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Analysis of Surface Uplift of Deep Foundation Pit of East Extension Dou Ge-Zhuang Station of Beijing Subway Line 7

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Abstract

Taking the construction of bottomless foundation pit of the East Extension Dou Ge-Zhuang Station of Beijing Subway line 7 as an example, combined with the influence factors of the station's geographical location, stratigraphic lithology, hydrogeology, and surrounding environment, the surface uplift of bottomless foundation pit of this station is directionally analyzed. According to the data of steel support and monitoring during the construction of the bottomless foundation pit, Midas geotechnical software is used to simulate the overall construction of bottomless foundation pit, and the mechanism of foundation pit uplift is analyzed, combined with the curve of soil mass variation during the simulation process, the solution to surface uplift is proposed, which is of great significance for similar cases of future projects.

Keywords - *Deep Foundation Pit; Subway Station; Surface Uplift; Steel Support; Midas Geotechnical Software*

I. INTRODUCTION

Due to its unique social factors, most of the opening excavation construction in Beijing subway works are in the form of the semi-relief slope. The bottomless foundation pit of the East Extension Dou Ge-Zhuang Station of Beijing Subway line 7 is supported by using steel support and bored grouting piles to carry out construction in combination with the method of wellpoint precipitation, which causes a large area of surface uplift. Because it is located in the centre of the city, it has a severe impact on the gas pipeline at the edge of the foundation pit. In this paper, the construction process of the deep foundation pit in Dou Ge-Zhuang Station is monitored in detail, and the mechanism of foundation pit uplift is analyzed, and the solution is proposed, which has particular reference significance.

The dewatering of bottomless foundation pit should run through the whole process of foundation pit excavation, so the protection of the underground pipeline should be emphasized in the construction process[1]. In recent years, there have been many analyses on the environmental impact of deep foundation pit dewatering on the surrounding environment of foundation pit in China, such as Liu Wei-li [2] analyzed the main factors that influence the surrounding environment caused by dewatering of bottomless foundation pit, Chen Yong-Cai et al.[3] analyzed the treatment measures of the deep foundation pit dewatering on the surrounding environment, and Zhu Qing-Jie et al.[9] emphatically analyzed the influence of pipe soil friction and pipe diameter on pipeline failure. In this paper, three-dimensional finite element software MIDAS[5-6] is used to study the impact of deep foundation pit excavation and dewatering on adjacent underground pipelines at the East Extension Dou Ge-Zhuang Station of Beijing Subway Station Line 7 [7-8], which can be used as a reference for other similar projects.

II. GEOLOGICAL CONDITIONS OF THE PROJECT

A. Project survey

The East Extension Dou Ge-Zhuang Station of Beijing Subway Line 7 is located on the east side of the intersection of the north road of Lang Xin-Zhuang and Lang Xin-Zhuang in the Planning of Chaoyang District, Beijing, and laid along the east and west side of Wantong road. The station has three floors, and the main structure is a frame structure. The standard section of the station is 22.1m wide and 20.81m high. The shield station is 25.9 m wide and 22.5m high. The station planning is shown in Figure 1 below:

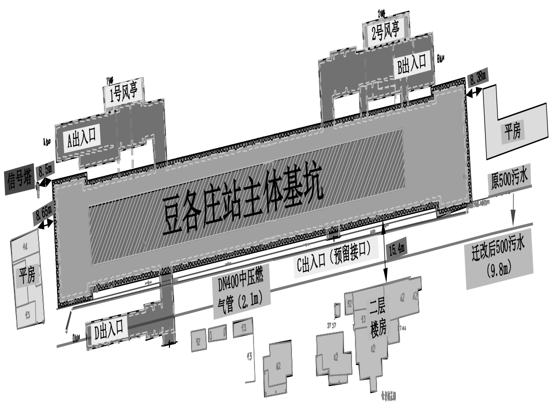

Fig. 1 location map of Dou Ge-Zhuang station

According to the technical management system of safety risk and the design of risk source in the construction stage of the Beijing Rail Transit Project, the risk of the foundation pit of the main body of this station is first-class. The risk of the central foundation pit is first class; the length of the foundation pit is 206m, the width of the standard section is 21.9m, and the depth is 24.51m. The shield well is 24.7m wide and 25.94m deep; its structure is simple. According to the foundation pit and tunnel project's own risk grade evaluation, the Dou Ge-Zhuang's risk grade is first class. Due to existing rail transit facilities in the affected area, the surrounding environmental risk level is grade one. According to Table 3.3.5, technical specification for urban rail transit engineering monitoring (GB050911-2013), the monitoring grade is first class.

B. Formation lithology

For details of the distribution of each soil layer and the physical and mechanical properties of each layer of soil in this filed, see works geological profile (Figure 2) and comprehensive statistical table of physical and mechanical properties of rock and soil (Figure 1)

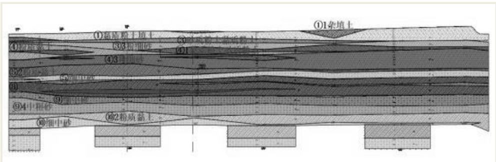

Fig. 2 geological profile

C. Hydrogeology

The west side of the proposed station is the west drainage trunk and Tonghui Irrigation Canal, separated by the existing road, the width of the road is about 9m. The upper opening of the drainage trunk is about 21m wide, with lining. During the survey, the water depth was about 0.50m, the water level elevation was about 25.12m, and it was about 80m away from the station structure. The upper opening of the Tonghui Irrigation Canal is about 25m wide without lining. During the survey, the water depth was about 1.5m, the water level elevation was about 26m, and it was about 54m away from the station structure. There is a fish pond on the east side of the station. The fish pond is lined with concrete. According to this investigation, it can be inferred that there is a specific hydraulic relationship between surface water and groundwater.

Three layers of groundwater are observed in this survey (drilling depth is 53m); the types of groundwater are interlayer water (III), confined water (IV), and confined water (VI). Detailed records of three-layer water observations are shown in Table 2.

No hysteretic water was found in this survey (I). Under the influence of precipitation or greening irrigation, the possibility of discovering the layer water during construction is not excluded.

Table 1 Comprehensive Statistical Table of Physical and Mechanical Properties of Rock and Soil

Soil layer number	Severe	Cohesive force	Internal friction angle	Static lateral pressure coefficientK_0	permeability coefficient K（m/d）	Standard bearing capacity of foundation soil f_k（kPa）
	kN/m^3	c（kPa）	φ（°）			
①Clay silt filling	（	（5）	（10）	/	/	/
①$_1$Miscellaneous	（16.5）	（0）	（8）	/	/	/
③Sandy silt clay	19.4	12	31	0.51	（1.0）	180
③$_3$Silty fine sand	19.5	0	（25）	（0.40）	（5）	190
④Silty clay	19.7	30	15	0.45	（0.05）	160
④$_1$Sandy silt clay	19.9	16	27	（0.43）	（1.0）	200
④$_3$Silty fine sand	（19.5）	0	（25）	（0.38）	（8）	220
⑤Fine medium	（20.0）	0	（28）	（0.36）	（15）	280
⑤$_1$Clay silt sandy	20.6	（15）	（28）	（0.43）	（1.0）	230
⑤$_2$Silty clay	20.4	27	19	0.44	（0.05）	200
⑧Silty clay	19.7	28	17.1	0.40	（0.05）	210
⑧$_2$Clay silt sandy	20.8	23	21	0.46	（1.0）	250
⑧$_3$Silty fine sand	（21.0）	0	（28）	/	（10）	280
⑨Fine medium	（21.3）	0	（32）	/	（20）	300
⑨$_2$Clay silt sandy	20.3	16	26	/	（1.0）	260
⑨$_4$Medium coarse	（21.3）	0	（35）	/	（30）	350
⑩Fine medium	（21.5）	0	（32）	/	（20）	330
⑩$_2$Silty clay	19.8	/	/	/	（0.05）	250

Table 2 Groundwater Characteristic Table

Properties of groundwater	Stable water/head buried depth（m	Stable water/head elevation （m）	Observation time	Main aquifer	Remarks	Condition of fill, diameter, and discharge
Interlayer water(III)	10.70~14.00	15.18~17.47	2016.01 2016.04	④3Silty fine sand	/	Side runoff and cross-flow supply, side runoff discharge
Confined water(IV)	13.65	14.72	2016.04	⑤Fine medium sand 、⑤$_1$ Sandy silty clay silty	Water head height is about 5m	Side runoff and cross-flow supply, side runoff discharge
Confined water(VI)	14.06~15.06	14.33~14.56	2016.04	⑨Fine medium sand 、⑨$_4$ Medium coarse sand	Aquifers are continuously distributed, water head height is about 10-11m.	Side runoff and cross-flow supply, side runoff and manual drainage

Table 3 Risk Works

Serial number	Name of risk works	Description of risk basic condition	Level of risk
1	Foundation pit of the main structure	The length of the foundation pit is 206m, the width of the standard section is 21.9m, and the depth is 24.51m. The shield well is 24.7m wide and 25.94m deep	Self-first level
2	The west end of the central excavation foundation pit is near the one-story bungalow	The western bungalow is 8.65m from the foundation pit and 25.94m deep. No foundation bungalow, and masonry structure	Environmental first level
3	The east end of the opening central excavation foundation pit is near the one-story bungalow	The eastern bungalow is 8.38m from the foundation pit and 25.53m deep. No foundation bungalow, and masonry structure	Environmental first level
4	Opening excavation main Foundation Pit near DN400 medium pressure natural gas pipe	DN400 medium pressure natural gas pipe, distributed from east to west, pipe top elevation is 27.06m, and minimum horizontal distance from the main body of the station is 2.1m	Environmental first level
5	Northside slope of opening excavation central foundation pit	The height of the north side slope of the foundation pit is about 15m, which is a natural accumulation slope and greatly influences the foundation pit.	Environmental first level

D. Surrounding environment of the project

The north side of the project is a natural slope with a height of about 15m and a distance of about 10m from the foundation pit. The soil pressure has a great influence on the stability of the foundation pit. Table 3 below is an introduction to its risk works:

III. CONSTRUCTION SUPPORT AND MONITORING DATA

The stability of foundation pit soil and the safety of construction ensured by, the construction unit adopts the method of half-open excavation in the process of foundation pit construction. First, the western part of the excavation and the slope is placed from the east shield well, which serves as the entrance to personnel and vehicles, as shown in Figure 3:

Construction sequence: (1) construction of bored cast-in-place pile(the diameter of the pile is 1m and the spacing distance between pile cores is 1.4m); (2)Excavation of foundation pit(excavation to the first support below 0.5m)→making crown beam and retaining wall→setting up the first steel support;(3)Excavation in turn to the second, three, four support below 0.5 m, erection of the second to the fourth steel supports. The first inner bracing is ϕ609 ×14 steel support with a distance of 6m across brace. Other inner supports are ϕ 800×16 steel with a distance of 3.0 m across brace.After the construction of the shield well on the west side is completed, the excavation is carried out to the bottom of the foundation pit, apply it as a comprehensive grounding, plain concrete cushion course, waterproof course.

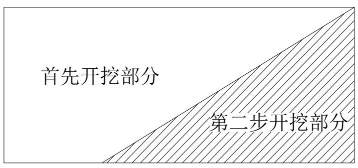

Fig. 3 excavation sequence diagram of foundation pit

After observation, from April 2017 to August 2017, a large-scale uplift occurred in the north and south of the foundation pit, and the maximum uplift was 2cm.

According to the data provided by the third party monitoring, the surface settlement on the west side of the foundation pit is shown in Figure 4:

to avoid it and ensure the safe construction of the project.Midas geotechnical software is used to simulate the numerical simulation, which is different from the half-width excavation used in the construction. This numerical

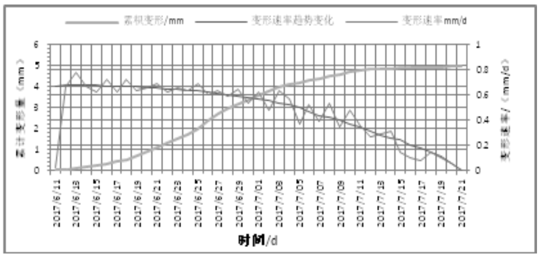

Fig. 4 surface subsidence diagram on the west side of foundation pit

The surface settlement on the east side of the foundation pit is, as shown in Figure 5:

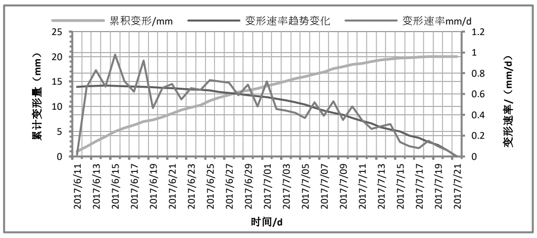

Fig. 5 surface subsidence diagram of the east side of foundation pit

It can be seen from the figure that the surface subsidence occurred on the west side of the foundation pit, while the settlement observation point in the middle of the foundation pit began to rise, and the amount of uplift on the east side gradually increased. This indicates that the uplift on both sides of the foundation pit is relatively large in the western half excavation. Due to the daily cleaning of the uplifted soil at the bottom of the foundation pit, most of the soil on both sides of the foundation pit is in the subsidence state.

IV. NUMERICAL SIMULATION

Layer number	Name of soil type	Severe (kN/m^3)	Cohesive force (kN/m^3)	Internal friction angle（°）	Modulus of compression（MPa）	Poisson ratio
①	Miscellaneous filling	18	5	10	9.67	0.33
②	Silty soil	19.4	14.2	14.7	15.32	0.35
③	Clay	18.3	38	11.5	5.9	0.32
④	Silty clay	19.4	36.1	27.5	7.18	0.35
⑤	Silt sand clamp silt	19.6	33	11.8	15.12	0.33
⑥	Silt sand	19.8	35	12.3	10.58	0.29

simulation uses the whole excavation, no slope on the east side, and the model is 220m wide,362m long, and 46m high, among, which the foundation pit depth is 26m. The calculation range is 3 times the foundation pit (3*26=78m), slope load is 25m from foundation pit, the building is 20m from foundation pit. The upper side of the model is a free boundary, the lower side limits horizontal direction, and vertical displacement, and the lateral side limits horizontal displacement. The station calculation and analysis model is shown in Figure 6.

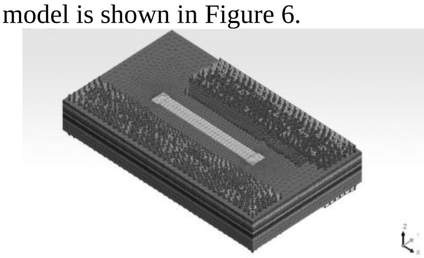

Fig. 6 computational and analysis model

Moore-Coulomb Constitutive Model is adopted in the soil body. To meet the accuracy of engineering requirements, the geological situation is simplified, and the simplified strata are divided into six courses. The parameters of each soil body are shown in Table 4.

The pile support in the foundation pit is simplified to a concrete wall with a depth of 32m. The effect of water is not considered in this numerical simulation. There is no concrete ground constraint on the two sides of the foundation pit, and the living load, such as material storage and a crane is ignored in the construction. In the course of numerical simulation calculation, the excavation of the soil body is realized by the passivation function, and the excavation is divided into five steps. The application of the pile and steel supporting structure is realized by activation command. The following two diagrams are the model diagram of row pile and steel support and the model diagram of foundation pit.

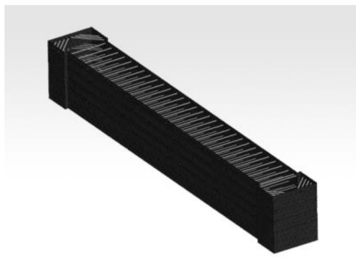

Fig. 7 model row pile and steel support drawing

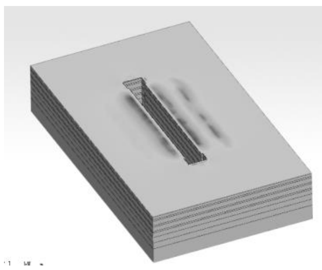

Fig. 8 model diagram of foundation pit

The simulation process of specific construction steps is shown below:

(1)The initial ground stress is balanced and the displacement is zeroed;

(2)The first step of foundation pit excavation is dug to -2.5m, crown beams and retaining walls are constructed, and the first row of steel support is erected;

(3)The second step of foundation pit excavation is -8.5m, and the second row of steel support is applied;

(4)The excavation depth of the third ~ fifth step of the foundation pit is -14.5m, -20.5m, -26m respectively, and the third, fourth and fifth rows of steel support are erected.

(5)Calculating and analyzing the results.

The results are calculated and analyzed as follows:

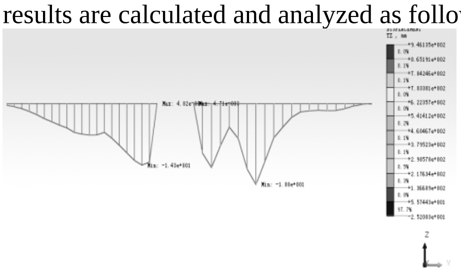

Fig. 9 the final settlement map of the ground surface from excavation to -2.5m in the middle of the foundation pit

The first step - Excavating to the middle of 2.5m foundation pit. It can be seen from the diagram that after the excavation of the foundation pit, the settlement of both sides of the soil body began to occur, in which there was a large deformation on the right side, and two sliding surfaces were formed in the soil.

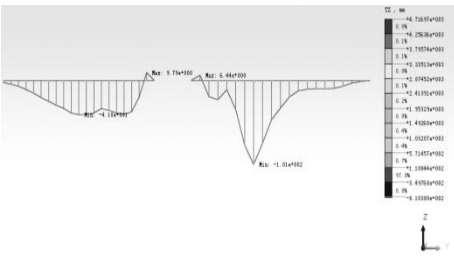

Fig. 10 final settlement diagram of the ground surface from excavation to the middle of -8.5m in the middle of the foundation pit

The second step - Excavating to the middle of the -8.5m foundation pit. It can be seen from the diagram that during the excavation of the foundation pit, the uplift of the soil on both sides occurred within about 5m. Because there is no concrete ground constraint in the model, the calculated uplift value is enormous.

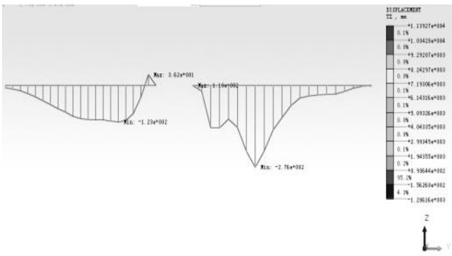

Fig. 11 the final settlement diagram of the ground surface from excavation to -14.5m in the middle of the foundation pit

The third step - Excavating to the middle of -14.5m foundation pit. It can be seen from the diagram that the soil body on both sides of the foundation pit continues to uplift, and the uplift range is gradually expanded.

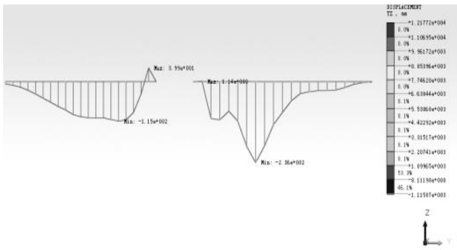

Fig. 12 final settlement diagram of the ground surface from excavation to -20.5m in the middle of the foundation pit

The fourth step - Excavating to the middle of -20.5m foundation pit. It can be seen from the diagram that the uplift of both sides of the soil stops, and the settlement begins, among which the settlement on the side near the slope is large. The main reason is that the slope load is large. With the increase of excavation depth, the sliding of soil is developing downward.

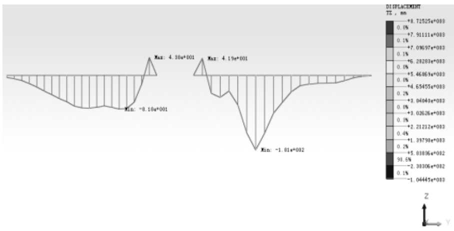

Fig. 13 the final settlement diagram of the ground surface from excavation to -26m in the middle of the foundation pit

The fifth step, excavating to the middle of -26m foundation pit. It can be seen from the diagram that after the excavation of the foundation pit, there is still an uplift in the north soil body, but the height of the uplift is reduced, and the uplift range is maintained at about 5m.

V. MECHANISM ANALYSIS OF SURFACE UPLIFT IN FOUNDATION PIT

Based on the results of this numerical simulation:

(1) The north side slope of the foundation pit of Dou Ge-Zhuang has a great influence on the foundation pit. A small uplift occurs in the soil body near the middle of the foundation pit under the joint action of the slope, the building, and the row pile. The mechanism behind it is that the whole excavation mode is used in the numerical simulation, and the uplift at the bottom of the foundation

pit is tremendous, which is different from the construction site in the form of semi-sloping. When the foundation pit is excavated with a full section, the reason of base uplift is two significant parts. Part of the reason is that the excavation of the foundation pit results in the relief of the pressure of the bottom soil, which makes the soil of the bottom of the foundation pit usual uplift. Another part of the uplift in the north side slope on both sides of the foundation pit soil pressure. This part of soil pressure is borne by steel support, which causes the sliding surface of the soil on both sides of the foundation pit to move down, resulting in an enormous lateral extrusion pressure on the soil body at the bottom of the foundation pit. This part of the extrusion force makes the soil body uplift at the bottom of the foundation pit.

In the construction of bottomless foundation pit in Dou Ge-Zhuang, to ensure the stability and construction safety of soil body around the foundation pit, the full section excavation was not adopted. However, the form of the semi-released slope was adopted, which led to the regular settlement of the ground surface of the foundation pit on the west side. However, due to the abnormal uplift of the foundation soil body on the eastern side, the massive uplift occurred only under the joint compression of the soil body in the bottom of the foundation pit and the north side slope, which has a significant impact on the gas pipeline at the edge of the foundation pit.

(2) At the beginning of excavation (first, second and third steps), the sliding surface of the soil body on both sides of the foundation pit is relatively shallow, and the sliding force of the sliding soil body is more extensive, especially in the north side, there are many sliding surfaces (or failure surfaces), which have tremendous pressure on the piles. The uplift of soil on both sides of the foundation pit is caused. However, as the excavation depth deepens, the sliding surface of the soil body gradually moves downward, so the uplift on both sides of the foundation pit decreases gradually.

(3) There is no uplift in the ground surface at the west shield. However, compared with the soil body in the middle of the foundation pit, the settlement is large. This is the drawback of full section excavation. It is necessary to strengthen the strength, stiffness, and stability of foundation pit support and to pay close attention to the settlement change.

VI. CONCLUSION

Due to the exceptional construction environment of the Beijing Subway, the excavation of bottomless foundation pit in each station is very different from that of an ordinary bottomless foundation pit. The standard method of slope excavation or half slope construction is not suitable in the construction environment of bottomless foundation pit of the Beijing Subway, especially the vital building or underground structure around the deep foundation pit. The excavation of bottomless foundation pit is under tremendous sliding soil pressure, so it is necessary to find an appropriate method of pressure relief and timely remove the uplifted soil at the bottom of the foundation pit, which can effectively reduce the uplift of soil around the foundation pit, to minimize the impact of deep foundation pit construction on the surrounding environment and ensure the smooth construction.

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