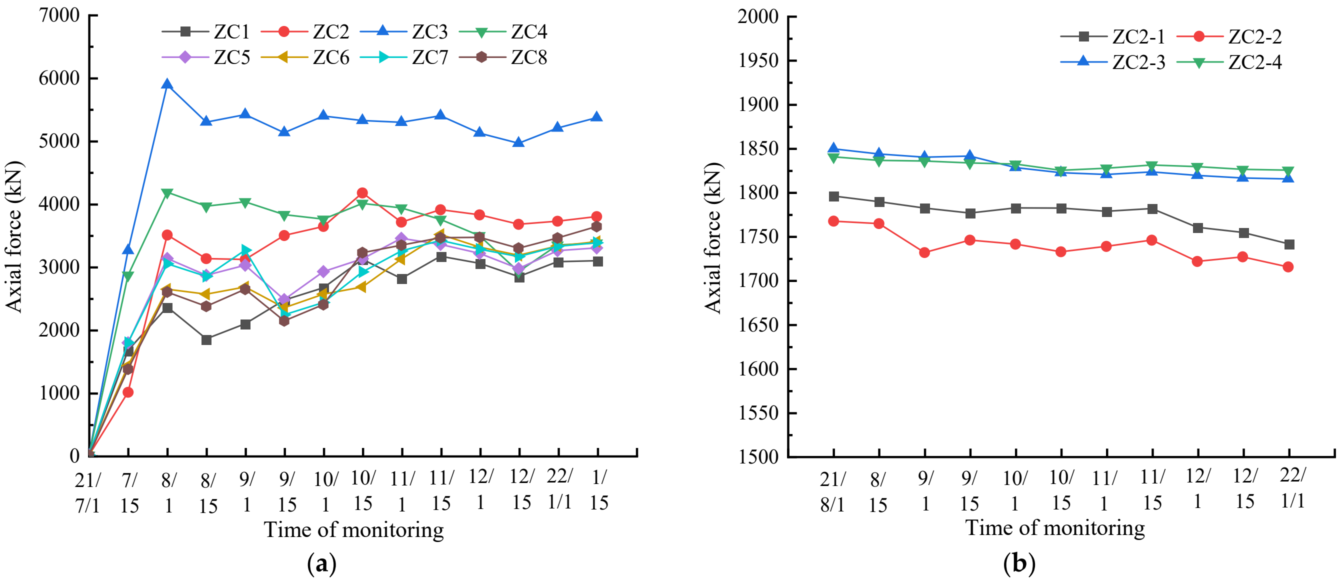


Figure 16. Axial force variation curve of internal bracing. (**a**) Axial force variation curve of first bracing. (**b**) Axial force variation curve of second bracing.

As shown in Figure 16a, before 1 August 2021, the axial force of each monitoring point on the first reinforced concrete bracing gradually increases, and after 1 August 2021, the axial force of each monitoring point Axial force is slightly reduced and then remains stable. This is due to the fact that before 1 August 2021, the excavation of the foundation pit earthwork will start after the construction of the first reinforced concrete bracing. As the excavation depth increases, the earth pressure that the first bracing needs to bear will increase, thus the axial force value is also gradually increasing. After 1 August 2021, the second steel pipe bracing was constructed. The second steel pipe bracing shared part of the earth pressure and reduced the earth pressure borne by the first bracing; therefore, the axial force of the first bracing decreased rapidly. It can be seen from Figure 16b that the axial force of the second steel bracing is gradually decreasing, but the decreasing range is small. This is due to the fact that after the construction of the second steel bracing, the third steel bracing and the fourth steel bracing will be constructed, and the third steel bracing and the fourth steel bracing have reduced the earth pressure on the second steel bracing. As a result, the axial force of the second steel bracing has been showing a decreasing trend. Among the four bracings, the first reinforced concrete bracing has the largest axial force at the monitoring point ZC3, with an axial force value of 5893.52 kN. Throughout the excavation of the foundation pit, the monitoring values of the bracing axial force monitoring points did not exceed the control value (14,000 kN) specified in the code [22], which meets the design requirements.

4.5. Settlement of the Columns

The construction picture of the column is shown in Figure 17. The monitoring number of column settlement shall not be less than 5% of the total number of columns, and not less than three. The column settlement monitoring point is arranged in the middle of the foundation pit and at the intersection of multiple bracings. The layout method is to paste the reflector to the top side of the column exposed by excavation. A total of nine monitoring points are in place, with numbers from L1 to L9, and the column settlement monitoring instrument is TS09 total station. Due to the destruction of some monitoring points in the process of construction, there are only four monitoring points that can read the data. The monitoring results of column settlement are shown in Figure 18.

Figure 17. The construction picture of the column.

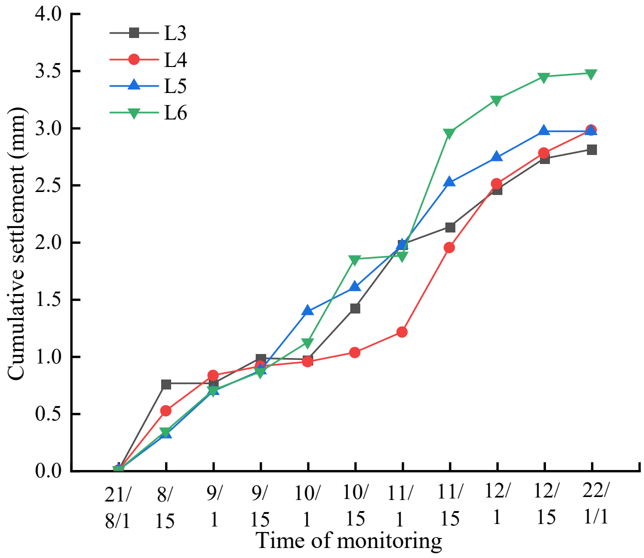


Figure 18. Time history curve of column settlement.

As shown in Figure 18, the cumulative settlement of the column increases gradually. This is due to the fact that in addition to the construction of the first reinforced concrete bracing, three steel bracings must be applied along with the excavation of the foundation pit. The bracing itself also has weight, the weight will increase as the number of supports increases, and the cumulative settlement of the column will increase accordingly. Moreover, it can be seen from Figure 18 that among the four monitoring points where monitoring data can be obtained, the cumulative settlement of L6 is the largest, with a settlement of 3.48 mm. Throughout the excavation of the foundation pit, the monitoring values of the column settlement monitoring points did not exceed the control value (10 mm) stipulated in the code [22], which meets the design requirements.

4.6. Horizontal Displacement of the Columns

The horizontal displacement monitoring point and the settlement monitoring point of the column are common points. The settlement monitoring instrument of the column is TS09 total station, and the monitoring results of horizontal displacement of the column are shown in Figure 19.

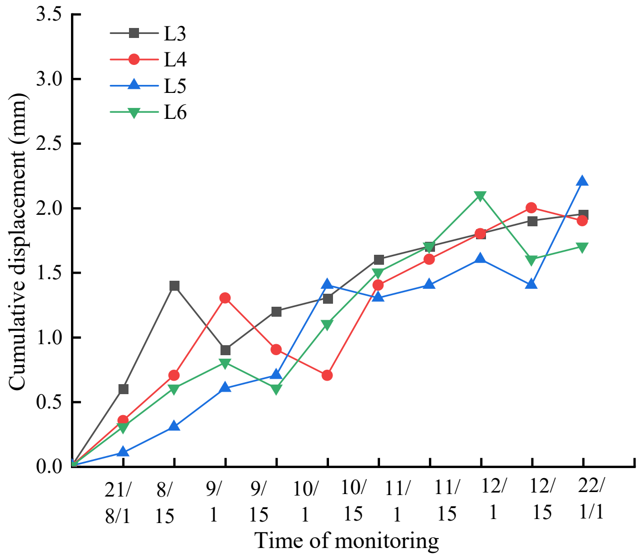


Figure 19. Time history curve of horizontal displacement of column.

As shown in Figure 19, the horizontal cumulative displacement of the column generally shows a tendency to increase, but the cumulative settlement of some monitoring points shows a decreasing trend in the small interval. Among the four monitoring points where monitoring data can be obtained, the horizontal cumulative displacement of L5 monitoring point is the largest, and the displacement value is 2.2 mm. In the whole process of foundation pit excavation, the monitoring value of the horizontal displacement monitoring point of the column did not exceed the control value (10 mm) set by the code [22], which meets the design requirements.

4.7. Settlement of the Building

Points are arranged around the building, and each building has no less than four monitoring points. A total of 37 monitoring points are set up, numbered as H1 to H37, and the building settlement monitoring instrument is Trimble DINI03 electronic level. Considering the importance of the location of the monitoring point, the monitoring point with large settlement is selected for analysis. The monitoring results of building settlement are shown in Figure 20.

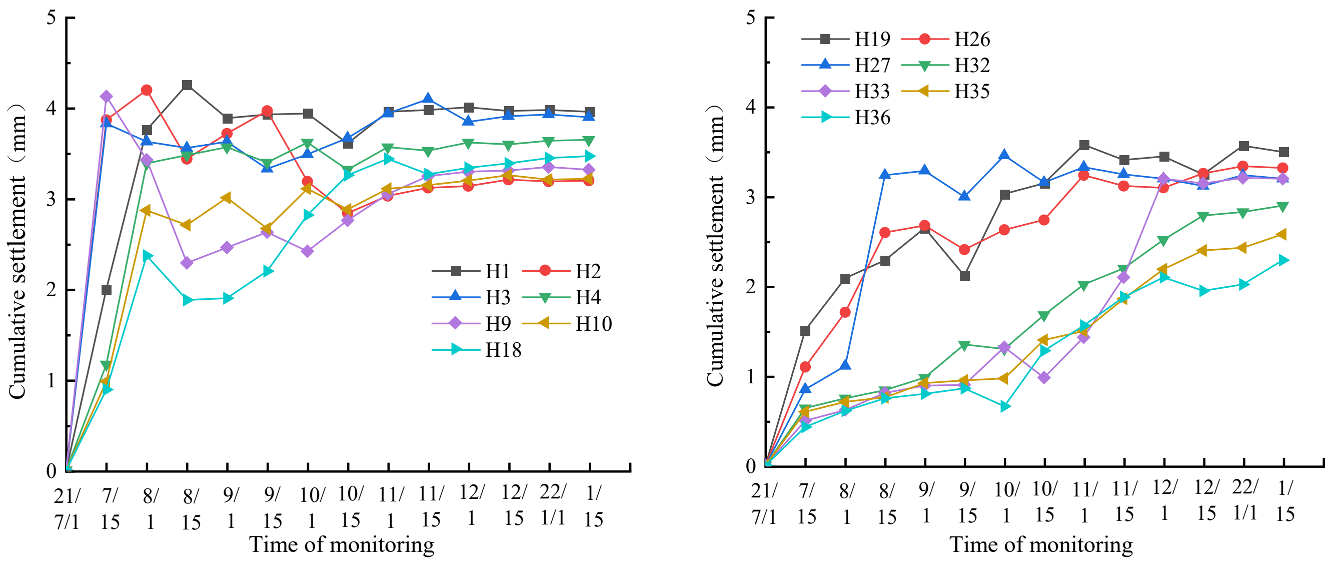


Figure 20. Time history curve of building settlement.

According to Figure 20, the cumulative settlement of the 14 monitoring points will first increase, then fluctuate within a certain range, and finally tend to stabilize. This is mainly related to the construction conditions of the foundation pit, the foundation pit begins to be excavated after the completion of the first bracing construction, and the settlement of the surrounding buildings will increase rapidly with the increase in the depth of the foundation pit. Then, the second, third, and fourth steel bracings are constructed to make the settlement of the surrounding buildings fluctuate within a certain range. When excavated to the bottom of the pit for foundation construction and the construction of the main structure of the station, the settlement of the surrounding buildings will remain stable. It can also be seen from Figure 20 that the closer the building is to the foundation pit, the greater the cumulative settlement. Among the 14 monitoring sites, the cumulative settlement of H1 is the largest, and the settlement is 4.26 mm. In the whole process of foundation pit excavation, the monitoring value of the horizontal displacement monitoring point of the column did not exceed the control value (10 mm) set by the code [22], which meets the design requirements.

4.8. Groundwater Level

The groundwater level monitoring points are arranged around the foundation pit, and at least one groundwater level observation hole is arranged on each side of the foundation pit. A total of seven monitoring points are in place, with numbers from W1 to W7. The SWJ-90 steel ruler water level meter is used to monitor the groundwater level, and the field picture of groundwater level is shown in Figure 21. Due to the destruction of two monitoring points during construction, there are only five monitoring points that can read the data. The monitoring results of building settlement are shown in Figure 22.

Figure 21. Field picture of groundwater level.

As shown in Figure 22, the groundwater table has been on a downward trend until 15 July 2021. This is due to the fact that in order to reduce the influence of groundwater on foundation pit construction during foundation pit excavation, dewatering wells are used to dewater the foundation pit. After 15 July 2021, the water table has risen. This is due to the fact that after the dewatering of the foundation pit, it is replenished by the surrounding water sources; therefore, the water level of the foundation pit rises slightly. After 1 August 2021, the groundwater level remains basically unchanged, and the height of the groundwater level is below the bottom of the foundation pit, which does not affect the construction of the foundation pit.

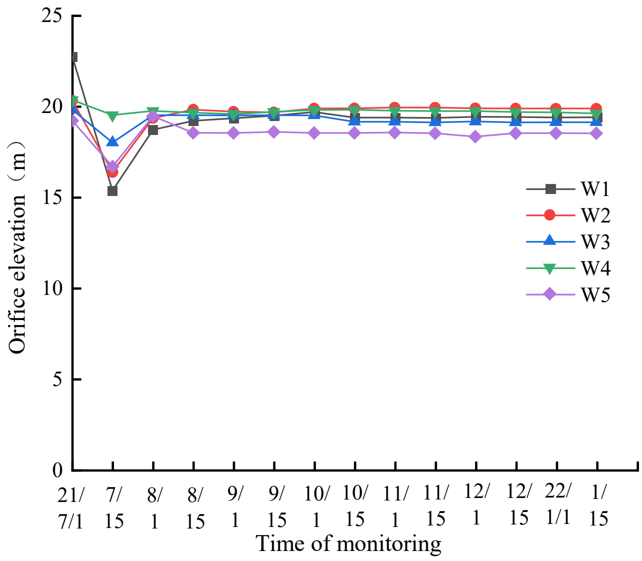


Figure 22. Time history curve of groundwater level.

4.9. Surface Settlement

A transverse monitoring section perpendicular to the boundary line of the foundation pit is arranged along the surface spacing around the foundation pit every 20 to 40 m, with four monitoring points on each side, with a total of 74 monitoring points. The surface subsidence monitoring instrument is TrimbleDINI03 electronic level, and the field picture of surface settlement is shown in Figure 23. Considering the importance of the location of the monitoring points, nine monitoring points close to the foundation pit are selected for analysis. The monitoring results of surface settlement are shown in Figure 24.

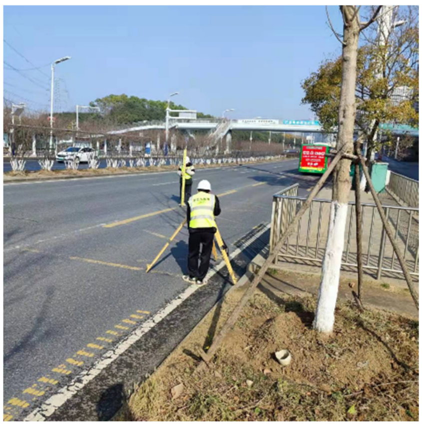


Figure 23. Field picture of surface settlement.

As shown in Figure 24, the surface subsidence shows an increasing trend. The cumulative settlement of each monitoring point increases rapidly before 1 November 2021, and slows down after 1 November 2021. This is due to the fact that on 1 November 2021, the excavation of the foundation pit has been completed, the depth of the foundation pit is no longer increased, and the impact on surface settlement is reduced. Among nine monitoring sites, the cumulative settlement of D18-1 is the largest, and the settlement is 10.95 mm. In the whole process of foundation pit excavation, the monitoring value of the surface settlement monitoring point did not exceed the control value (30 mm) set by the code [22], which meets the design requirements.

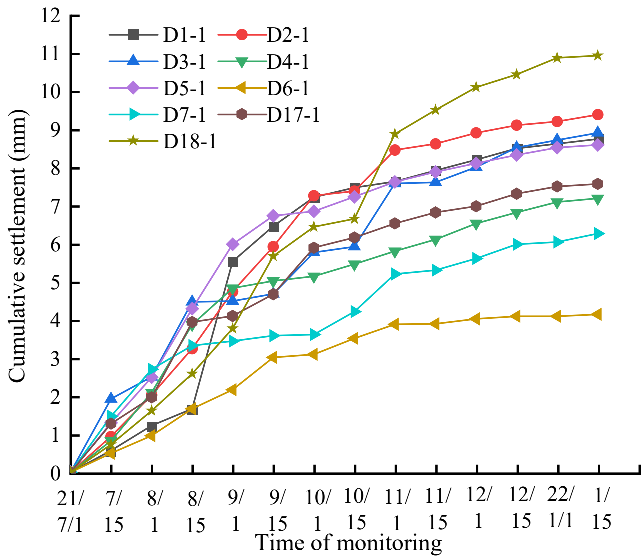


Figure 24. Time history curve of surface settlement.

4.10. Pipeline Settlement

The underground pipeline located in the main influence area shall set up one monitoring point every 5 m to 15 m, and the underground pipeline in the secondary influence area shall set up one monitoring point every 1500 m, with a total of 35 monitoring points. The surface subsidence monitoring instrument is Trimble DINI03 electronic level. Considering the importance of pipeline location, the monitoring points close to the foundation pit are selected for analysis. The monitoring results of pipeline settlement are shown in Figure 25.

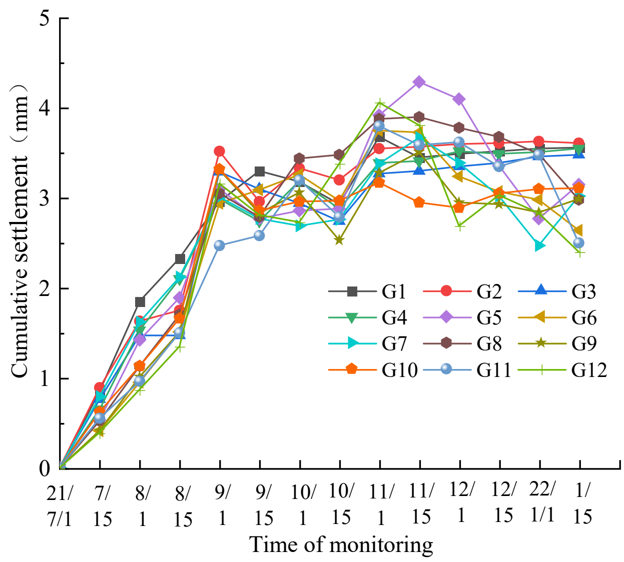


Figure 25. Time history curve of pipeline settlement.

As shown in Figure 25, before 1 September 2021, the cumulative settlement at each monitoring point continued to increase. After 1 September 2021, the cumulative settlement of each monitoring point fluctuated to a small extent, but after 1 November 2021, the cumulative settlement of G1, G2, G3, and G4 remained basically unchanged. Among 12 monitoring sites, the cumulative settlement of G5 monitoring site is the largest, and the settlement is 4.29 mm. In the whole process of foundation pit excavation, the monitoring value of surface settlement monitoring point did not exceed the control value (10 mm) set by the code [22], which meets the design requirements.

4.11. Settlement of the Bridge Abutment

One settlement monitoring point is arranged on one side of the bridge abutment and one side along the bridge, and two settlement monitoring points are set up on each bridge abutment, a total of 60 monitoring points are set up. The instrument for monitoring the settlement of bridge abutment is Trimble DINI03 electronic level. Due to the importance of the bridge abutment position, the monitoring point close to the foundation pit is selected for analysis. The monitoring results of settlement of the bridge abutment are shown in Figure 26.

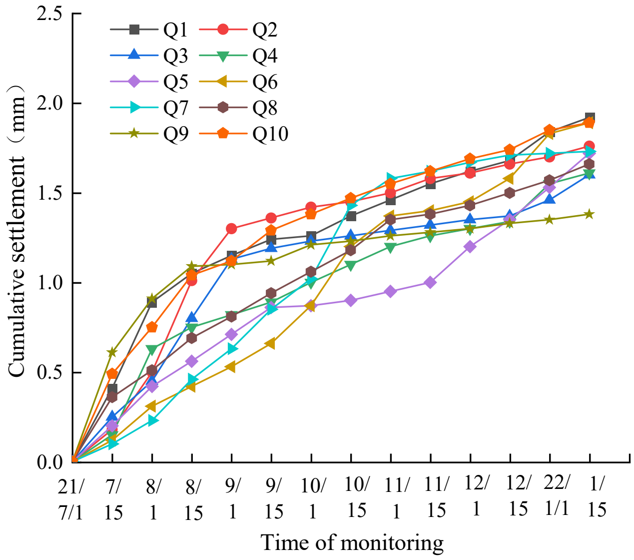


Figure 26. Time history curve of settlement of the bridge abutment.

As shown in Figure 26, with the increase in the excavation depth of the foundation pit, the settlement of the bridge abutment continues to increase. The cumulative settlement of each monitoring point increases rapidly before 1 September 2021, and slows down after 1 September 2021. Among 10 monitoring sites, the cumulative settlement of Q1 monitoring site is the largest, and the settlement is 1.92 mm. In the whole process of foundation pit excavation, the monitoring value of bridge abutment settlement monitoring points did not exceed the control value (5 mm) set by the code [22], which meets the design requirements.

4.12. Horizontal Displacement of the Bridge Abutment

One horizontal displacement monitoring point is arranged on one side of the bridge abutment and one horizontal displacement monitoring point on the side along the bridge, and two horizontal displacement monitoring points are set up on each bridge abutment, with a total of 60 monitoring points. The horizontal displacement monitoring points are arranged by directly pasting Leica reflective paste. The instrument for monitoring the horizontal displacement of bridge abutment is TS09 total station. Due to the importance of the position of the bridge abutment, the monitoring point closer to the foundation pit is selected for analysis. The monitoring results of the horizontal displacement of the bridge abutment are shown in Figure 27.

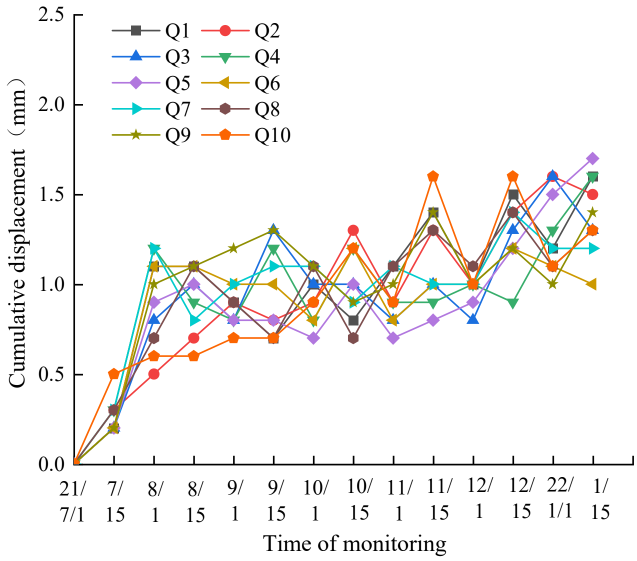


Figure 27. Time history curve of horizontal displacement of the bridge abutment.

According to Figure 27, the horizontal displacement of the bridge abutment is generally increasing, but it decreases in some time periods. Before 1 August 2021, the horizontal cumulative displacement of bridge abutment is increasing, but after 1 August 2021, the horizontal cumulative displacement of bridge abutment decreases sharply. This is due to the fact that the second bracing is applied after 1 August 2021, which controls the deformation of the foundation pit and reduces the horizontal cumulative displacement of the bridge abutment. Among the 10 monitoring points, the horizontal cumulative displacement of Q5 monitoring point is the largest, and the displacement value is 1.7 mm. In the whole process of foundation pit excavation, the monitoring value of the horizontal displacement monitoring point of the bridge abutment did not exceed the control value (5 mm) set by the code [22], which meets the design requirements.

4.13. Tilt of the Bridge Abutment

One tilt monitoring point is arranged on one side of the bridge abutment and one tilt monitoring point on the side along the bridge, and two tilt monitoring points are arranged on each bridge abutment, with a total of 60 monitoring points. The tilt monitoring points are arranged with L-shaped monitoring prisms, and one L-shaped monitoring prism is arranged on the transverse direction of the pier and the side along the bridge. Two prisms on the same side of the pier are a group of tilt monitoring points. The instrument for monitoring the inclination of bridge abutment is TS09 total station. Due to the importance of the location of the bridge abutment, the monitoring points close to foundation pit are selected for analysis. The monitoring results of the tilt of bridge abutment are shown in Figure 28.

As shown in Figure 8, before 1 August 2021, the tilt of bridge abutment is increasing, and after 1 August 2021, the tilt of bridge abutment is basically horizontal. However, after 15 August 2021, the cumulative tilt of bridge abutment decreases sharply. This shows that before the application of the second support, the foundation pit excavation has a great influence on the tilt of the bridge abutment. After the application of the second support, the influence of excavation on the tilt of the pier becomes smaller. Among the 10 monitoring points, the cumulative tilt of Q2 monitoring point is the largest, and the displacement value is 0.0519 mm. In the whole process of foundation pit excavation, the monitoring value of the bridge abutment tilt monitoring point did not exceed the control value (0.2 mm) set by the code [22], which meets the design requirements.

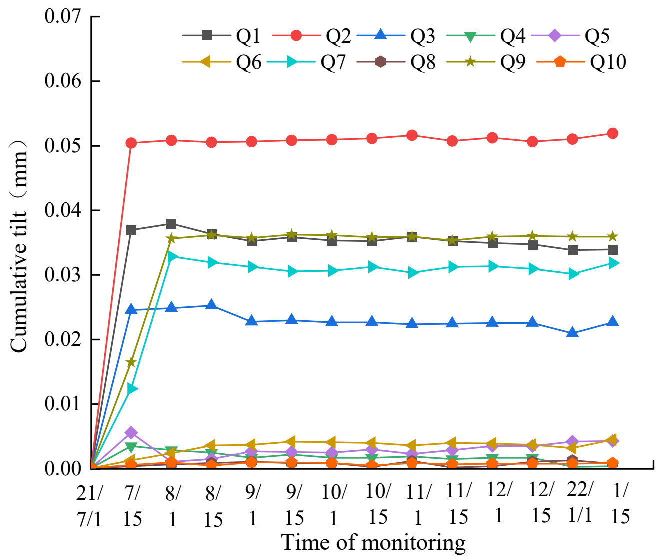


Figure 28. Time history curve of tilt of the bridge abutment.

5. Conclusions

The foundation pit of Lingbi Road Station of Hefei Rail Transit Line 8 not only has a large excavation depth, but also contains groundwater in the excavation depth. In the view of environmental risk and groundwater risk around the foundation pit, it is determined that the support structure of the foundation pit is the composite internal bracing of the underground diaphragm wall, and the dewatering measures are to set up a pressure-reducing well and a water-collecting open drain in the pit, and set up an observation well and an emergency backup well outside the pit. According to the characteristics of the foundation pit, a monitoring plan was set up. During the construction of the foundation pit, 13 items such as the horizontal displacement at the top of the wall, the axial force of the support, and the groundwater level were monitored in real time. The following conclusions were drawn by analyzing the monitoring data of the 13 items.

(1) The risk analysis of the foundation pit before the excavation of the water-containing deep foundation pit at Lingbi Road Station is very necessary, and the countermeasures given can greatly reduce the risk level of the foundation pit.
(2) During the monitoring process, the monitoring data of 13 monitoring items such as the horizontal displacement at the top of wall, the axial force of the bracing, and the groundwater level did not exceed the control value, and the construction process of the foundation pit was safe.
(3) The selection of support structure, the selection of support structure parameters, and the design of dewatering scheme for water-containing deep foundation pit at Lingbi Road Station are all reasonable, and the composite internal bracing structure of underground diaphragm wall is suitable for deep foundation pit support in Hefei area.
(4) The foundation pit of Lingbi Road Station is a typical foundation pit project with complex surrounding environment, large excavation depth, and water within the excavation depth range. The study in this paper also provides a case reference for the design of deep foundation pit support for subway stations in Hefei.

Author Contributions: Conceptualization, D.W. and S.Y.; methodology, D.W., S.Y. and J.Z.; validation, D.W. and S.Y.; formal analysis, D.W. and J.Z.; investigation, S.Y. and J.Z.; resources, D.W. and S.Y.; data curation, D.W. and J.Z.; writing—original draft preparation, D.W. and J.Z.; writing—review and editing, S.Y. and J.Z.; supervision, D.W.; project administration, D.W.; funding acquisition, D.W. and S.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (No. 52168050).

Data Availability Statement: Due to legal issues, the data in the article cannot be provided free of charge.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Han, K.H.; Su, D.; Hong, C.Y.; Chen, X.S.; Lin, X.T. An analytical model for face stability of tunnels traversing the fault fracture zone with high hydraulic pressure. *Comput. Geotech.* **2021**, *140*, 104467. [CrossRef]
2. Ye, S.H.; Li, D.P. Monitoring and simulation analysis of deep and large foundation pit excavation in complex environment. *China Civ. Eng. J.* **2019**, *52*, 117–126.
3. Shakya, K.M.; Saad, A.; Aharonian, A. Commuter exposure to particulate matter at underground subway stations in Philadelphia. *Build. Environ.* **2021**, *186*, 107322. [CrossRef]
4. Kim, C.; Kim, S.W.; Kang, H.J.; Song, S.M. What Makes Urban Transportation Efficient? Evidence from Subway Transfer Stations in Korea. *Sustainability* **2017**, *9*, 2054. [CrossRef]
5. An, P.Z.; Liu, Z.M.; Jia, B.X.; Zhou, Q.; Meng, F.L.; Wang, Z.X. Comparison and Economic Envelope Structure Schemes for Deep Foundation Pit of Subway Stations Based on Fuzzy Logic. *Comput. Intell. Neurosci.* **2022**, *2022*, 1148856. [CrossRef] [PubMed]
6. Pronozin, Y.A.; Bragar, E.P. Changes in soil properties at unloading of base of deep foundation pit. In Proceedings of the International Scientific-Technical Conference on Geotechnical Fundamentals and Applications in Construction-New Materials, Structures, Technologies and Calculations (GFAC), Saint Petersburg, Russia, 6–8 February 2019; pp. 290–295.
7. Wu, J.; Ye, S.H.; Wang, Z.Q.; Yang, D. Application and automatic monitoring and analysis of hybrid support structure in ultra-deep foundation pit engineering in the Lanzhou area under complex environmental conditions. *Water* **2023**, *15*, 1335. [CrossRef]
8. Gotman, A.L.; Gotman, Y.A. Numerical Analysis of the Shorings of Deep Foundation Pits with Regard for the Soil Solidification. *Soil Mech. Found. Eng.* **2019**, *56*, 225–231. [CrossRef]
9. Morozovskiy, P.; Babanina, A.; Ziiaeva, K.; Shulzhenko, S. Optimization of parameters of the bearing structures of deep excavations with minimization of environmental impacts. In Proceedings of the International Scientific Conference on Business Technologies for Sustainable Urban Development (SPbWOSCE), Saint Petersburg, Russia, 10–12 December 2019; p. 01002.
10. Sun, W.; Chen, H.J.; Li, B.; Liu, Y.F. Monitoring and finite element analysis of deep horizontal displacement of foundation pit enclosure pile of a subway transfer station during construction. In Proceedings of the 2nd International Conference on Big Data and Artificial Intelligence and Software Engineering (ICBASE), Zhuhai, China, 24–26 September 2021; pp. 319–323.
11. Yang, T.; Xiong, S.Y.; Liu, S.L.; Liu, Y.; Zhao, H.; Li, Y.W. Numerical Analysis of the Influence of Deep Foundation Pit Construction on Adjacent Subway Stations in Soft Soil Areas. *Adv. Civ. Eng.* **2022**, *2022*, 6071868. [CrossRef]
12. Hong, C.Y.; Zhang, J.Y.; Chen, W.B. An Integrated Intelligent Approach for Monitoring and Management of a Deep Foundation Pit in a Subway Station. *Sensors* **2022**, *22*, 8737. [CrossRef] [PubMed]
13. Yang, J.H.; Kong, D.Y. Deformation of deep and large foundation pit in soft soil of Fuzhou Subway. *Arab. J. Geosci.* **2020**, *13*, 36. [CrossRef]
14. Wang, W.; Han, Z.; Deng, J.; Zhang, X.Y.; Zhang, Y.F. Study on soil reinforcement param in deep foundation pit of marshland metro station. *Heliyon* **2019**, *11*, e02836. [CrossRef] [PubMed]
15. Liu, H.F.; Li, K.Z.; Wang, J.Q.; Cheng, C.X. Numerical Simulation of Deep Foundation Pit Construction under Complex Site Conditions. *Adv. Civ. Eng.* **2021**, *2021*, 6669466. [CrossRef]
16. Zhang, Y.G.; Yi, L.X.; Zhang, L.; Yang, Y.P.; Hao, X.; Li, H.; Ma, H.F. Causation Identification and Control Measures of Deformation by Integrated Dewatering-Excavation Process Simulation of a T-Shaped Deep Foundation Pit. *Water* **2022**, *14*, 535. [CrossRef]
17. Zhao, J.P.; Tan, Z.S.; Yu, R.S.; Li, Z.L.; Zhang, X.R.; Zhu, P.C. Deformation responses of the foundation pit construction of the urban metro station: A case study in Xiamen. *Tunn. Undergr. Sp. Tech.* **2022**, *128*, 5527–5538. [CrossRef]
18. Wu, B.; Zhao, R.; Meng, G.W.; Chen, H.H.; Huang, W.; Liu, J.L.; Cheng, Y. Safety risk assessment of asymmetric construction of subway deep foundation pit based on fuzzy theory. *J. Civ. Environ. Eng.* **2022**, *44*, 8–15.
19. Ye, S.H.; Zhao, Z.F.; Wang, D.Q. Deformation analysis and safety assessment of existing metro tunnels affected by excavation of a foundation pit. *Undergr. Space* **2021**, *6*, 421–431. [CrossRef]
20. Shen, Y.S.; Wang, P.; Li, M.P.; Mei, Q.W. Application of Subway Foundation Pit Engineering Risk Assessment: A Case Study of Qingdao Rock Area, China. *KSCE J. Civ. Eng.* **2019**, *23*, 4621–4630. [CrossRef]
21. Zhou, Y.; Li, S.Q.; Zhou, C.; Luo, H.B. Intelligent Approach Based on Random Forest for Safety Risk Prediction of Deep Foundation Pit in Subway Stations. *J. Comput. Civ. Eng.* **2019**, *33*, 05018004. [CrossRef]
22. *GB 50497-2019*; Technical Standard for Monitoring of Building Excavation Engineering. China Planning Press: Beijing, China, 2019.