Forest Chemicals Revew
www.forestchemicalsreview.com
ISSN: 1520-0191
July-August 2021 Page No. 1238-1255
Article History: Received: 12 May 2021 Revised: 25 June 2021 Accepted: 22 July 2021 Publication: 31 August 2021

Analysis on the Influence of Deep Foundation Pit Construction with Surrounding Environment of Metro Station in Zhongyuan Area

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Abstract:

The surface settlement, horizontal displacement, supporting axial force, settlement, and stress of the retaining structure in the entire process construction are examined using the deep foundation pit excavation of a metro station in Zhengzhou as a backdrop. The results show that as the foundation pit's excavation depth increases, the retaining wall's maximum horizontal displacement travels downward from the top, and the deformation curve shifts from a comparable cantilever beam to a "bow" curve. The initial reinforced concrete support and retention structure must be protected against breaking due to lateral displacement at the top of the wall. The excavation of the foundation pit causes the surrounding surface to settle. All of the supports are in a safe functioning condition during the foundation pit excavation procedure.

Keywords*: Metro station, Deep foundation pit, Settlement of building, Deformation, Monitoring*

I. INTRODUCTION

The excavation of urban underground space has become the preferred alternative for resolving increasingly obvious tensions and promoting the city's sustainable and healthy development. The building of urban rail transit is the most important of these. Most urban rail transit systems, on the other hand, are built underground, with generally circular caverns excavated in difficult ground materials. The surrounding stratum will unavoidably be disrupted

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throughout the construction process, and the original equilibrium state will be destroyed, resulting in stratum and surface settling. When the settlement is uniform, the impact on roads, pipelines, and neighboring structures will be minimal. However, tunnel excavation causes uneven settlement, and when the uneven settlement reaches a specific range, a variety of troubles emerges [1].

Several mature methodologies, such as the empirical formula method, numerical simulation method, random medium theory, and statistical analysis method, have been developed as a result of recent study on surface subsidence caused by tunnel excavation. Ibrahim employed an earth pressure balance machine (EPBM) shield to quantify the surface subsidence induced by parallel tunnel excavation in clay and sand, as well as the interaction of surface subsidence over twin tunnels and the relationship between shield parameters and surface subsidence. Yan investigated the mechanism of rock-burst prevention methods and compared two distinct pressure-relief blasting schemes in Jinping tunnel's second grade surrounding rock section. The surface sinking characteristics of a single tunnel and a double tunnel on a two-section foundation were investigated, and the surface subsidence produced by a single tunnel was determined using a normal distribution. Zhang et al. examined on-site data and discovered that the arch cover construction technology was better suited to the excavation of large-span tunnels in "soft top and hard bottom" surrounding rock. Surface subsidence can be effectively reduced if construction control measures are put in place [2]. The diameter of the left and right pilot tunnels should also be kept at 2.5 times that of the main tube. On the basis of field observed data, Meng et al. employed the Peck method and random medium theory to compare and analyze the characteristics of surface sinking produced by the construction of large-span shallow tunnels. The research described above is primarily based on numerical simulation techniques. There are currently only a few studies on the surface subsidence and deformation of large-span tunnels, and the conclusions drawn from these studies using numerical simulation are also quite different, indicating that conclusions drawn using methods like numerical simulation and random medium theory cannot accurately reflect actual changes in surface subsidence. The measuring and study of the subway station's deep foundation pit excavation is required due to the difficult geological conditions in the Zhengzhou area [3].

The horizontal displacement of the retaining pile, the axial force of bracing, and the surface subsidence of the foundation pit during the excavation process are investigated using field monitoring data from the subway transfer station's foundation pit excavation. Statistical analysis methods based on a large number of recorded monitoring data are used to analyse the surface subsidence and deformation laws produced by excavation of a large-span tunnel. The importance of providing reference and direction for ground surface subsidence studies cannot be overstated.

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II. OVERVIEW OF THE PROJECT

2.1 Overview of the Design

Zhengzhou municipal control stations' civil engineering projects include Zhengzhou Rail Transit Line 6, Phase I of Line 7, Phase I of Line 8, Phase II of Line 9, Line 10, Line 11, and others.

This tender section is one of the underground transfer stations of Zhengzhou Rail Transit Line 11 Project. Line 11 starts from Jingbei 4th Road Station in the north, mainly passes along Jingkai 8th Avenue-Jingnan 8th Road-Jingkai 18th Avenue-Airport High-speed Corridor-Mengxiang Road-Zhenggang Sixth Road, and finally stops at Wentong Road Station on the west side of Guanghui Street. The total length of the line is about 36.645km, all of which are underground lines, with a total of 18 stations. The station of this project is JINGKAIZHONGXINGUANGCHANG staion, which is the second station of Line 11. The schematic diagram of the construction plan is shown in Fig 1.

JINGKAIZHONGXINGUANGCHANG staion is located on the south side of the intersection of Jingkai 8th Avenue and Hanghai East Road. It is set up along the north-south direction of Jingkai 8th Avenue, and transfers to the "T"-shaped passage of Line 5 station. The planned red line width of Jingkai Eighth Avenue is 60m, and the planned red line width of Hanghai East Road is 50m. Both are urban main roads with large traffic volume. The northwest side of the station is the Jianhai International Center (under construction), the northeast side is the central square of the Economic Development Zone, the southwest side is the Geer International Hotel, and the southeast side is the Yihua Furniture Plaza. Within the station site, there are other pipelines with shallower buried depths and greater diameters. The pipelines have mostly been relocated to the east and west sides of the station foundation pit, with some being closer to it. Some pipelines are unable to be relocated in order to be suspended protect. Uneven settlement, cracking, leaking, and leakage of subterranean pipelines may occur as a result of excavation of the station foundation pit.

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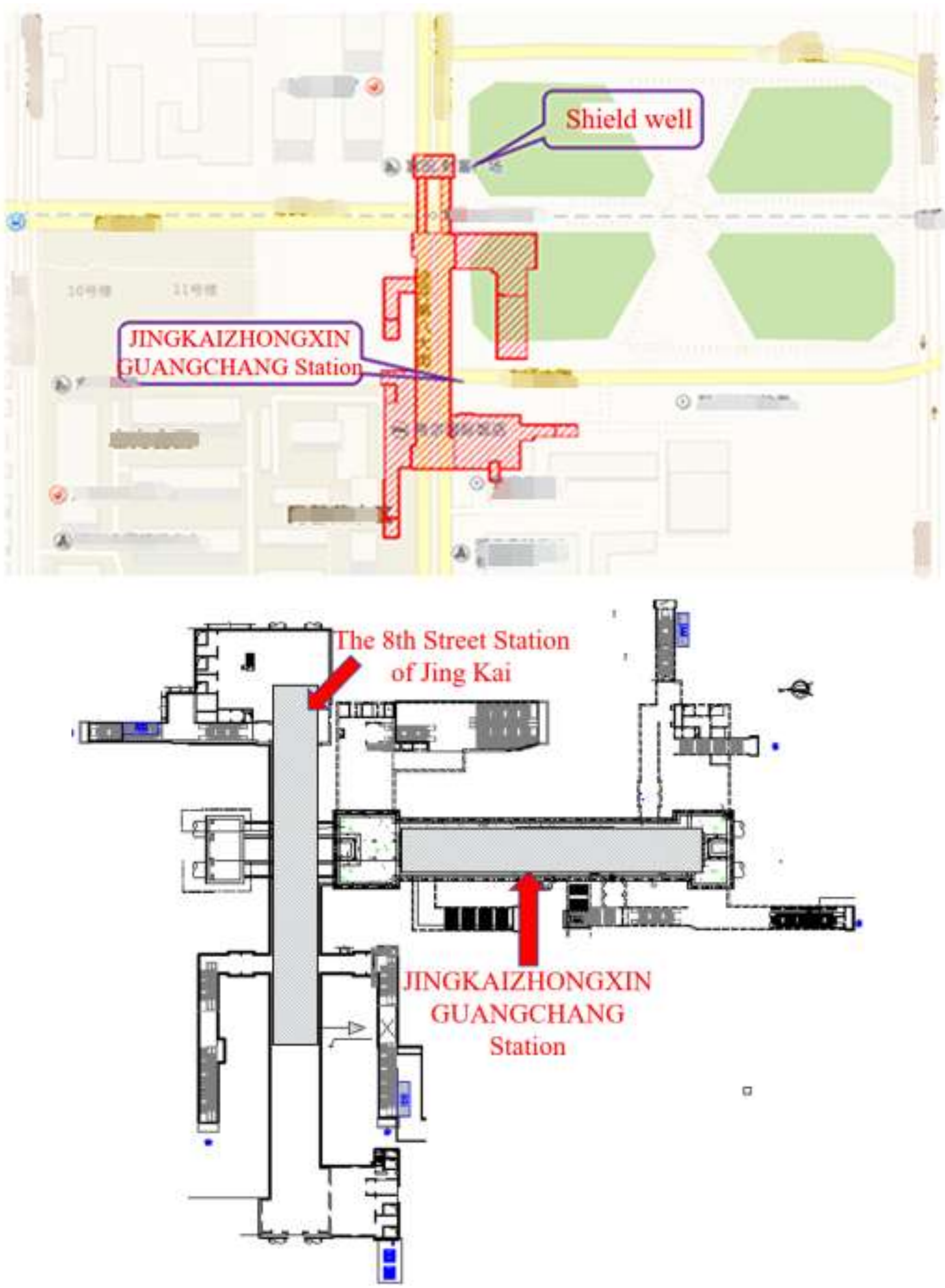

Fig 1: Schematic diagram of plane position

2.2 Engineering Geological Conditions of the Site

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The JINGKAIZHONGXINGUANGCHANG station is located at the intersection of Hanghai East Road and Jingkai Eighth Avenue in Zhengzhou. The ground elevation is between 94.75m and 95.84m, and the terrain is flat. The stratum is dominated by Quaternary loose sediments, the underlying bedrock is buried deeply, and the thickness of the Quaternary overburden along the line is larger than 80m. It is located in the Yellow River floodplain. The strata buried in the range of 0-40m are mainly Quaternary Holocene (Q4) strata with the lithological performance that the 3m-deep surface layer is basically reclamation soil, while the deeper layer is mainly slightly dense to medium dense silt and plastic silty clay. The lithology of the layers buried within 40–65m is mostly medium-dense to dense silt, fine sand, silt, plastic to hard plastic silty clay, and Quaternary Upper Pleistocene (Q3) strata. The strata buried below 65m is mainly the Quaternary Middle Pleistocene (Q2) strata, and the lithology is hard plastic silty clay. The geological section is shown in Fig 2.

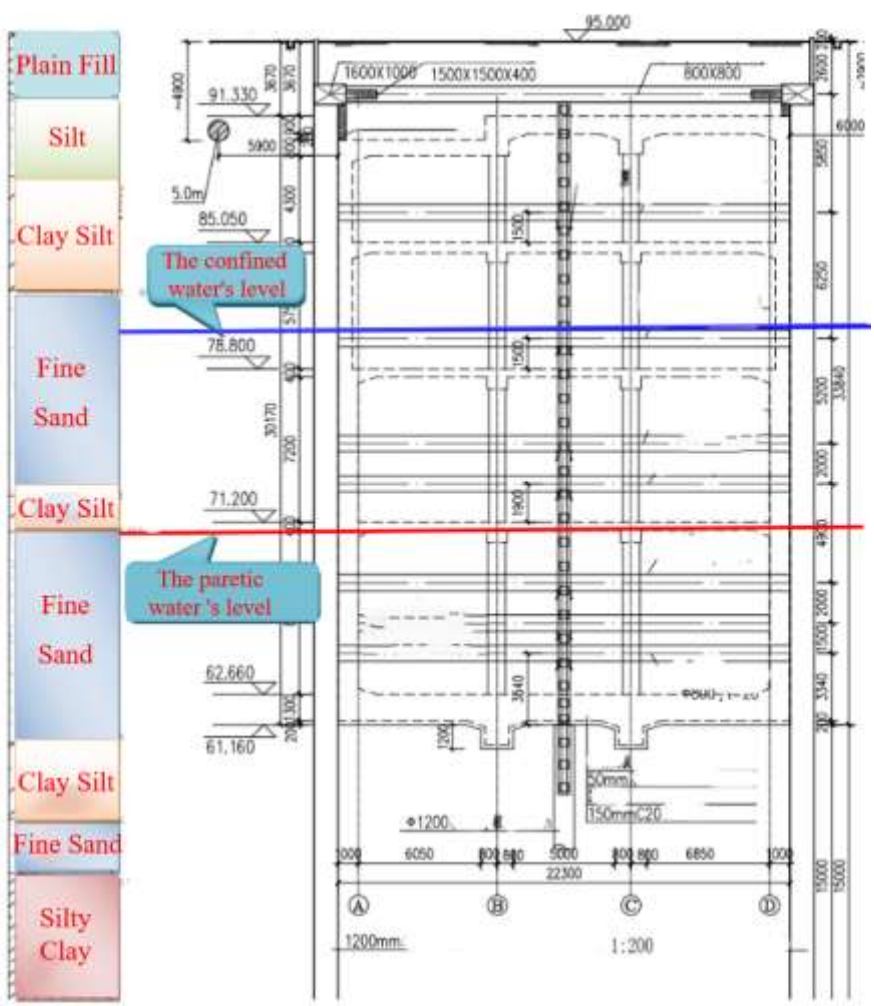

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Fig 2: Geological section

2.3 Hydrogeological Conditions

Within the scope of the proposed site, under normal circumstances without engineering precipitation, the buried depth of the diving groundwater level should be between 14.00~15.00m with the elevation between 80.00 and 82.00m, and the confined water roof should be buried at 24.0~27.0m. The water-repellent layer above the aquifer is a clayey silt layer with thickness of 1.50~5.50m, and the confined water head is about 5m. The geological section of the enclosure is shown in Fig 3.

Fig 3: Geological section of the enclosure

III. DEEP FOUNDATION PIT SUPPORT STRUCTURE IN SUBWAY STATION DESIGN AND MONITORING SCHEME

3.1 Deep Foundation Pit Supporting Structure Design

The JINGKAIZHONGXINGUANGCHANG station's primary structure is an underground four-story three-span box frame structure built using the open-cut construction method, and the retaining structure is a continuous underground wall with internal bracing. The specific support plan is as follows:

1) The main retaining structure of the station adopts a 1200mm thick underground continuous wall with a crown beam on the top of the wall.

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2) The standard section of the foundation pit is vertically equipped with seven bracings and one replacement bracing, and a concrete crown beam (1000×1600mm) is set on the top of the wall. The first bracing is an 800×800mm concrete bracing set on the crown beam with the spacing of 6m. The other six bracings (second to seventh) and replacement bracing adopt 20mm thick steel pipe with diameter of 800mm, and the spacing is 3m. The end shaft section of the foundation pit is vertically equipped with six bracings and one replacement bracing. The first bracing is an 800×800mm concrete bracing set on the crown beam with the spacing of 6m. The second, third and six bracing adopt 20mm thick steel pipe with diameter of 800mm, and the spacing is 3m. The fourth bracing is a 1000×1200mm concrete bracing. The fifth bracing is a 1200×1200mm concrete bracing with spacing of 5m. Steel replacement bracing is set on the side wall of main structure. The Standard section of JINGKAIZHONGXINGUANGCHANG station is shown in Fig 4.

The 8th Street Station of Jing Kai is an underground two-span three-story structure, the negative first floor is a municipal tunnel, and the negative second and negative third floors are the station structure. The main retaining structure adopts the method of combining drilled grouting piles and underground continuous walls. The municipal tunnel on the first floor uses drilled grouting piles with diameter of 800mm and spacing of 1200mm. The main station retaining structure uses 800mm thick underground continuous walls. A reinforced concrete crown beam is attached to the top of the drilled grouting pile and serves as an anti-floating pressure top beam during the station's use stage. The crown beam is 800*800mm in size. The gaps between pressure top beam and the roof are backfilled with C30 micro-expansion concrete, and spacings between the piles are filled with C20 sprayed concrete. On top of the subsurface continuous wall, an 800*800mm reinforced concrete crown beam is installed.

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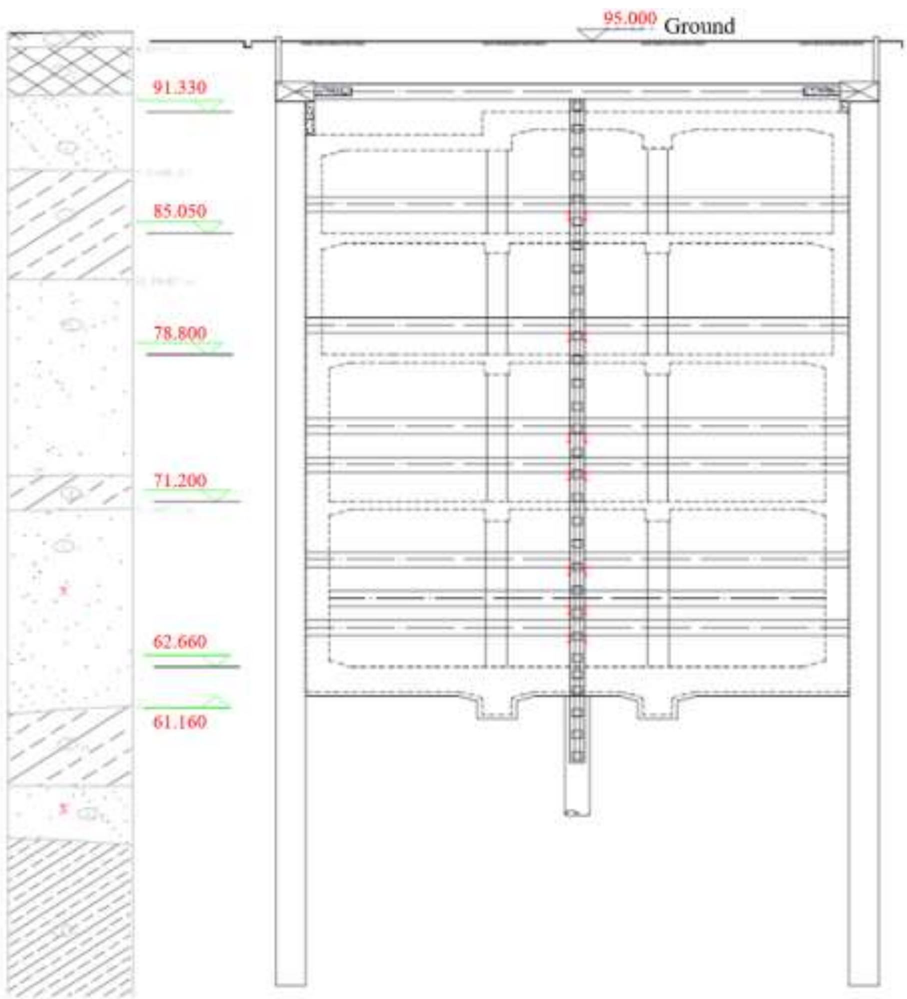

Fig 4: Standard section of JINGKAIZHONGXINGUANGCHANG station

3.2 Monitoring Projects and Methods

Building monitoring should be carried out during the construction of urban rail transit projects, according to the "Technical Specifications for Urban Rail Transit Engineering Monitoring" (GB 50911-2013). During subway construction, the construction unit chooses a construction monitoring unit to keep an eye on the tunnel's main structure and the surrounding environment in accordance with the design specifications. In addition, to augment the construction bidding monitoring, a third-party monitoring unit is chosen [4-6]. According to the conditions of the subway station's surrounding environment, construction methods, and engineering geology, the horizontal displacement of the retaining wall, ground subsidence, and

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axial force of bracings are monitored to ensure the safety of the foundation pit construction, as shown in Table I.

Table I. Monitoring items, measuring point layout and monitoring accuracy.

Monitoring items	Position /Objects	Monitoring Point Layout	Point Number	Frequency	Controlled Value	
					Rate	Accumulative Value
Horizontal Displacement Of Retaining wall	Inside Retaining wall	Arranged in the middle, outside corners and representative parts of foundation pit, with a horizontal spacing of 20-40m.	ZQT-01 ～ ZQT-18	Excavation period:2/day , Stable period:1/2 days	±2mm/d	±30mm
Ground subsidence	Surrounding soil of retaining structure	Arranged in the middle of the side of the foundation pit or other representative parts with section perpendicular to the side of the pit, the number of, monitoring point on each section: ≥5, the horizontal, spacing of the monitoring	DBC01-01 ～ DBC18-05	Excavation period:2/day	±2mm/d	±25mm

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		sections: ≤20m				
Axial force Of bracing	Ends of steel bracing, key parts of concrete bracing	Each layer is 12, a total of 6 layers	ZCL01-01～ZCL12-06	1/day	100% design value	

3.3 Construction Technology of Foundation Pit and Arrangement of Monitoring Points

The monitoring data of the main functioning condition was analysed during the construction of the foundation pit. The major monitoring stations of the foundation pit were chosen based on the construction circumstances. Fig 5 depicts the configuration of the foundation pit monitoring locations.

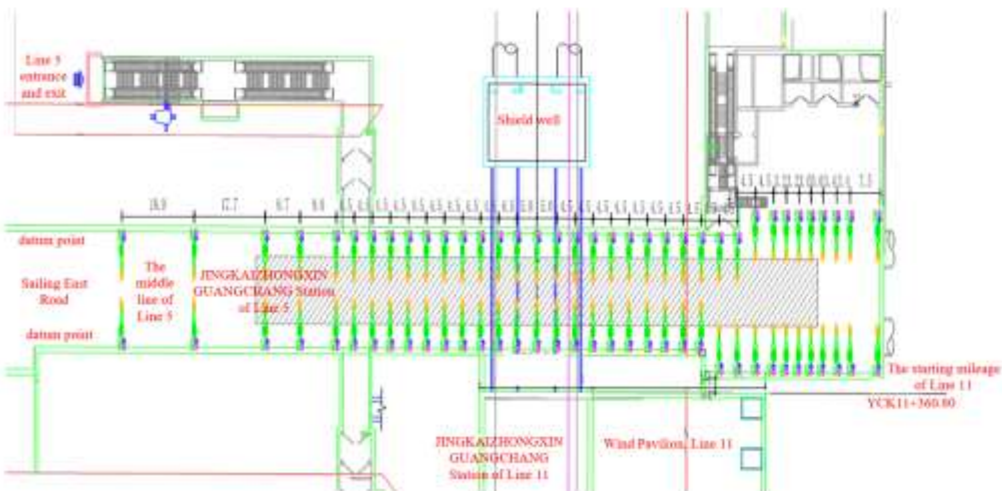

Fig 5: Layout of monitoring points

IV. ANALYSIS OF MONITORING DATA

4.1 Ground Subsidence

Considering the symmetry of foundation pit excavation plane, measuring lines DBC01, 06, 07 and 18 are selected. Fig 6 depicts the findings of on-site monitoring of ground subsidence throughout the construction process. There was a slight elevation on the ground near the

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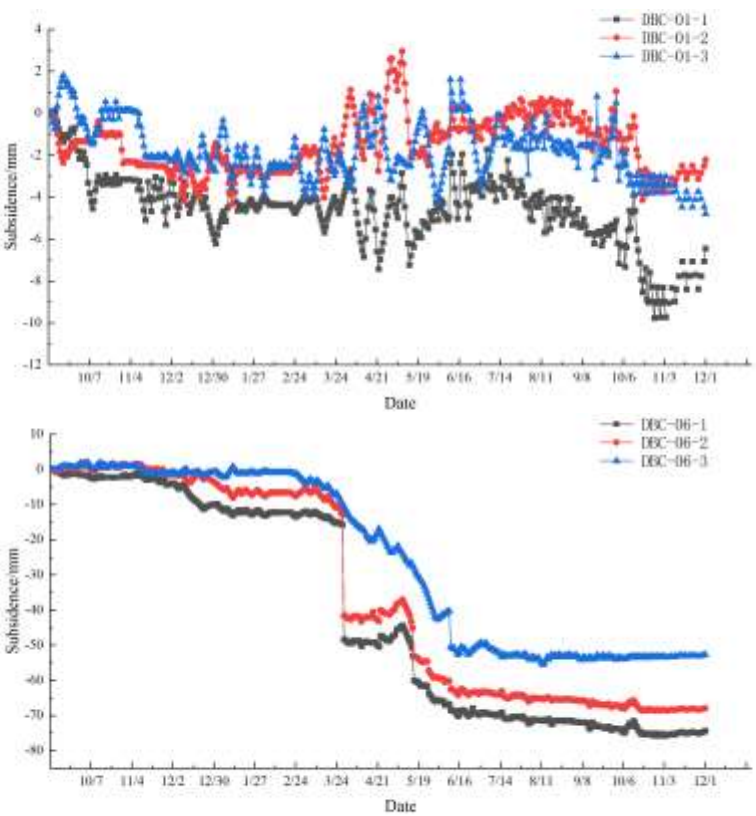
foundation pit at the start of the excavation [7]. This is primarily due to the loss of the original state following the excavation of the overlaying soil, causing the soil at the pit's bottom to rebound and the surface soil to elevate. With more excavation and unloading, the surface subsidence value and its rate continued to increase. Later, the surface soil appeared large uplift, which is due to the equipment of lateral steel bracing, which increased the lateral force of the soil body, and the soil around the foundation pit was compressed, resulting in stress concentration and uplifting. In DBC06, a sharp and large subsidence occurred after March 24. This may be due to the increasing impact of unloading as the excavation depth increases, and the nearby soil has a greater impact due to the presence of man-made buildings. The vertical force generated severe soil shearing near the foundation pit, resulting in significant soil damage. The soil stress was transferred and eventually balanced as the supporting structure and retaining structure were continuously implemented, and ground subsidence was decreased and stabilized. The slight change in subsidence at this stage may be due to the creep characteristics of supporting structures.



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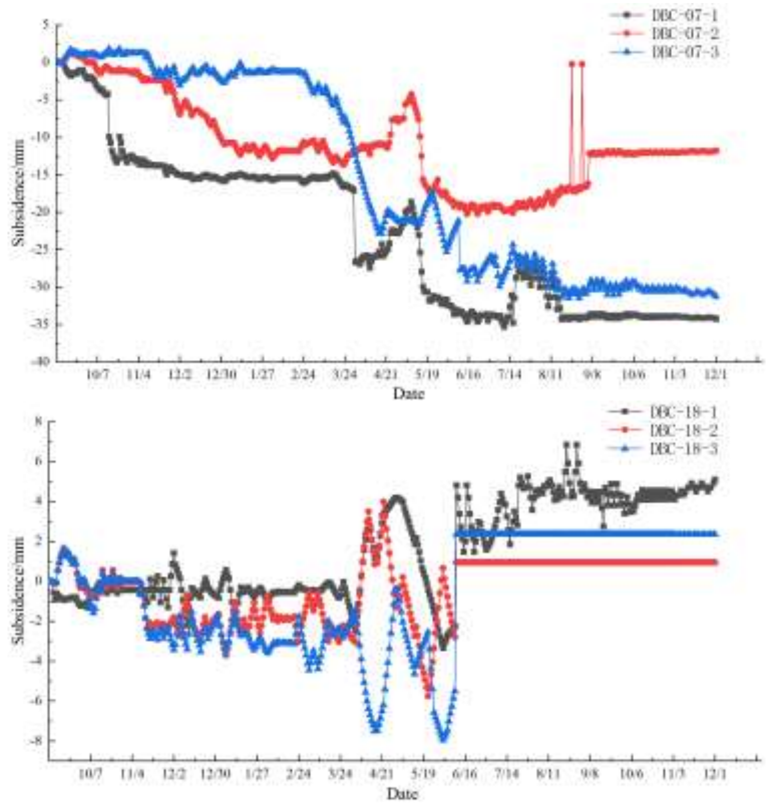

Fig 6: Monitoring results of surface settlement in the whole construction process

4.2 Horizontal Displacement of Retaining Wall

The horizontal displacement curve of the retaining wall is plotted during the whole building process using representative locations of transfer sections, ZQT-1, ZQT-5, and ZQT-14 measuring points, as illustrated in Fig 7. Due to the excavation sequence and site conditions, the retaining structures must be fitted in parts and layers during the excavation operation, causing the support system to change from a single to numerous supports. A positive number indicates that the retaining wall's displacement has moved to the inside of the foundation pit, whereas a negative value shows that the retaining wall's displacement has moved to the outside of the foundation pit. Because the site's first bracing was made of concrete, the displacement curve appears convex in the early stages of excavation. The force generated by the bending moment exceeded the earth pressure in the initial stage due to the low earth pressure combined with the greater stiffness of the subsurface continuous wall, causing the retaining wall to move inward. The wall expanded outward due to the dumping of the foundation pit soil. The soil arching effect rose dramatically as the excavation depth increased, and the maximum lateral displacement position steadily went downward as the excavation depth increased.

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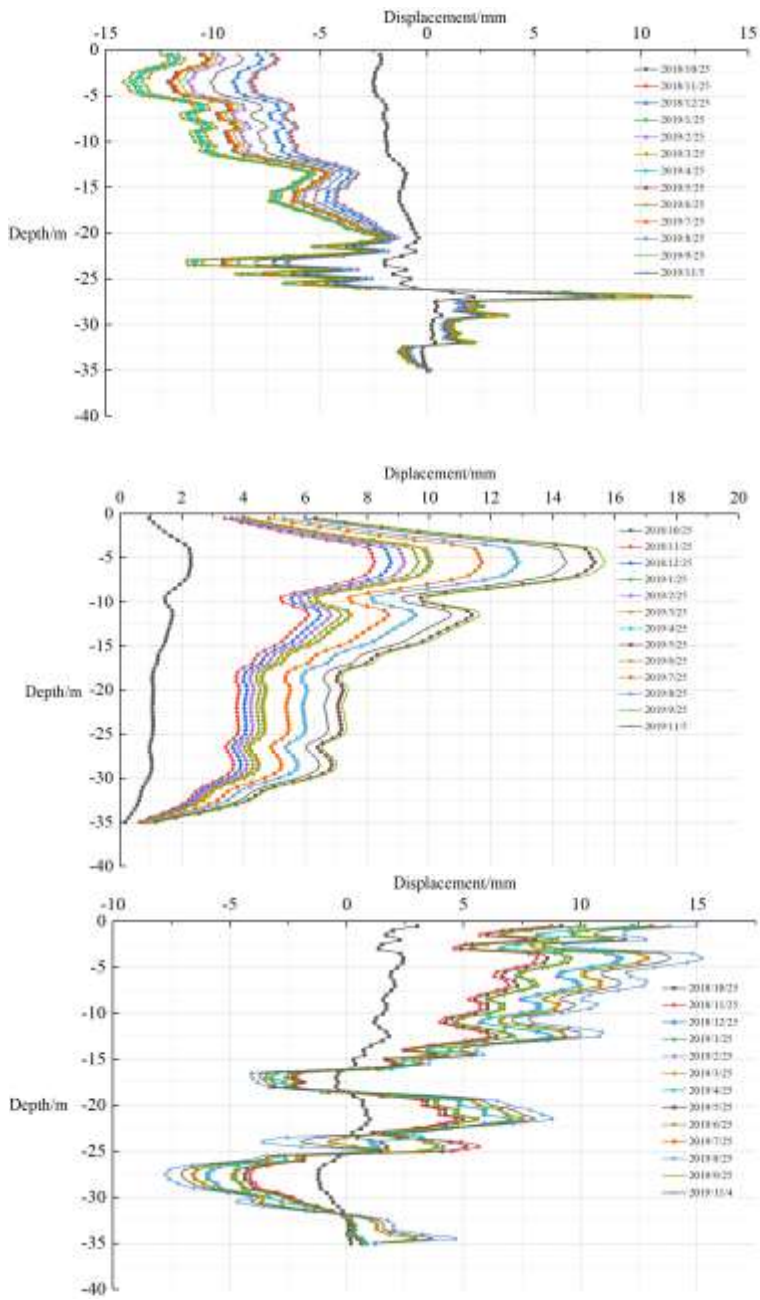

Fig 7: During the construction phase, the results of the horizontal displacement of the enclosure wall were monitored.

The following conclusions can be drawn from analysing the horizontal displacement of the pile at the crucial position of the retaining structure during foundation pit building. The

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retaining wall's deformation properties are essentially the same as the overall deformation curve, which is a "bow-shaped" curve. The horizontal displacement at the top was the greatest while excavating shallow soil. The maximum horizontal displacement steadily drifted downward as the excavation depth increased, to around 2/3 of the depth of the foundation pit. The results reveal that the retaining wall deformation during the excavation period complies with the specification, and the retaining structure's state is relatively stable [8-10]. The movement of the pile top to the outside of the foundation pit should be monitored. Due to the lateral displacement of the pile top, it is important to prevent the initial reinforced concrete bracing and retaining structure from breaking. Furthermore, the monitoring data show that the displacement at the wall's toe was very minimal, showing that the bottom end was roughly secured and restricted during the construction process, meeting the construction criteria.

4.3 Axial Force of Bracing

Bracing axial force monitoring is one of the main contents of foundation pit monitoring, and it provides an important indicator of the safety status of the foundation pit support system. Three representative measuring points ZCL-1, ZCL-2 and ZCL-4 are selected to analyse the changes of bracing axial force during the excavation of foundation pits. A positive value represents pressure while a negative value represents tension. In the initial stage of each bracing equipment, the axial force increased at the greatest speed. The bracing axial force of the sixth measuring point of ZCL-1 decreased first and then increased abruptly. This may be due to the sudden increase in the pressure of the soil under the upper load as the excavation depth increases. As shown in Fig 8, the bracing axial force of the tenth and twelfth measuring point increased, and the maximum bracing axial force was 676.6KN. The axial force at eighth measuring point of ZCL-2 was basically unchanged at first, and then gradually decreased, which is due to the soil squeezing and bracing uplift. The bracing axial force of the eleventh measuring point tended to be stable throughout the whole process. The bracing axial force of the seventh measuring point gradually increased at first, then abruptly increased which may be due to sudden damage to the soil, and finally tended to a stable state, with the maximum axial force of 5465.3KN. The bracing axial force of the eleventh measuring point and the twelfth measuring point of ZCL-4 increased, and the bracing axial force of the ninth measuring point reduced, with the maximum axial force of 1694.4KN. Based on the results of the wall's lateral displacement, it can be deduced that when the depth of the foundation pit was increased, the position of the maximum lateral deformation gradually shifted down, and the maximum displacement rose continually. Increases in excavation depth had a greater impact on the axial force of the bottom bracing due to the effect of deformation synergy.

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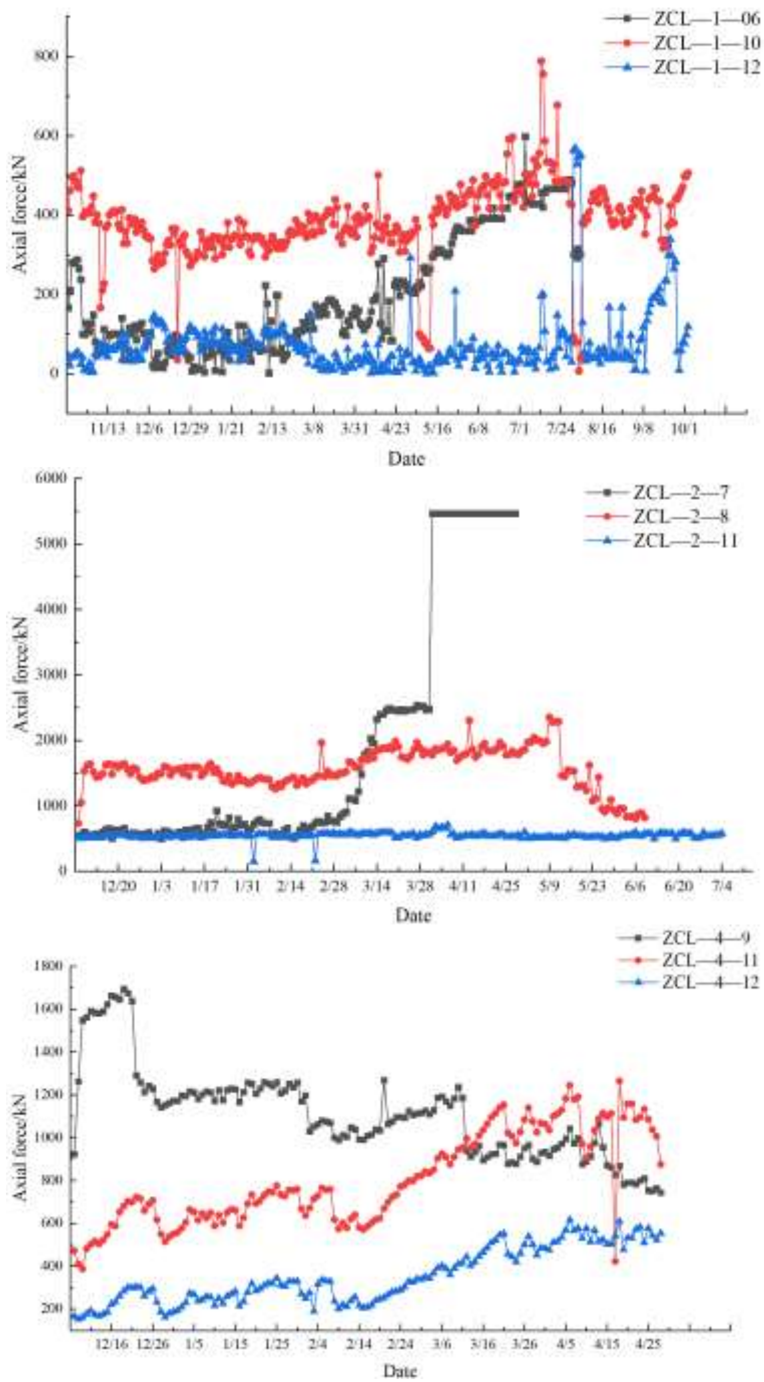

Fig 8: On-site monitoring results of supporting axial force in the whole construction process

4.4 Influence on Groundwater during Construction

To ensure the safety and minimize the negative effects of the deep foundation pit

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construction on the local water environment, the groundwater impact estimation and groundwater recharge were carried out during the construction process. The calculation results showed that when the excavation depth reached 18.5 ~ 19.05 m, the bottom of the foundation pit was in a critical state of stability, and the confined water does not need to be reduced. But when the excavation depth reached 22.5 m, the confined water head needed to be reduced to 9.45 m for the safety of the foundation pit. The groundwater pumped for precipitation was reused after three-stage precipitation as the recharge water. At the same time, the water was pressurized by installing a pressure pump during the recharge process, to achieve the required pressure for recharge. According to construction experience, the recharge pressure of groundwater is generally between 0.06 to 0.10 MPa. Multiple recharge experiments were carried out to find out the optical recharge pressure for great water level recovery effects, and the pressure was finally determined to be 0.10 MPa. During the recharge period, the groundwater level outside the pit should be monitored at any time. As shown in Fig 9, when there was leakage in the water stop curtain, measures should be taken in time to stop the leakage to avoid the impact on the surrounding environment due to the leakage of the diving layer.

Fig 9: Schematic diagram of dewatering in site foundation pit

V. CONCLUSIONS

The lateral displacement of the retaining wall, surrounding ground subsidence, and internal bracing axial force induced by foundation pit excavation are investigated using monitoring data throughout the whole building process of a deep foundation pit for a subway station. The following are the primary conclusions:

(1) As the depth of the excavation increased, the rate of surface subsidence increased as well. Subsidence of the soil around the foundation pit was minimized by friction between the subsurface continuous wall and the surrounding soil [10-14]. The largest subsidence point was not near the foundation pit, but rather some distance away. The safety of the surrounding environment can be assessed by monitoring the maximum sinking point around the foundation

pit.

(2) In accordance with the law of surface subsidence, the retaining wall's lateral displacement occurred primarily during the outer pit's excavation stage, accounting for around 80% of the total. With the depth of the excavation increasing, the maximum lateral displacement position gradually shifted below. The displacement at the wall toe was quite minor, showing that the bottom end of the structure was roughly fixed and restricted during construction.

(3) The excavation depth was closely connected to the retaining wall's maximum horizontal displacement. When excavating shallow soil, the retaining pile's highest horizontal displacement was near the top, and its deformation was similar to that of a cantilever beam. The site of the greatest horizontal displacement steadily drifted downward as the excavation depth grew.The pile's deformation curve progressively altered from that of a cantilever beam to that of a "bow shape."

(4) Based on the analysis of the pile lateral displacement and bracing axial force monitoring data, it can be concluded that as the pile displacement increased and the maximum lateral deformation position gradually moved downward, the increase in excavation depth had a greater impact on the bracing axial force of the bottom layer due to the synergistic effect of the structure and the soil deformation.

(5) The calculations revealed that the bottom of the foundation pit was in a critical state of stability when the excavation depth reached 18.5 19.05 m, and the confined water did not need to be reduced. The confined water head had to be adjusted to 9.45 m when the excavation depth reached 22.5 m for the foundation pit's safety. When the water stop curtain leaks, immediate action should be made to halt the leak so that the impact on the surrounding environment from the diving layer leak is minimized [15].

ACKNOWLEDGMENTS

This research was supported by Key projects of Xihua University (Z201036); Sichuan Provincial College students' Innovation and Entrepreneurship training Project in 2019 (S201910623016); The Project of Innovation Fund for Graduate students of Xihua University in 2020 (YCJJ2020068).

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