ISSN 1330-3651 (Print), ISSN 1848-6339 (Online)
https://doi.org/10.17559/TV-20230208000333
Preliminary communication

Deformation Law and Spatial Effect of Deep Foundation Pits for Subway Construction in Soil-Rock Composite Strata in Seasonally Frozen Areas

Meiyan WANG, Dajun ZHAO, Wei WANG*, Pengda MA, Shan JIANG

Abstract: The stability and safety of metro deep foundation pit in the soil-rock composite stratum in the seasonally frozen area are the key issues in the design and construction of the foundation pit. In order to ensure the soil-rock composite stratum in the seasonally frozen area, the deformation of the supporting structure is within the safe range when the deep foundation pit is excavated. At the same time, it will reduce the impact of the construction of metro deep foundation pit on the surrounding buildings. During the construction of foundation pit, close monitoring shall be carried out and the actual monitoring data shall be studied and analyzed. During the excavation of each layer of the foundation pit, monitor the displacement change of the foundation pit support structure and the settlement change of the surrounding ground surface, study the deformation law of the subway deep foundation pit in the soil-rock composite layer, and discuss the spatial effect of the foundation pit excavation in the seasonally frozen area. This paper mainly takes the deep foundation pit project of Anxin Road Station of Changchun Metro Line 5 as the research object, and analyzes the actual monitoring results. The results show that: (1) With the long side of the foundation pit, the deformation of the retaining structure of the foundation pit increases with the distance from the pit corner, and the middle of the long side of the foundation pit is less constrained by the retaining structure. (2) During the excavation of soil-rock composite foundation pit in seasonally frozen soil area, the pile displacement, axial force of support and uplift of support structure caused by rock excavation are relatively small, while the lateral displacement of foundation pit below the rock surface and thawing settlement deformation of soil are basically unchanged. The maximum lateral displacement of the foundation pit at the upper part of the rock surface moves upward. During the construction of deep foundation pit, there is a large displacement before the erection of the third layer of steel support. Attention should be paid to the soil properties of the deep silty clay layer, as well as to the rapid construction and synchronous maintenance.

Keywords: soil settlement; soil rock composite stratum; spatial effect; subway station

1 INTRODUCTION

With the dense urban population, urban traffic congestion brings inconvenience to people's travel. At this time, the construction of underground transportation is particularly important [1-3]. However, how to minimize the scope of action of buildings and structures near the basic subway trench construction, control the settlement and failure of supporting buildings, and control the safety and stability of construction is one of the main challenges of subway construction. Unlike conventional pits, the deep foundation ditch in a subway is mostly distributed in a narrow and long form, which is a typical three-dimensional space building with significant spatial effects [4, 5]. However, it is often designed, calculated or analyzed as a two-dimensional plane problem, resulting in some drawbacks. Therefore, the spatial effect problem in deep basic pit construction has been discussed in China abroad. Through many experiments and analyses, it is found that the factors affecting space action in subway basic pits mainly include the form of the support [6], the shape of the pit [7, 8], the excavation sequence and depth [9], and the construction time [10, 11] and the overall performance of the space effect of the basic pit is that the lateral movement distance of basic pit and stress borne by the supporting building increase with the distance from the basic pit becoming larger. Angle [12, 13]. Besides, the change of the soil layer within the discover depth and the soil species at the embedded end also have great impacts on deformation regularity and spatial effect metro basic pit project [14, 15]. Many scholars have carried out research on the deformation law and spatial effect of deep foundation pits in soft soil areas [16-18]. These pits also have significant spatial effects, and the lateral displacement of the support structure in the middle of the pit, the support axial force and the settlement of the surrounding structures are the largest in general. It is also found that the space force of basic pit could be effectively suppressed to a certain extent with internal supports [19]. The above research provides in theory support for the support and optimization base pit combining soil and rock engineering in soft soil base area. The above research can provide valuable theoretical and technical help for basic pit support in areas with small soil bearing capacity. However, for the geological conditions of soil rock composite strata, the existing studies theory of deformation and spatial effects of subway deep foundation ditch are relatively few, especially for the study on the spatial effects of subway middle and deep excavation seasonal frozen areas.

Based on the construction space effect, the interaction between the foundation pit and the underlying tunnel in the soil-rock composite stratum is studied by numerical analysis method [20, 21]. The local model of the pit angle is established to analyze the pit angle effect of the foundation pit in the soil-rock composite stratum and the influence of the support structure on the external angle deformation [22, 23]. However, the results of the above study do not take into account the strong regional characteristics of foundation pit engineering. Therefore, this paper takes the deep foundation pit project of Anxin Road Station of Changchun Metro Line 5 as the research object, and based on the spatial effect, carries out monitoring and research on the special soil-rock composite strata in this area, in order to explore the change rules of the displacement and settlement of the supporting structure, the axial force of the internal support, the surface settlement, the building settlement, and the change of the spatial effect of the foundation pit, in order to provide the design, provide reference basis for construction and optimization.

2 PROJECT PROFILE
2.1 Overview of the Deep Basic Pit

The deep basic pit project of Anxin Road Station of Changchun Rail transit line 5 is located at the intersection of Silicon Valley Street, Anxin Road and Pingxin Road, and along the north-south position of Changchun Silicon Valley Avenue, as shown in Fig. 1. The main basic pit is 216.1 m long, 19.9 m wide, 24.7 m wide and 16.5 m ~ 18.5 m deep. The basic pit support building is composed of multi row pile support and internal support. Bored cast-in-place piles are used for row pile support, and three steel bearings are set along the excavation depth. See Tab. 1 for support system parameters and see Fig. 2 for support building section.

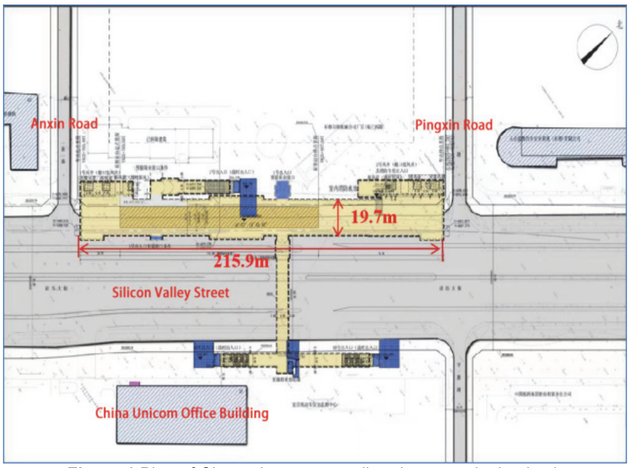


Figure 1 Plan of Changchun metro soil-rock composite basic pit

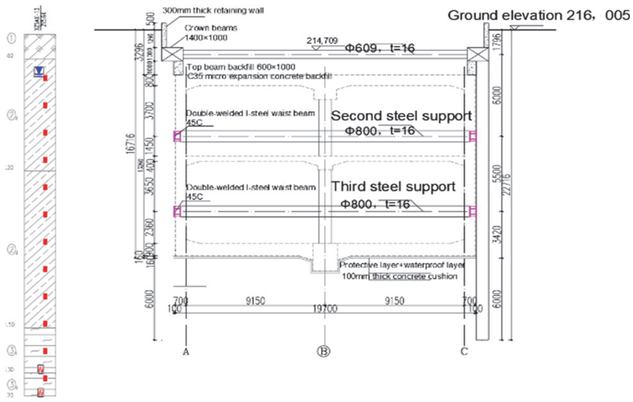


Figure 2 Structural support diagram of Changchun metro

2.2 Engineering Geology

The landform of the project site is alluvial terrace (II). Strata from the upper to the lower ① miscellaneous fill, ②$_2$ silty clay, ②$_3$ silty clay, ③$_1$ fully weathered mudstone and ③$_2$ strongly weathered mudstone. The ground water is distributed in silty clay and weathered mud strata, with a water level depth of 2.50 ~ 3.90 m. Affected by the seasonal atmospheric precipitation, the water level in this area varies from 2.0 to 3.0 m, and the dynamic water level varies above 3.0 m. The basic physical and mechanical property indexes of the soil layer are shown in Tab. 2.

Table 1 Structural paramete value of Internal Support of Changchun Metro

Internal support of basic pit	Bale size / mm	Horizontal spacing / mm	Vertical spacing / m	Unit weight	Elastic modulus	Poisson ratio
Drilled-and-grouted pile (standard section)	ø 800	@1300	—	25	20	0.2
Drilled-and-grouted pile (end shaft section)	ø 1000	@1400	—	25	20	0.2
Crown beam (standard section)	1400 × 1000	—	1.3	25	20	0.2
Crown beam (end shaft section)	1600 × 1000	—	1.3	25	20	0.2
The first layer of steel support frame	ø 609	—	1.3	78.5	200	0.3
Second layer steel support frame	ø 800	—	6.0	78.5	200	0.3
The third layer of rigid support frame	ø 800	—	5.5	78.5	200	0.3

Table 2 Physics and Mechanical attributes of soil and rock stratum inside the basic pit of Changchun Metro

Soil layer and number	Moisture content / %	Unit weight / kN/m³	Cohesion / kPa	Internal friction angle / °	Compression modulus / MPa	Layer thickness / m	Characteristic value of bearing capacity / kPa	Permeability coefficient / m/d
① Miscellaneous fill	—	17.5	—	—	—	1.5	—	—
②$_2$ Silty clay	22.2	19.6	31	17	4.4	9.5	180	0.3
②$_3$ Silty clay	24.8	20.1	32	17	7.0	8.7	200	0.3
③$_1$ Completely weathered mudstone	25.7	19.9	38	23	7.5	3.3	260	0.5
③$_2$ Strong weathered mudstone	16.0	21.1	33	25.7	11.7	8.0	450	0.4

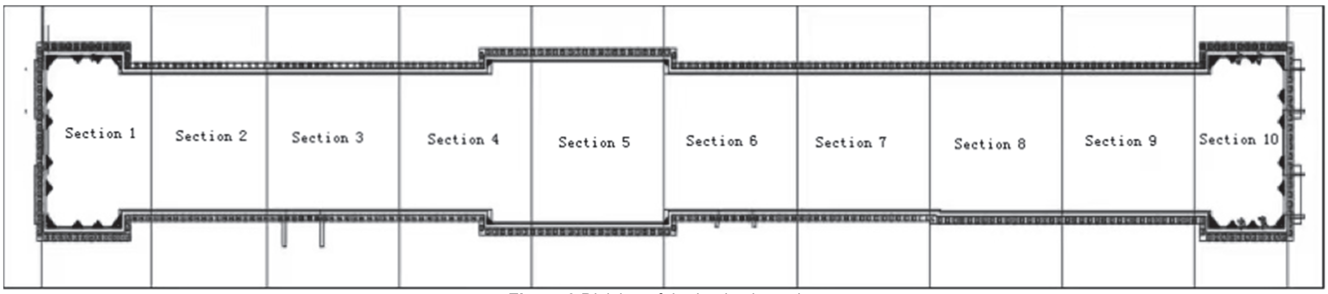


Figure 3 Division of the basic pit section

2.3 Foundation Pit Excavation and Monitoring Scheme

Open excavation sequential construction method is adopted for basic pit construction. Excavate from top to the next floor, and each layer shall be excavated to 50 cm below the design elevation of steel support. Construction of Changchun Metro open excavation basic pit by sequential construction method. The excavation was carried out layer by layer from top to bottom, with each layer excavated to 50 cm below the design elevation of the steel support. The excavation depth is −1.8 m for the pile-top crown beam and first steel support, −7.8 m for second steel support, −13.3 m for third steel support and −16.8 m for the pit bottom. According to the characteristics of the special narrow and long deep foundation pit, the deep foundation pit construction of the project will be excavated in sections, and the construction working surface sections are shown in Fig. 3.

Due to the dense distribution of viaducts, buildings and pipelines around the foundation ditch, the surrounding area of the foundation ditch is monitored to study the settlement of the surrounding environment during excavation. See Tab. 3 for the number of monitoring items and monitoring points, and the monitoring points arranged near the subway basic pit are shown in Fig. 4, the construction schedule is shown in Tab. 4.

Table 3 Basic pit monitoring items

Monitoring program	Number of monitoring points	Number
Detection point of horizontal movement distance at the top of supporting pile in basic pit	44	ZQS1-44
Settlement of the support pile top	44	ZQC1-44
Horizontal shifting of the supporting pile	16	ZQT1-16
Groundwater level	6	DSW1-6
Inner-support axial force	12	ZCL1-12
Movement of internal building of basic pit	15	JGC1-15
Lowering distance of pipe	21	GXC1-21
Surface settlement	180	DBC1-1-27-3

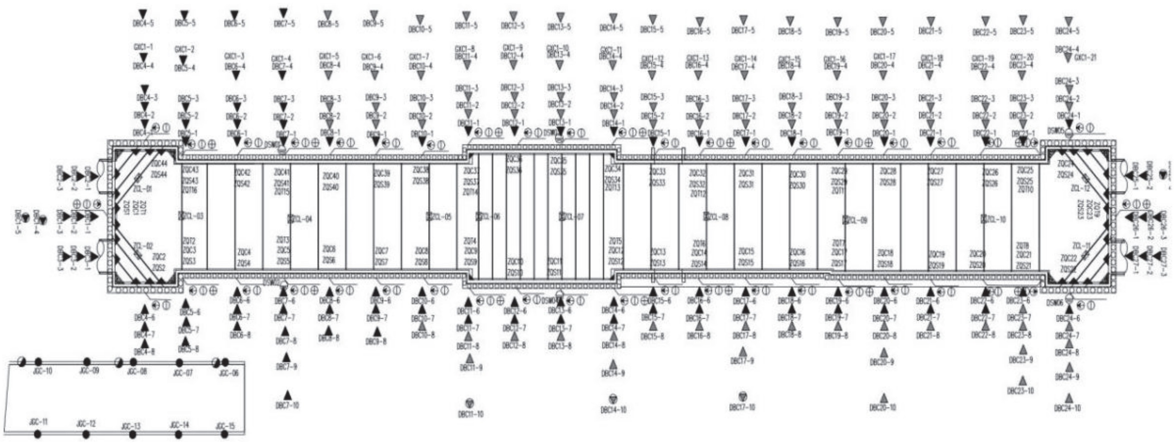


Figure 4 Monitoring layout plan of the foundation ditch

Table 4 Construction schedule

Order number	Task name	Time limit for a project	Start time	End time
1	Excavation and initial support of station foundation pit	420 days	July 18, 2020	September 10, 2021
2	Construction of station retaining pile	131 days	July 18, 2020	November 25, 2020
3	Crown beam and retaining wall	81 days	October 1, 2020	December 20, 2020
4	Dewatering well	57 days	October 10, 2020	December 5, 2020
5	Excavation, steel support installation and net spraying between piles	163 days	April 1, 2020	September 10, 2021

3 MONITORING RESULTS AND ANALYSIS OF SUPPORT STRUCTURE

3.1 Space-Time Effect of Deep Foundation Pit

The failure mode of soil mass behind the retaining structure of foundation pit can be divided into two types according to the boundary line between the sliding body and the ground surface: circular arc and linear arc combination. When the side length of the foundation pit is short, and the pit wall is all within the influence range of the soil arch, then the sliding body is all the soil between the soil arch and the foundation pit wall, and the intersection line between the sliding body and the surface is a circular arc. When the side length of the foundation pit is long, the potential sliding surface of the soil behind the foundation pit will intersect with the soil arch. At this time, it will appear that the side displacement of the foundation pit is affected by the soil arch, the fracture surface is curved, the middle part is not affected by the soil arch, and the fracture surface is linear, as shown in Fig. 5 [24].

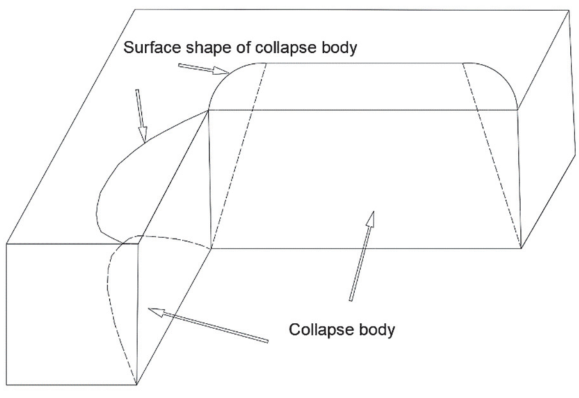


Figure 5 Two failure modes of foundation pit under space effect

In order to study the manifestation of the spatial effect of foundation pit, it is necessary to clarify how the spatial effect is formed. In fact, the spatial effect of foundation pit is a kind of combined destruction form of foundation pit. In an ideal state, the failure of the foundation pit can be considered according to the plane strain. At this time, the fracture surface of the foundation pit is the plane shown in Fig. 6, but the foundation pit is not infinite, which leads to the formation of the soil arch shown in Fig. 7 behind the wall of the foundation pit. The impact of the soil arch should also be considered for the failure of the foundation pit.

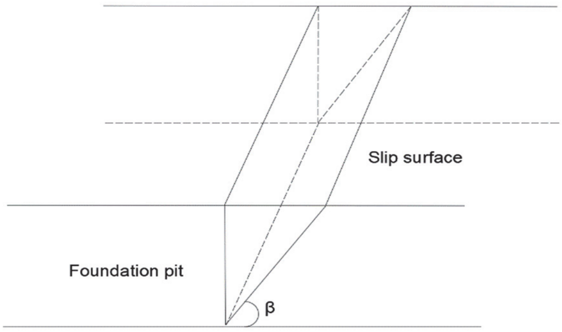


Figure 6 Slip surface form of foundation pit under ideal condition

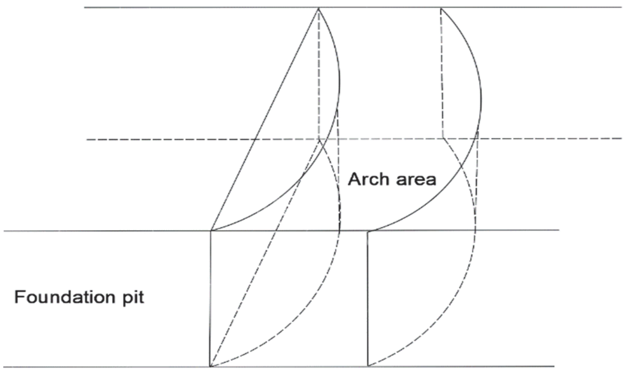


Figure 7 Soil arch behind foundation pit retaining structure

In order to study the generation mechanism and influence range of spatial effect of foundation pit, several different combinations of sliding surface and soil arch are listed as shown in Fig. 8 to Fig. 10.

(1) When the angle of the sliding surface of the soil behind the foundation pit wall is small or the excavation depth of the foundation pit is large, the intersection line of the sliding surface and the ground surface is at the outside of the soil arch, or the sliding surface passes through the arch body and is tangent to the outer boundary of the soil arch, then the soil behind the foundation pit retaining structure is affected by the space effect, and the fracture body is the upper semi-cylindrical lower wedge, as shown in Fig. 8.

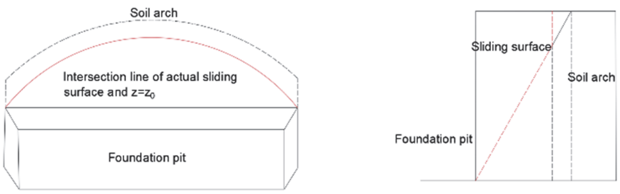


Figure 8 The area of foundation pit wall is completely affected by space effect

(2) When the angle of the soil sliding surface behind the retaining structure of the foundation pit is large, or the excavation depth of the foundation pit is small, the intersection line of the sliding surface and the ground surface will be close to the foundation pit wall. When the sliding surface is just tangent to the inner side of the soil arch, the critical point of the foundation pit affected by the space effect will be reached, as shown in Fig. 9. At this time, the scope of the pit wall is still affected by the corresponding space.

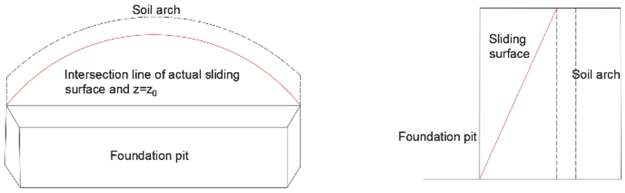


Figure 9 Critical state of space effect

(3) When the excavation depth of the foundation pit continues to decrease, or the angle of the soil sliding surface behind the retaining structure continues to increase, the sliding surface will intersect with the ground surface at the inner side of the soil arch. At this time, the pit angle will be affected by the soil arch within a certain range. The fracture surface is curved, and the middle of the foundation pit will not be affected by the soil arch. The fracture surface is straight, as shown in Fig. 10.

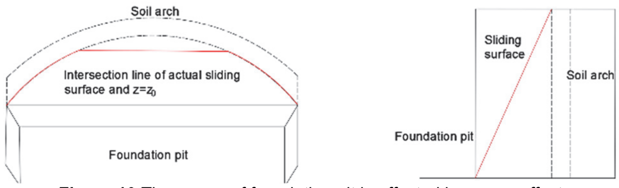


Figure 10 The corner of foundation pit is affected by space effect

Through the analysis of the formation mechanism and influence scope of the above foundation pit spatial effect, it can be seen that when the foundation pit retaining structure moves towards the pit, the soil behind the foundation pit wall will form a soil arch, and the interaction between the potential sliding surface and the soil arch existing in the original soil will eventually form different forms of soil failure, which is the essence of the foundation pit spatial effect.

3.2 Analysis on the Horizontal Displacement Quantity Monitoring of the Supporting Construction

During the construction of subway base pit, the soil movement inside the base pit reflects the displacement distance of the supporting pile building. Through the analysis of engineering level of supervision data movement distance of the existing support pile building, obviously the architecture depth of subway excavation for basic pit can affect the stability of the support pile building, causing its displacement. According to the monitoring data, displacement monitoring points such as ZQS-02, ZQS-03 and ZQS-04 are selected, and displacement curves are drawn according to the working conditions. As shown in Fig. 11, movement distance of pile top changes with time and excavation depth. The movement distance is determined by the top orientation of the pile. It is negative when moving towards the interior and front of the basic pit. When moving towards the outside of the basic pit, as shown in Fig. 11, the change curve of pile top displacement with time and excavation depth is negative when the retaining structure moves to the inside of the foundation pit, and positive when it moves to the outside of the foundation pit.

The engineering circumstances of subway basic pit construction are as follows: Engineering situation 1 - pile construction; Project situation 2 - construction of the thickness of the first layer of soil in basic pit and rigid support reinforcement. Case 3 - Build a second layer of soil in basic pit and setting of steel support. Project situation 4 - Excavation to 13 meters below the surface and repair accordingly. Condition 5 - Excavation to the third layer and steel bearings; And condition 6 - excavation to the pit bottom, pour the bottom plate until it hardens.

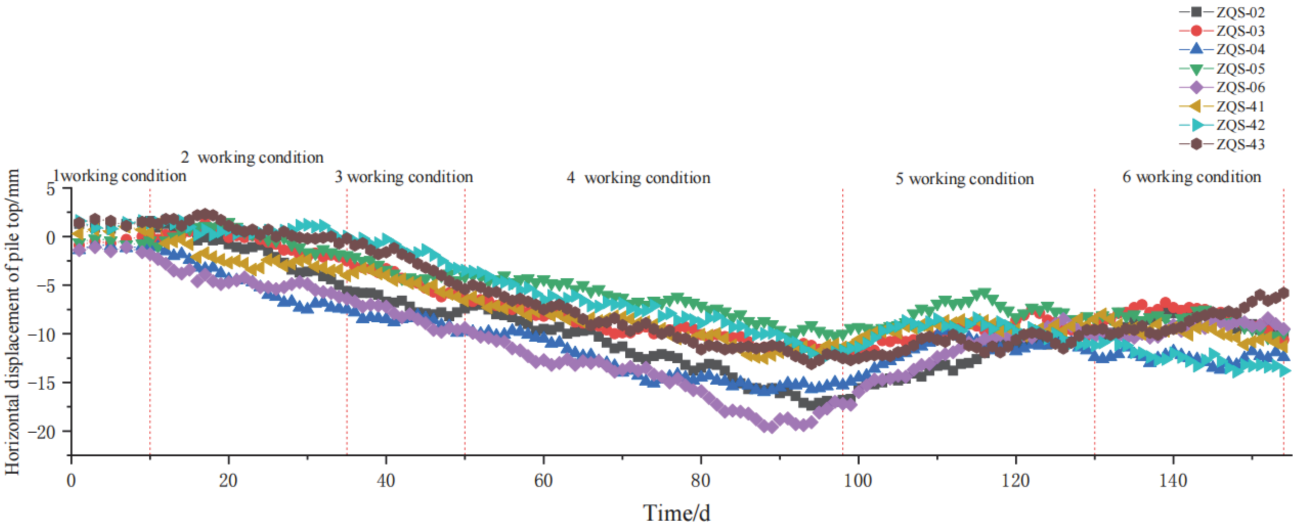
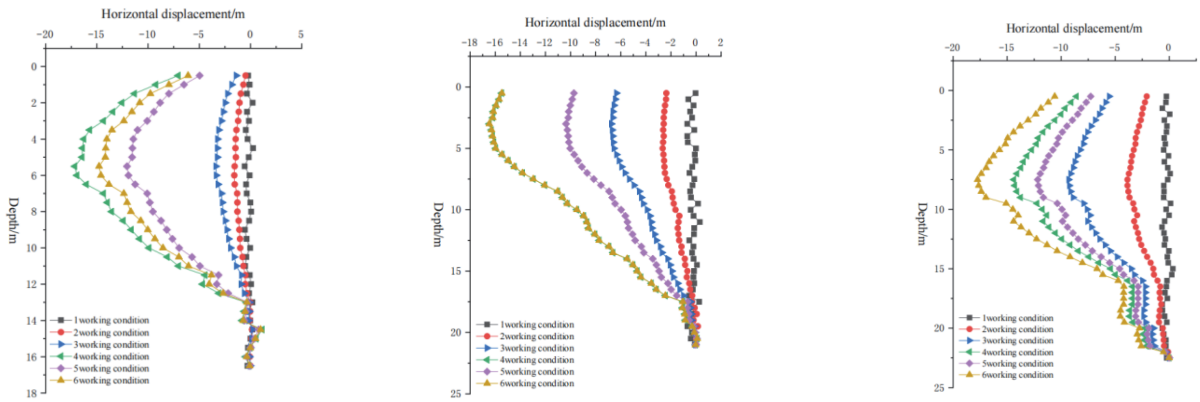


Figure 11 Horizontal movement distance of pile top



(a) Lateral movement distance of pile ZQT-01 (b) Lateral movement distance of pileZQT-15 (c) Lateral movement distance of pile ZQT-16

Figure 12 Lateral movement distance of pile

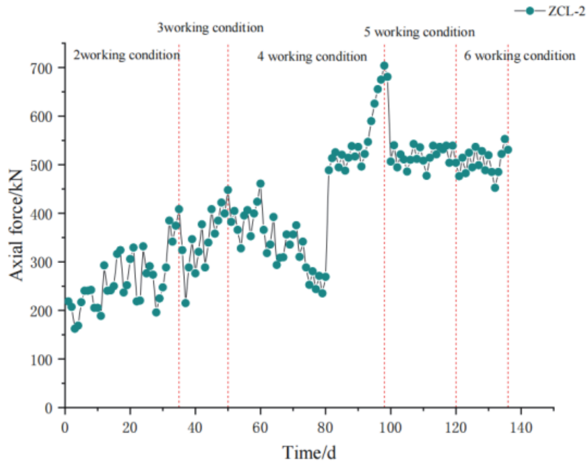
As shown in the movement curve in Fig. 11, periods of the initial architecture of the basic pit (condition 1), the retaining structure moves along the basic pit and stays away from the basic pit. Therefore, the bottom of the basic pit starts to move upward, pushing the support accumulation and soil interaction, and making the pile top move inward from the basic pit. The first layer of the basic pit is constructed (Working state 2), and side motion distance of the support pile top is proportional to the construction jinshen of the basic pit. As the first layer of soil is not the main force bearing area, the construction jinshen of basic pit is small, the steel support is installed in time, and side motion rate of the top of the retaining pile is small. Working conditions 3 and 4 are the excavation of silty clay. Since this layer was silty clay layer, which was quite sensitive in terms of property, the top of the support pile moves a large distance. With the excavation going continuously downward, the soil layer changed from silty clay to completely weathered mudstone, which had good properties and made support piles well-embedded and limited the horizontal displacement of the basic pit soil to some extent. Therefore, the drainage of the pile top showed a slowdown tendency from the end of condition 4. When the pile is excavated to 13.3 m under five working conditions, lateral movement distance of the top of the soil retaining pile reduced by the third steel support. Excavate to 16.8 m under 6 working conditions, and the bottom plate is hardened by cement pouring. The depth will not increase the horizontal top movement distance of support pile, which indicates that the hardening effect of the bottom plate and the supporting effect of strongly weathered mudstone on the soil alleviate the horizontal displacement of the soil.

The displacement distance from the pile to the original position is an important index of the deformation of the walls pile structure. Select ZQT-01, ZQT-15, and ZQT-16 as the small mileage section, near the midpoint of the long side of the foundation pit, and near the external corner of the foundation pit for comparative analysis, as shown in Fig. 12. Not hard to get that the transverse displacement of the middle part of the basic pit supporting construction pile is larger and the two ends are smaller. As the support is timely, the excavation depth under Condition 1 and Condition 2 is small, and the movement rate of support pile structure is slow. With the continuous building of the subway basic pit, the maximum quota moving location of retaining stacking structure inside basic pit will shift from the middle to the upper while the depth increases. However, in the reference [25], periods of the continuous basic pit architecture, the maximum displacement distance of the holding force pile appears at the lower part of the middle of the basic pit, and (a) and (c) occur above the middle of the soil layer. At the same time, maximum lateral movement distance of support pile in (b) occurs in the upper part of the soil. layer. This is because the rock stratum position of ZQT-01 and ZQT-16 in the basic pit is lower than ZQT-15, and the height of the rock stratum in the basic pit makes the lateral direction movement position of the pile in the basic pit support to be offset upwards. The height of the rock surface in the foundation pit makes the lateral displacement position of the pile in the foundation pit move up. The height of the rock surface has an obvious influence on the lateral displacement position of the foundation pit. In the actual project, no close attention should be paid to the height of the rock surface, and rapid excavation support should be carried out in the part of the foundation pit excavation with the maximum displacement to reduce the lateral displacement of the soil.

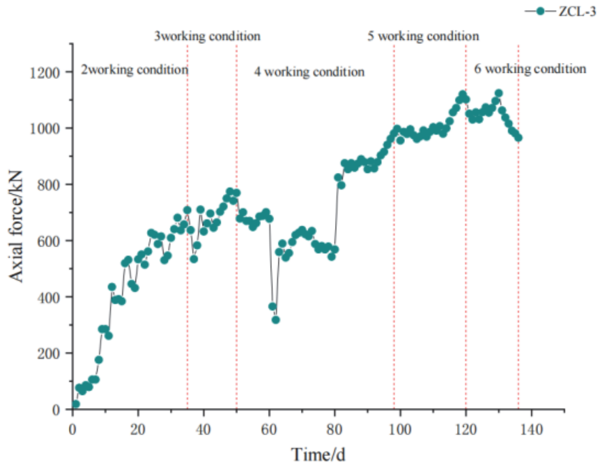
3.3 Analysis on the Axial Strength Monitoring of the Internal Support

Because the project is located inside the city, with many vehicles, large moving and unstable load, the daily axial force monitoring of the foundation pit fluctuates slightly with the impact of the moving load outside the pit, and is within the safe range. According to the existing monitoring data of the project, ZCL-2 monitoring points in the small mileage section of the pit, Monitoring point ZCL-3 near the corner of the pit and monitoring point ZCL-4 in the middle of the pit. Three different monitoring points were compared to analyze the influence of the axial pressure of the inner support on depth of basic pit construction and influence of the height of the rock surface in the soil layer on the axial pressure of the inner support. As shown in the attached drawings 13, in Condition 2 and Condition 3, with the acceleration of the construction process, the depth of basic pit construction also step by step, the axial force of the support increases in this process, while in Condition 4, the axial force rate can be reduced. The Condition 5 and Condition 6 working conditions are due to the stabilization of the inner support axial force after the floor is poured and gradually hardened.

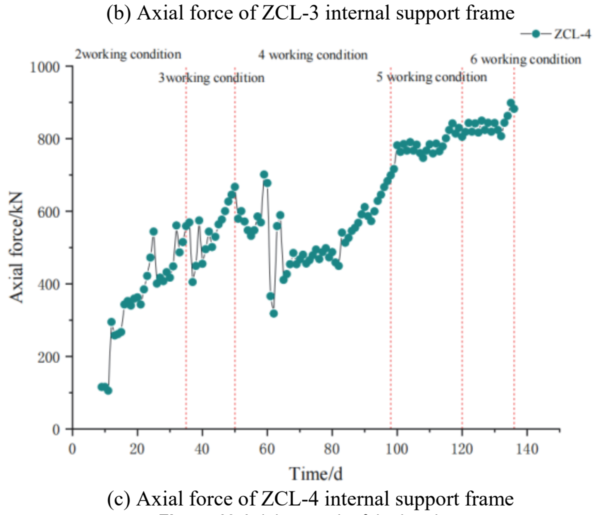
In Fig. 13, for the small mileage section shown in (a), when the excavation is carried out under shallow working conditions 1~3, the soft soil layer is squeezed by the excavation of the foundation pit. At this time, the axial force of the support gradually increases with the excavation. After the end of condition 3, due to the erection of the second rigid support, the axial force of the support is reduced.



(a) Axial force of ZCL-2 internal support frame



(b) Axial force of ZCL-3 internal support frame



(c) Axial force of ZCL-4 internal support frame

Figure 13 Axial strength of the bracket.

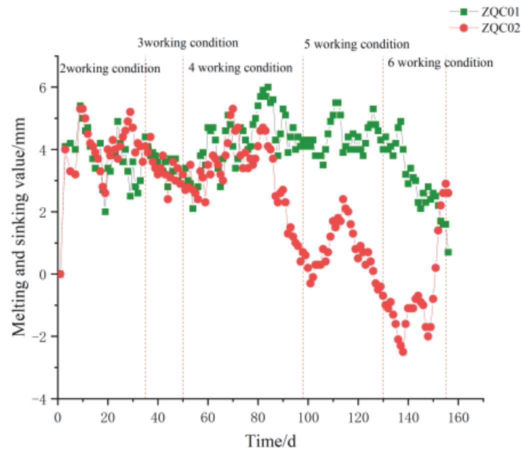
However, as the foundation pit continues to be constructed, the third support is not erected until the intersection of the soft soil layer and the rock layer, and the axial force of the support increases sharply after the excavation depth increases. After the excavation in Condition 4, the excavation depth increases but the axial force is stable. In Condition 5, because the excavation position is near the rock stratum, the rock stratum supports the soil greatly, and the displacement of the soil mass is small. The supporting effect of the soil mass supported by the third layer of steel makes the axial force of the support to continue to be stable in Condition 5 and 6.

Fig. 13b and Fig. 13c shows that ZCL-3 is located near the pit corner. Fig. 13c shows that when the second layer of silty clay layer is excavated, because it is located at the long side of the foundation pit, the supporting axial force is larger than the small mileage end, and the foundation pit shows obvious spatial effect. As shown in Fig. 13b and Fig. 13c, because the location is far from the pit angle, the displacement of the location is large, and the axial force of the support continues to increase with the increase of the excavation depth. Under condition 5, the soil layer is rock stratum, and the axial pressure of the bracket is relatively stable. In the condition 6, the axial pressure of the bracket is relatively stable due to the pouring of the bottom plate. According to the relationship support of axial force and the excavation depth, soil layer and rock surface, the excavation depth of silty clay layer shall be strictly controlled during the on-site construction of subway basic pit. Meanwhile, pay attention to the simultaneous operation of the support to avoid the steel support working under the large excavation depth, which will increase sharply the axial force of the internal support and bring harm to the project.

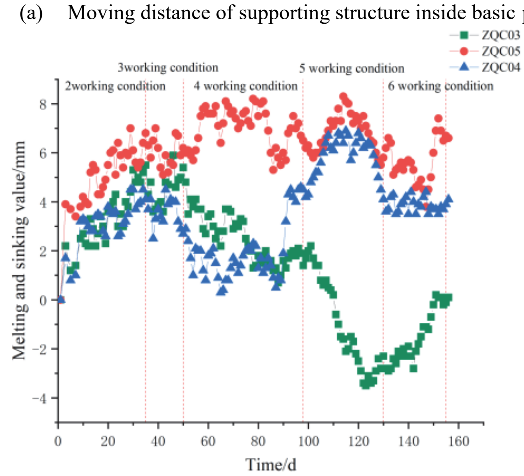
3.4 Analysis of the Monitoring of the Uplift and Settlement of the Supporting Construction

During the on-site construction of the basic pit, the depth gradually deepens with the construction, and the alter state of the bottom of the basic pit cannot be monitored. However, due to the friction between the basic pit and the supporting stacking, the friction can be well used to study the change of the pit bottom.

Therefore, the effect of depth of basic pit during architecture on the lifting settlement of the supporting building can be analyzed by monitoring the lifting settlement of the supporting stacking. As shown in Fig. 14, the rumble and sink curve of the support structure. It can be seen from Fig. 14 that the retaining pile has obvious heave during the excavation of the foundation pit. This is because with the excavation of the soil mass, the soil mass releases its self-weight stress, which makes the pit bottom soil rebound upward. The shallow soil layer is mostly silty clay layer. With the excavation of the foundation pit, the soil outside the pile is squeezed, and the soil mass in the foundation pit has poor bearing capacity, resulting in the heave of the retaining structure. As shown in (a) in Fig. 14, the uplift and settlement curve of the excavation support pile in the small mileage section of the foundation pit shows that during the soil excavation process of the support pile, with the increase of the excavation depth, the pressure of the soil outside the pit on the foundation pit increases, and the soil at the bottom of the foundation pit rises upward, driving the support pile to move up. When ZQC-01 and ZQC-02 are excavated to the rock stratum in May, the soil mass is relatively dense and has strong compressive capacity. The pressure of the rock stratum on the foundation pit is reduced, the uplift of the pit bottom is reduced, and the supporting pile has a downward trend. As shown in (b) in Fig. 14, The long side of the foundation pit location of different points support pile rumble sinking. With the excavation of the foundation pit soil, the maximum uplift of the retaining piles is about 6 mm, and the maximum subsidence is about - 7 mm. Compared with the retaining piles in the small mileage section, it can be seen that the distance between the retaining piles and the pit corner of the foundation pit is relatively close, and the vertical uplift trend of the retaining piles is relatively slow.



(a) Moving distance of supporting structure inside basic pit



(b) Moving distance of supporting structure inside basic pit

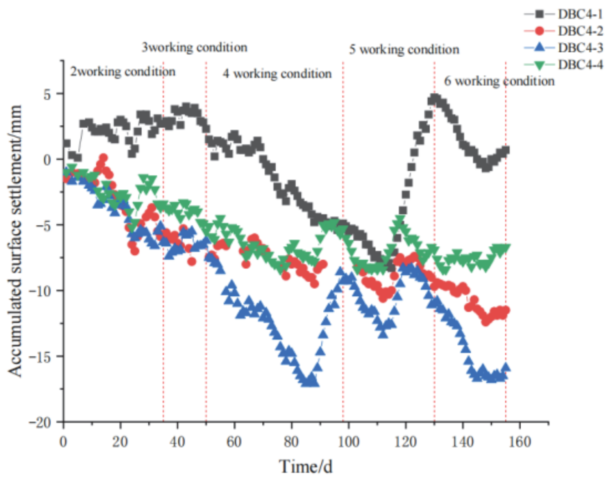
Figure 14 Moving distance of supporting structure inside basic pit

Among them, ZQC03 is located near the pit corner of the foundation pit, ZQC04 and ZQC05 are far away from the pit corner, and the rule of uplift and subsidence of the column measuring points is basically the same. The uplift value of the pit bottom increases with the increase of the excavation depth, but after the completion of the floor construction (condition 5), the uplift rate and the uplift value of the column are significantly reduced. It can be seen that the bottom plate should be poured as early as possible to effectively control the uplift and deformation at the bottom of the foundation pit through its own weight. Compared with the bulge value of each measuring point, in general, before the construction of the bottom plate is completed, its bulge value is relatively large, while the maximum bulge value of ZQC03 measuring point near the pit corner is relatively small, which is 6 mm, and the bulge value of ZQC04 and ZQC05 measuring points far away from the pit corner are 8 mm. It can be seen that from the side of the foundation pit to the middle of the foundation pit, its uplift value gradually increases, and also shows a significant spatial effect.

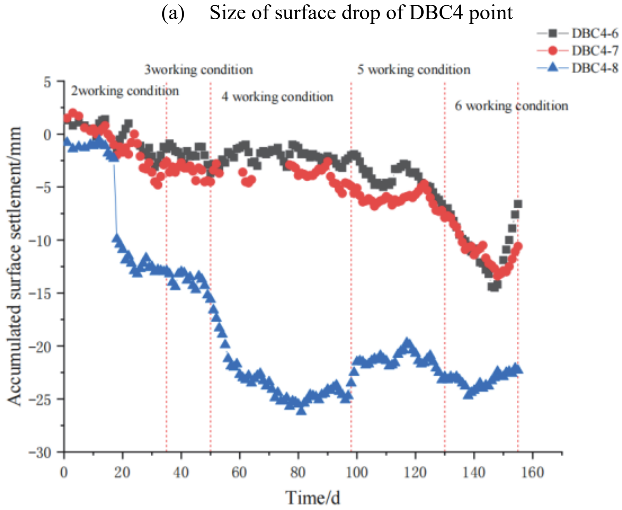
4 ANALYSIS ON SETTLEMENT MONITORING OF THE SURFACE AND SURROUNDING BUILDINGS

4.1 Analysis on Surface Settlement Monitoring

Influence of lateral displacement distance of internal support structure of basic pit on drainage and distortion of nearby earth wire, which is triangular and concave [26]. Select the ground settlement monitoring points 1-9 neighborhood the shorter lateral of the basic pit DBC-4, the corner position DBC-5 and longer side midpoint of basic pit DBC-7. Reduction size of ground surface curve is shown in the Fig. 9 to Fig. 11. The surface settlement value around the foundation pit shows a trend of increasing and then decreasing along the direction away from the pit wall. Under condition 5, the surface settlement began to decrease during the third support, but the settlement did not slow down when the distance between the monitoring position near the basic pit and the basic pit becomes larger.



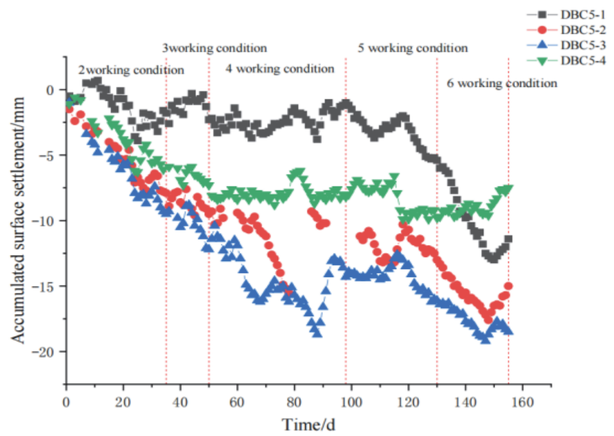
(a) Size of surface drop of DBC4 point



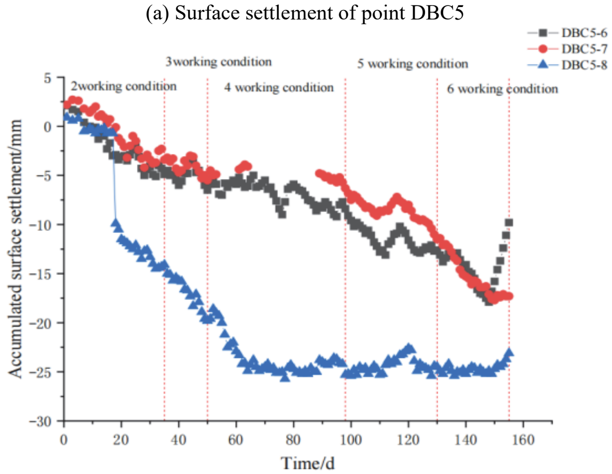
(b) Size of surface drop of DBC4 point

Figure 15 Monitoring of surface falling distance at DBC4 point

As shown in Fig. 15a and Fig. 15b, point DBC-4 was located near the short side of the basic pit. Fig. 15a diagram settlement value of point DBC4-3 was the largest, while that of point DBC4-1 the smallest. As shown in Fig. 15b, the maximum value of surface settlement was found at points DBC4-8, and the minimum value of surface settlement was found at points DBC4-6. It is obvious from the data study that with the continuous excavation of the construction process, the depth of the basic pit gradually deepens, the ground settlement of the basic pit monitoring points gradually added from 0 millimeter to 25 millimeter, and DBC4-3 and DBC4-8 have the largest settlement long distance from subway basic pit. The maximum settlement displayed in Fig. 15a and Fig. 15b does not occur near the basic pit, but in the area near the basic pit. The main reason is that according to construction depth of subway basic pit, the soil stress is released, so that the active earth pressure outside the basic pit grows, and the pile moves to the inside of the basic pit. Through the comparison of the maximum displacements of DBC4-3 and DBC4-8, it was found that, as DBC4-8 was close to the building, the weight of the building made the point experience a larger displacement. In construction, the most important thing to pay attention to is adjacent buildings near the basic pit, and large surface settlements should be closely monitored to avoid potential safety hazards.



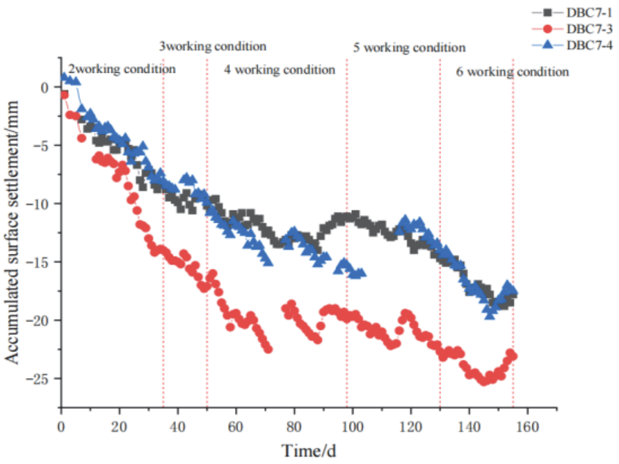
(a) Surface settlement of point DBC5



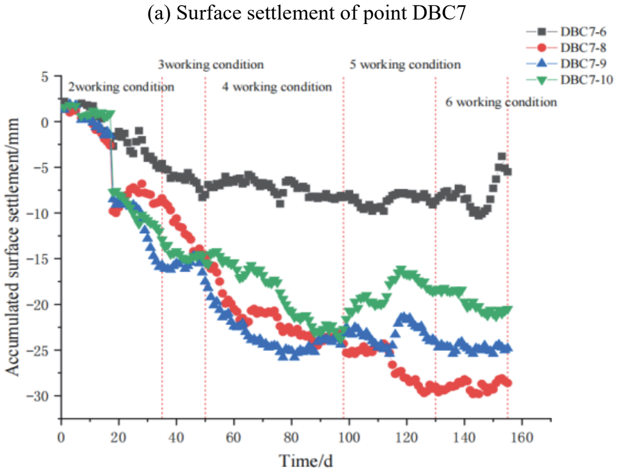
(b) Surface settlement of point DBC5

Figure 16 Monitoring on the surface settlement of point DBC5

As shown in Fig. 16, point DBC-5 was located near short side position of basic pit. Fig. 16b shows that the surface drop-out value of point DBC5-3 was the largest, while that of point DBC5-1 the smallest. It is easy to draw from the Fig. 16b that the surface settlement value of DBC5-8 is the largest and that of DBC5-6 is the smallest. It can be concluded fom Fig. 16 that as the construction continues, the depth continues to increase, lowering of each monitoring point in the basic pit gradually increases from 0 mm to 25 mm, of which DBC5-3 and DBC5-8 have the largest settlement at distance from subway basic pit. This phenomenon is the same as the ground settlement trend of DBC4 point, which can indicate more that a safety distance of 5 m should be kept while the foundation pit is being excavated to avoid the application of excessive load, which will cause the ground settlement warning.



(a) Surface settlement of point DBC7



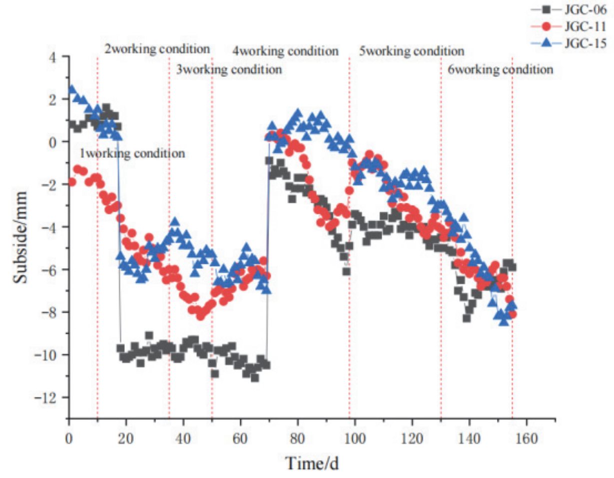
(b) Surface settlement of point DBC7

Figure 17 Monitoring on the surface settlement of point DBC7

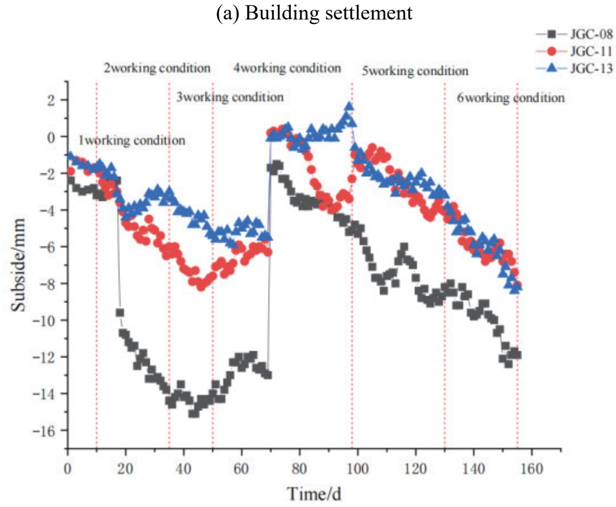
As shown in Fig. 17, DBC-7 is located at the midpoint of the long side of the foundation pit. As shown in Fig. 17a, the surface settlement value of DBC7-3 point is the largest, with the settlement value of 25 mm, and that of DBC7-1 point is the smallest, with the settlement value of 17 mm. As shown in Fig. 17b, the surface settlement value at DBC7-8 is the largest, with the settlement value of 30 mm, and that at DBC4-6 is the smallest, with the settlement value of 8 mm. With the continuous basic pit being a construction process, the depth of the basic pit continues to deepen, and the settlement value was from 0 mm to 30 mm, showing that the part of the longer on one side of the basic pit experiences a bigger settlement compared with the short noodles, which is in line with the spatial function of the basic pit. In actual construction, the long side of the basic pit cannot be overloaded or used to park heavy equipment. During basic pit construction, timely support should be such as to protect the longer side of the basic pit from being under the influence of large downward movement.

4.2 Analysis on the Monitoring of Building Settlement

Fig. 18 expressed the existing buildings nearby. The buildings near the foundation pit were selected to monitor their settlements. Select points JGC-6, JGC-15, JGC-8, JGC-13 and JGC-11 near the foundation pit buildings to analyze the building settlement curve during the foundation pit construction.



(a) Building settlement



(b) Building settlement

Figure 18 Building settlement

Fig. 18 shows that near the pit points JGC-6 and JGC-8, the pit has a large settlement from working condition 2 to 4. With the constantly deepening of construction subway basic pit, there will be a large displacement near the location of the basic pit. Fig. 10a shows that the trend of building settlement was the same at JGC-13 and JGC-11, which were far from the foundation pit. Fig. 12b shows that for these two points JGC-11 and JGC-13, the settlements were relatively small. The settlements of the buildings were generally greater than that of the earth curved surface, mainly because the self-weight of the buildings aggravated the deformation of the soil. In practical engineering, there should be no heavy equipment and soil load between the building and the foundation pit, so as not to accelerate the settlement rate near the building.

5 CONCLUSIONS

Taking the soil rock composite basic pit project of Anxin Road Station of Changchun Subway routes 5 as an example, this document analyzes the monitoring data of the basic pit construction in the soil rock composite geological conditions of the seasonally frozen soil area, and draws the following conclusions:

(1) There are obvious spatial effects on the lateral displacement, support axial force, surface settlement and building settlement deformation of the foundation pit retaining structure. The closer the pit angle is, the greater the impact of the spatial effect of the foundation pit is. The lateral displacement, support axial force, surface settlement and building settlement of the foundation pit retaining structure are reduced to varying degrees. However, with the distance from the pit angle, its spatial effect gradually weakened. At the long side of the foundation pit, with the increase of the distance from the pit angle, the displacement of the retaining structure of the foundation pit is greater, and the spatial effect in the middle of the long side of the foundation pit basically disappears.
(2) The analysis of the monitoring data shows that the axial force of the foundation pit support, the lateral displacement of the retaining pile structure and the pile heave of the foundation pit during the excavation of the third layer of silty clay all show a large increase in the excavation stage of the foundation pit, and gradually become stable after the bottom plate plays its role, indicating that the bottom plate is of great significance for the control of the safe construction of the foundation pit. The completion of the foundation pit floor construction can effectively reduce the lateral deformation of the foundation pit, the axial force of the support, the uplift of the foundation pit bottom and the settlement of the building. During construction, attention should be paid to the timely pouring of the bottom plate, so as to increase the stability of the foundation pit and reduce the impact on the surrounding environment.
(3) During the excavation of soil-rock composite foundation pit in seasonally frozen soil area, the pile displacement, axial force of support and uplift of support structure caused by rock excavation are relatively small, the lateral displacement of foundation pit below the rock surface and the thawing settlement deformation of soil are basically unchanged, and the maximum value of lateral displacement of foundation pit above the rock surface moves upward, indicating that the displacement and deformation characteristics of metro deep foundation pit in soil-rock composite stratum are different from those of soil foundation pit, and have better stability.

Funding

This article is supported by Jilin Science and Technology Development Plan Project (20220203058SF).

6 REFERENCE

[1] Zhang, L. M., Chao, W. W., Liu, Z. Z., Cong, Y., & Wang, Z. Q. (2022). Crack propagation characteristics during progressive failure of circular tunnels and the early warning thereof based on multi-sensor data fusion. *Geomechanics and Geophysics for Geo-Energy and Geo-Resources*., *8*, 172. https://doi.org/10.1007/s40948-022-00482-3

[2] Xu, P. Y., Zhang, L. M., Zhang, J. Y., Wang, J. X., & Zhang, P. C. (2023).Progressive Failure Characteristics and Failure Symptoms of Straight-Walled Arched Sandstone Tunnels. *Acadlore Transactions on Geosciences.*, *2*(1), 46-57. https://doi.org/10.56578/atg020105

[3] Zhang, L. M., Cong, Y., Meng, F. Z., Wang, Z. Q., Zhang, P., & Gao, S. (2021). Energy evolution analysis and failure criteria for rock under different stress paths. *Acta Geotechnica*., *16*(2), 569-580. https://doi.org/10.1007/s11440-020-01028-1

[4] Finno, R. J., Blackburn, J. T., & Roboski, J. F. (2007). Three-dimensional effects for supported excavations in clay. *Journal of Geotechnical and Geo environmental Engineering*, *133*(1), 30-36. https://doi.org/10.1061/(ASCE)1090-0241(2007)133:1(30)

[5] Yu, J. L. & Gong, X. N. (1999). Spatial behavior analysis of deep foundation pit engineering. *Journal of Geotechnical Engineering*, *21*(1), 21-25.

[6] Liu, N. W., Gong, X. N., Yu, F., & Fang, K. (2014). Analysis on spatial effect and influencing factors of foundation pit with internal support structure. *Geotechnical Mechanics*, *35*(8), 2293-2298.

[7] Wang, J. H., Xu, Z. H., & Wang, W. D. (2010). Wall and ground movements due to deep excavations in Shanghai soft soils. *Journal of Geotechnical and Geoenvironmental Engineering*, *136*(7), 985-994. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000299

[8] Long, M. (2001). Database for retaining wall and ground movements due to deep excavations. *Journal of Geotechnical and Geoenvironmental Engineering*, *127*(3), 203-224. https://doi.org/10.1061/(ASCE)1090-0241(2001)127:3(203)

[9] Li, J. P., Chen, H. H., Li, L., & Ma, J. S. (2018). Experimental study on excavation depth and spatial effect of soft soil foundation pit. *Chinese Journal of Highway*, *31*(2), 208-217.

[10] Tan, Y., Wei, B., Zhou, X., & Diao, Y. (2015). Lessons learned from construction of Shanghai metro stations: importance of quick excavation, prompt propping, timely casting, and segmented construction. *Journal of Performance of Constructed Facilities*, *29*(4), 04014096. https://doi.org/10.1061/(ASCE)CF.1943-5509.0000599

[11] Yang, B. Z. & Zhong, X. M. (2008). Numerical analysis of deep foundation pit excavation process based on FLAC-3D. *Journal of Hebei University of Technology*, *25*(3), 15-18.

[12] Lin, Z. H. (2020). Deformation Law and Spatial Effect analysis of Deep Foundation Pit with Upper Soft and Lower Hard. *Journal of Underground Space and Engineering*, *16* (6), 1792-1800.

[13] Lei, M.F., Peng, L. M., Shi, C. H., & An, Y. L. (2010). Study on spatial effect of long and deep foundation pit construction. *Geotechnical Mechanics*, *31*(5), 1579-1596.

[14] Zhang, L. M., Zhang, D., Cong, Y., Wang, Z. Q., & Wang, X. S. (2023). Constructing a three-dimensional creep model for rocks and soils based on memory-dependent derivatives: A theoretical and experimental study. *Computers and Geotechnics*., *159*. https://doi.org/10.1016/j.compgeo.2023.105366

[15] Yang, P. Y., Wu, X. E., & Chen, J. H. (2018). Elastic and plastic-flow damage constitutive model of rock based on conventional triaxial compression test. *International Journal of Heat and Technology*, *36(3),* 927-935. https://doi.org/10.18280/ijht.360320

[16] Lou, C. H., Xia, T. D., & Liu, N. W. (2019). Analysis of Spatial Effect of Foundation Pit on Surrounding Environment in Soft Soil Area. *Journal of Geotechnical Engineering*, *41*(S1), 249-252.

[17] Zhang, Y. S., Xue, X. C., Zhuang, H. Y., & Liu, X. Z. (2018). Study on the influence of soft soil layer on the surface settlement of subway narrow and long deep foundation pit. *Journal of Underground Space and Engineering*, *14*(6), 1639-1651.

[18] Zhang, N. (2021). Study on deformation law of deep foundation pit in soil rock composite stratum. *Journal of Railway Engineering*, *38*(7), 1-5.

[19] Yu, X. & Song, L. (2020). Deformation analysis of support system of irregular deep foundation pit under spatial effect.

Journal of Wuhan University of Science and Technology, *43*(5), 384-389. https://doi.org/10.3969/j.issn.1674-3644.2020.05.010

[20] Lin, P., Liu, P., Ankit, G., & Singh, Y. J. (2021). Deformation Monitoring Analysis and Numerical Simulation in a Deep Foundation Pit. *Soil Mechanics and Foundation Engineering*, *58*(1), 56-62. https://doi.org/10.1007/s11204-021-09706-2

[21] Ding, J. S., Xian, Y. Q., & Liu, T. J. (2011). Numerical Modeling of Affection of Foundation Pit Excavation on Metro Tunnel. *Advanced Materials Research*, *368-373*, 2562-2566. https://doi.org/10.4028/www.scientific.net/amr.368-373.2562

[22] Qin, Z., Tao, Z., Chen, Z., Zhang, Z., Tang, C., Liu, H., & Ren, Q. (2022). Deformation analysis and prediction of foundation pit in soil-rock composite stratum. *Frontiers in Physics*, *9,* 817429. https://doi.org/10.3389/fphy.2021.817429

[23] Sun, Y. & Li, Z. (2022). Study on Design and Deformation Law of Pile-Anchor Support System in Deep Foundation Pit. *Sustainability*, *14*(19), 12190. https://doi.org/10.3390/su141912190

[24] Bian, X., Hu, H., Zhao, C., Ye, J., & Chen, Y. (2021). Protective effect of partition excavations of a large-deep foundation pit on adjacent tunnels in soft soils: a case study. *Bulletin of Engineering Geology and the Environment*, *80*, 5693-5707. https://doi.org/10.1007/s10064-021-02256-9

[25] Yang, Y., Li, X., & Chen, Y. (2022). The Influence of Different Excavation Methods on Deep Foundation Pit and Surrounding Environment. *Proceedings of the 8th International Conference on Civil Engineering*, 109-129. https://doi.org/10.1007/978-981-19-1260-3_11

[26] Shang, D. Y. (2020). Deformation and stability of external angle of deep foundation pit of subway station in soil rock composite stratum. *Journal of Beijing Jiaotong University* *44*(06), 25-33.

Contact information:

Meiyan WANG, Prof.
Country College of Construction Engineering, Jilin University,
Changchun 130026, China
Department of Civil Engineering,
Shandong Vocational College of Science and Technology,
Weifang 261053, China
E-mail: wmy15@mails.jlu.edu.cn

Dajun ZHAO, Prof.
Country College of Construction Engineering, Jilin University,
Changchun 130026, China
E-mail: zhaodj@jlu.edu.cn

Wei WANG, Prof.
(Corresponding author)
School of Civil Engineering, Changchun Institute of Technology,
Changchun 130021, China
E-mail: 0215051@ccit.edu.cn

Pengda MA, PhD
School of Civil Engineering, Changchun Institute of Technology,
Changchun 130021, China
E-mail: mapengda@stu.ccit.edu.cn

Shan JIANG
The Fourth Engineering Co., Ltd.,
China Railway No.3 Engineering Group Co., Ltd., Beijing 100000, China
E-mail: mpengda@163.com