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MONITORING AND CONTROLLING ON SURFACE SETTLEMENT IN SAND AND GRAVEL STRATA CAUSED BY SUBWAY STATION CONSTRUCTION APPLYING PIPE-ROOF PRE-CONSTRUCTION METHOD (PPM)

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ABSTRACT

Pipe-roof Pre-construction Method (PPM) is regarded as a safer method to construct underground space, especially suitable for the construction sites with dense surface buildings, underground pipelines and complicated geological conditions. Xinleyizhi Station of Shenyang Metro constructed by PPM. In order to ensure safety in construction, the whole construction process was closely monitored. In this paper, monitoring results of surface settlement in PPM is analyzed. According to the monitoring results, the most serious settlement occurred in pipes jacking, which was the first and the most crucial step in PPM. The settlement reasons in each step are discussed, and controlling methods of surface settlement in each step are elaborated. Through close monitoring and timely control, the construction of Xinleyizhi Station completed smoothly. Because of the obvious advantages of PPM, the method will be used more widely in construction of shallow buried excavation under complicated surrounding and geological conditions.

KEYWORDS

Pipe-roof Pre-construction Method (PPM), Pipe jacking, large-scale excavation,Surface settlement

INTRODUCTION

A technology using dense large diameter steel pipes to create rectangular underground working space was applied in the construction of Antwerp Central Station in 1970s [1-2]. Based on “Antwerp technology”, Professor Lunardi [3] created “Cellular Arch Method” to build a long-span single arch subway station in Milan. These technologies were introduced into Korea, and have been used successfully in tens of underground projects [4]. Xinleyizhi Station of Shenyang Metro is the first subway station applying these technologies in China. Large diameter pipes jacking densely is the first and the most crucial step, then all subsequent construction steps are implemented under the preset protection in these two kinds of technologies. Considering the common features of the two kinds of technologies, and in order to distinguish from traditional Pipe-roof Method, Chinese researchers call them “Pipe-roof Pre-construction Method (PPM) [5] uniformly.

The construction process of PPM is complex, which can be divided into 4 steps (Figure 1):

(1) Jacking steel pipes and moving away the soil in pipes (STEP1)

(2) Cutting pipes, welding steel plates and concrete filled steel tubes to form a connected underground gallery (STEP2)

(3) Filling reinforced concrete into the underground space to form permanent structure (STEP3)

(4) Large cross-section excavation under the protection of existing permanent structure (STEP4).

In traditional Pipe-roof Method, as supplementary mean to reduce settlement in underground excavation, the pipes just are jacked in some difficult or important partial sections as temporary structure. While in PPM, large diameter jacked pipes are used to create underground space, and eventually become a part of the permanent structure. Because any steps are carried out under the completed protective measures, PPM is safer than other underground excavation methods. PPM is regarded as a superior method to construct large cross-section underground space, especially suitable for the construction sites with dense surface buildings, underground pipelines and complicated geological conditions.

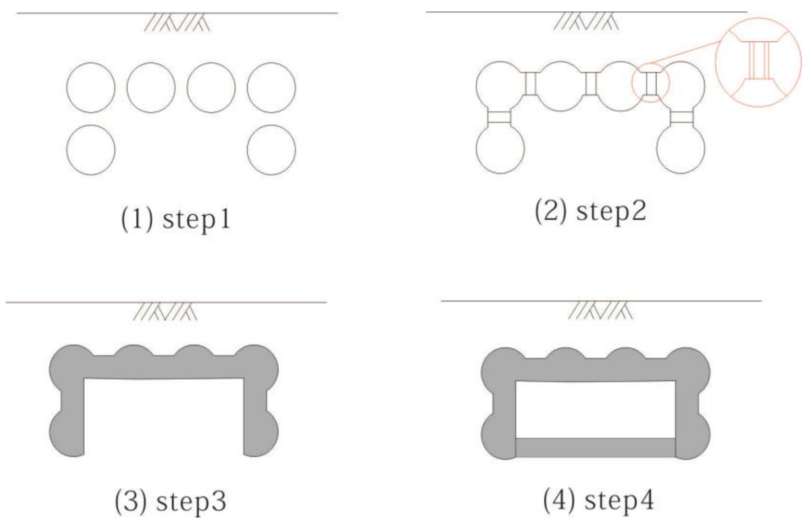

Fig.1 - Construction process of PPM

PPM has gained increasing attentions in the recent years, some researchers have researched on structure stress [6-7], structure deformation [8], seismic performance of structure [3]. As same as other underground construction methods, it is important to control the surface settlement, which may cause damages to surface buildings. The prediction methods of surface settlement in STEP1 and STEP4 were studied by Li [9] and Yang [10-11]. But research on settlement reasons and control methods during the whole period in PPM is relatively lacking.

METHODS

1 Project overview and field measurement

Single arch reinforced concrete structure was adopted in Xinleyizhi Station. The total construction area was about 9800m^2. The whole length of station is 179.8m. The main part was 26.2m wide and 18.9m high. The height of overlying soil is 7.6m-11.2m. The main part of subway station was located under an important municipal road. There were many buildings located on both sides of the road, the distance between the nearest building and No.2 shaft was just 9.7m. In the shallow stratum of construction area, many kinds of underground structures and pipelines were densely distributed. The strata consisted of miscellaneous filling, sand, gravel and a small quantity of cohesive soil. The main part of the station was located in sand and gravel strata. Groundwater was unconfined, and the groundwater table depth was 8.7-14.2m, which meant that most of pipes were jacked in the saturated soil in STEP1. The permeability coefficient was generally between 50 to 110m/d, the hydraulic gradient was about 0.1%. Open cutting method was used only in construction of two shafts, PPM was adopted in both ventilation audits (rectangular structure) and main part (long-span arch structure). Two shafts were used as workspace to build ventilation audits, and then ventilation audits were used as workspace to build a main part. The surface settlement in construction of main part is researched in this paper.

Plan of Xinleyizhi Station is shown in Figure 2. During the construction of the main part, 19 monitoring cross sections (Figure 2) were set up to measure surface settlement, and 8 monitoring points (Figure 3) were set up in each cross section except cross section 1. The digits in the pipes (Figure 3) show the order of pipe jacking.

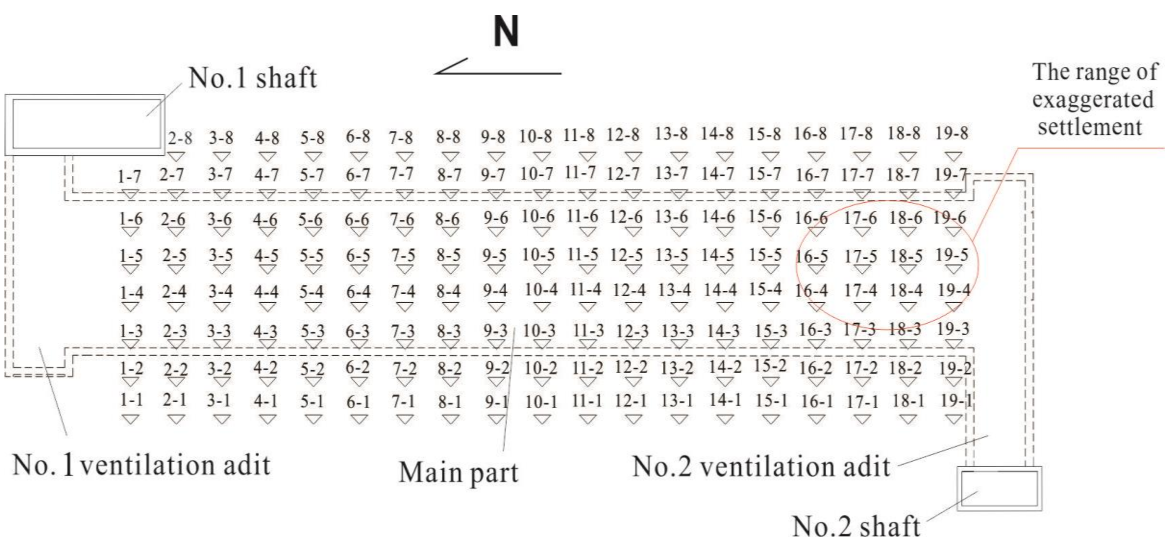

Fig.2 - Plan of Xinleyizhi Station and sections layout of settlement monitoring

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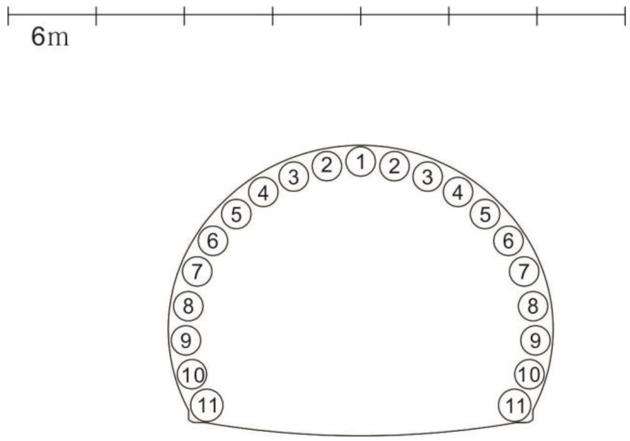

Fig.3 - Monitoring points layout of each section

The maximum settlements of section 16-19 in STEP1 was more than the warning value (60mm), in which the maximum settlement of section 16 was 62mm, and the maximum settlement of section 17-19 was more than 100mm.The main reason of exaggerated settlement (the range of exaggerated settlement is marked in Figure 2) was as follows: a Φ1200mm concrete sewage pipe located under point 5 section 18.The joints of the concrete sewage pipe leaked seriously. Leakage led to scouring of soil surrounding the concrete pipe. In addition, water loss near to No.2 ventilation audit during layer 3 pipe jacking exacerbated the local settlement.

The surface settlement-time curve (Figure 4) of the surface settlement was made according to the average accumulated values of 15 sections' (section 1-15) maximum settlement points in each step. From the surface settlement - time curve: the total settlement was 44.7mm, in which settlement caused by step 1 accounted for 65%, settlement caused by step 2-3 accounted for 8%, and settlement caused by step4 accounted for 27%. After the completion of construction, there was still tiny surface settlement, and the settlement tended to be stable after 20 days, which illustrated the sand and gravel strata had been stabilized within 20 days after construction disturbance.

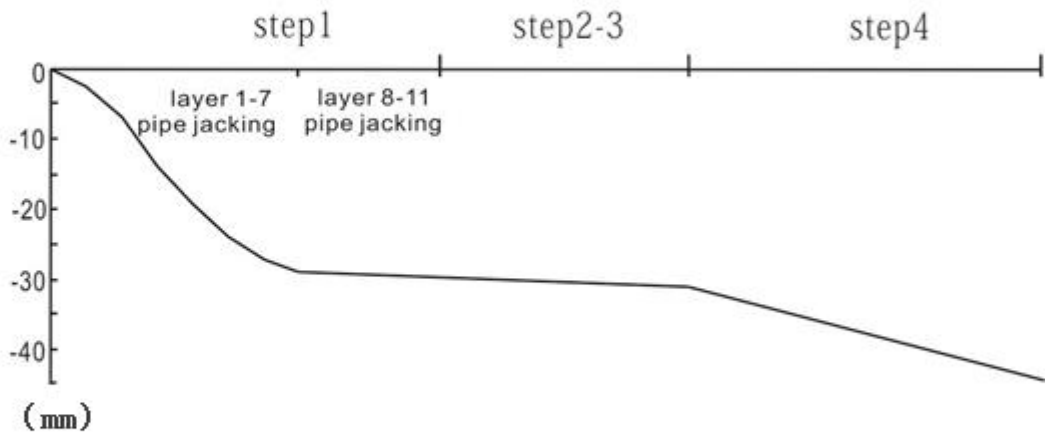

Fig.4 - Surface settlement - time curve

In STEP1, the vast majority of settlement happened in the pipe jacking of layer 1-7 (Figure 5). After the layer 7 pipes were jacked, the settlement was tiny in the pipe jacking of layer 8-11. The maximum settlement occured at point 5 in each section, which was just above the apex of arch structure. The settlement troughs were generally symmetrical. With the increase of pipe jacking layers, the settlement troughs were wider and wider, but the settlement increment of the maximum settlement point were smaller and smaller.

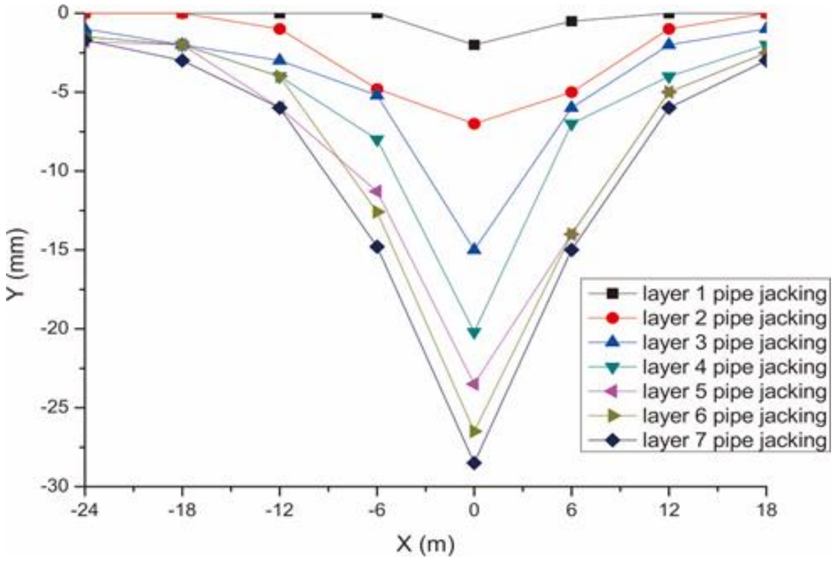

Fig.5 - Typical accumulated transverse surface settlement curve in STEP1

2 Reasons of surface settlement in each step

2.1 Settlement reasons in STEP1

In STEP1, Pipes were jacked with several jacks, and pipe jacking processes were as follows:

① working face excavating (Excavation face diameter was slightly less than the guide pipe diameter, and the excavation length was about 0.3-0.5m.).

② guiding pipe jacking (external diameter of the guiding pipe was 20mm wider than the external diameter of following pipes).

③ following pipe jacking.

④ synchronous grouting of bentonite slurry into the gap between the pipe and soil.

Fig.6 - Pipes jacking

The factors influencing settlement in pipes jacking are as follows:

① Soil disturbance induced by pipes jacking. Stress release in soil changed porosity or some other physical and mechanical properties of original soil, which induced settlement. Disturbance factors in single pipe jacking consist of excavation of working face, friction caused by pipes moving, and so on. In this high density pipes jacking, typical steel pipe diameter was 2000mm, pipes spacing was only 2550mm. Repeated soil disturbances by repeated pipes jacking caused to more surface settlement. The smaller spacing between the existing pipe and the new pipe means more interaction between them, and greater impact on the surface settlement.

② The soil loss caused by pipes jacking. Reasons of soil loss mainly include: external diameter differences between guiding pipe and following pipe, over excavation caused by rectification for axis offset and other construction reasons.

③ 'shielding effect' from existing pipes. Compared to soil, existing jacked pipes' stiffness was higher, which could prevent the upper soil's downward displacement caused by new pipes jacking. Reliable high stiffness support system was formed after the pipe jacking of layer 1-7, which resisted the stratum deformation effectively in subsequent pipes jacking. So the settlement was tiny in the pipes jacking of layer 8-11.

2.2 Settlement reasons in STEP2 and STEP3

After pipe jacking, pipes were cut, and some soil between two pipes was moved away, then steel plate and concrete filled steel tubes were welded as surpport structures. After a connected underground gallery formed, assembling reinforcement and concrete pouring were executed (Figure 7).

Settlement was tiny in STEP2 and STEP3. According to the construction process, the factors influencing settlement and controlling method in pipe jacking are as follows:

① After pipes were cut, the soil between two pipes may collapse. Soil loss leads to settlement.

② During cutting and supporting, the deformation of the steel pipes leads to the surface settlement.

Fig.7 - Cutting,suportting and concrete pouring

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2.3 Settlement reasons in STEP4

After the permanent long-span arch structure was build, large-scale excavation was executed to form the available underground space. The soil was divided into hall layer and platform layer in excavation. The hall layer was divided into part 1 and part 2, which were excavated from both ends to the middle. The platform layer was divided into part 3 and part 4, and each part was divided into several segments to be excavated from north to south. A series of steel pipes as temporary supporting beams were set at 2.2m above the bottom slab. After platform layer excavation of each segment, temporary structures were removed, the bottom slab, the middle pillars and slab were built sequentially.

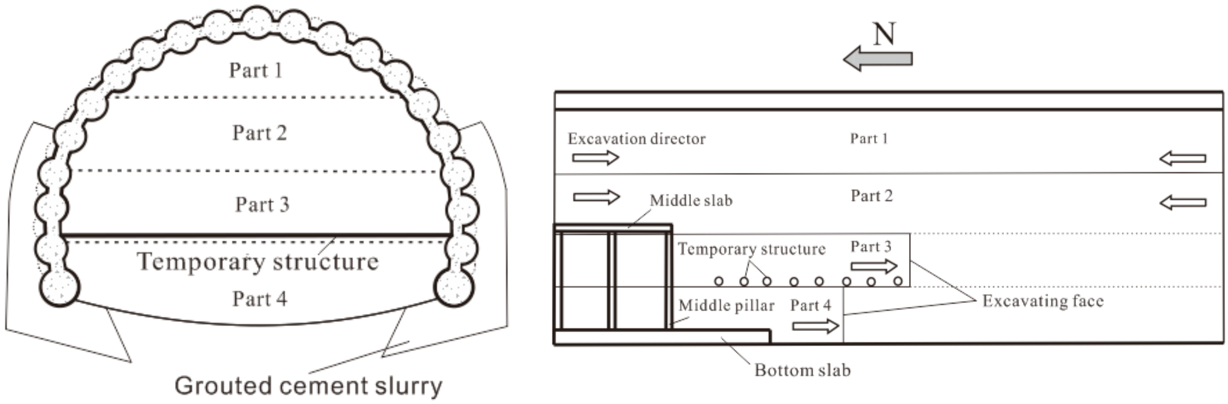

Fig.8 - Large cross-section excavation

In this step, the maximum accumulated settlement reached 18mm, and most of the measured points in this step were not more than 14mm. Permanent structure construction usually follows soil excavation in traditional underground construction method. Being different from traditional method, large cross-section excavation follows permanent structure construction in PPM. Therefore the settlement was lower in large cross-section excavation compared to traditional method. Local dewatering was implemented in order to construct the bottom slab expediently, which led to surface settlement. In addition, the deformation of the structure and the sinking of the whole arch structure also caused surface settlement.

3 Control measures of surface settlement

(1) Control measures in STEP1

In the process of pipe jacking, unexpected soil and water loss would cause serious settlement. Control measures for unexpected soil and water loss were as follows:

① In this project, a detachable steel ring with sealing ring was installed at the departure and reception site of pipes to prevent the groundwater loss. Except that the water and soil loss in the early stage of layer 3 pipe jacking was problematic, the sealing measures were satisfactory for the rest of the time.

② Before pipe jacking, the presence and condition of existing nearby underground pipelines should be investigated in detail, and the pipeline damage expected to be caused by the construction should be estimated. Reinforcement or repair of such pipelines would prevent accidental water and soil loss caused by pipeline leakage.

③ Overbreak was forbidden. Moreover, the pipe alignment should be closely monitored to prevent any offset.

④ In the loose and saturated soil, the pipe was initially jacked to form a 1 meter soil plug in the first pipe, then a sealing reinforcement area whose length was more than 1.5m was created by pre-grouting before the soil was excavated in the pipe (Figure 9).

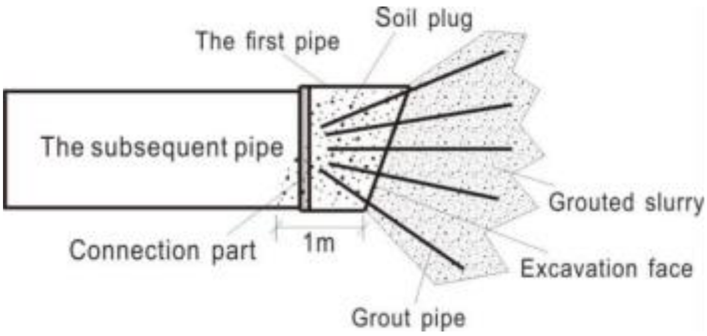

Fig.9 - Pre-grouting at the loose and saturated section

The settlement caused by the diameter difference and the repeated soil disturbances was normal for this constructed method. It could not be completely avoided, but could be controlled by appropriate construction measures. Firstly, synchronous grouting was helpful. The synchronous grouting could reduce the friction between the pipe and the soil to decrease the disturbance effect, and to fill the gap between the pipe and soil to decrease soil loss simultaneously. Secondly, grouting outside the pipe after pipe jacking was also crucial. Grouting could play a dual role of waterproofing and filling. Finally, local grouting with a suitable grouting amount and pressure would uplift the soil in some locations with serious settlement.

(2) Control measures in STEP2 and STEP3

In order to prevent the loss of soil between pipes after pipes cutting, the control measures included:

① Design appropriate pipe spacing. If the spacing between the jacking pipes was too large, after pipes cutting, the soil between two pipes might collapse. If the steel pipe spacing was too small, more pipes jacking, longer construction period and more cost would be needed. It was very important to choose proper spacing of pipe jacking based on soil arching effect [12].

② If the soil between two pipes collapsed, cement mortar should be filled as soon as possible

③ Grouting was necessary to fill any such gaps after welding.

④ In order to prevent the steel pipes deformation, interval pipe cutting should be adopted, and protected steel plate and supported concrete filled steel tube should be set up as quickly as possible. Reasonable control measures can keep the settlement in 5mm during STEP2 and STEP3.

(3) Control of surface settlement in STEP4

Except the steel pipe roof increased the stiffness of permanent structure, other measures were taken to control structural deformation:

① Grouting around arch feet

During the process of excavation, the load on the ground beneath the arch feet was huge. Unstable soil would have brought overlarge horizontal displacement and settlement to the arch feet. It was crucial to keep the stability of soil around the arch feet in the process of construction. After the completion of the steel pipe cutting, grouting around the arch feet was implemented through the underground gallery to increase the stiffness and strength of the soil, which would ensure the restraint effect to the arch feet and reduce the convergence and sink of the arch feet.

② Temporary support

In the process of excavation of the platform layer, some temporary support structures could be set at appropriate sites to control convergence of the arch feet. Reinforced concrete or steel structure could be used. In this construction, a series of steel pipes were set at 2.2m above the bottom slab, which played an important role to control the arch shell structure deformation.

③ Optimization of segment length during the platform layer excavation

The platform layer was excavated piecewise from north to south and the excavation segment length was an important factor in terms of the surface settlement. A small excavation segment length, which meant that the bottom slab could be done in time to form a closed circular structure, was helpful to control the deformation of arch shell structure. But the smaller excavation segment length meant the slower construction. So optimization of excavation segment length was very important. When the middle part was excavated, both the completed bottom slab in the north and the remaining soil in the south could provide support. The spatial supporting effect of the arch shell structure made the excavation in the middle relatively safer. So the highest risk appeared in the excavation near the northern end. To ensure safety, the excavation pace was 8m near the north end, and was adjusted to 18m in the middle to improve construction efficiency.

According to the monitoring results, most of the arch crown settlements were less than 8mm. Most of the points' arch feet settlements were less than 3mm. The tiny settlements of arch crown and arch feet had less effect on surface settlement. Most of the surface settlement in this step was considered to be caused by dewatering locally in bottom slab construction.

Because of the good control of the surface settlement during the early construction, local dewatering was allowed during the construction of the bottom slab. If the settlement had been large during the early construction, the dewatering would lead to excessive settlement. If the local dewatering was not allowed, watertight pre-grouting could be adopted before the construction of bottom slab. Moreover, if the geological conditions would be very serious, the bottom slab could also be constructed by PPM as well as the arch structure, which will further reduce the structural deformation and surface settlement.

CONCLUSION

(1) PPM was more secure than the traditional underground excavation method. The surface settlement in PPM was acceptable. Especially in large-scale excavation, the surface settlement could be controlled very well.

(2) The settlement during the pipe jacking phase reached 65% of the total construction settlement. The settlement of the pipe jacking excavation could be divided into two stages, the settlement curve of the layer 1-7 pipes jacking stage was steep, and the settlement curve of the layer 8-11 pipes jacking stage was gentle. In pipes jacking, the impact from repeated disturbance and shielding effect could not be ignorable. Repeated disturbance increased settlement, but shielding effect reduced settlement. In a word, as long as the accidental loss of water and soil could be avoided, the surface settlement caused by pipe jacking could be controlled well.

(3) During construction, spatial supporting effect of the structure was obvious. Reasonable utilization of the beneficial spatial supporting effects and prevention of the disadvantageous spatial supporting effects would be helpful to the construction.

(4) In this project, dewatering only occurred during the construction of bottom slab, which prevent serious surface settlement caused by dewatering. Dewatering can be completely prevented in the whole process if necessary, which will reduce the settlement further.

According to the specific engineering requirements, there can be more improvements in each step in PPM to highlight its advantages. In general, PPM will be used more widely in construction of shallow buried excavation under complicated surrounding and geological conditions.

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REFERENCES

[1] Musso G, 1979.Jacked Pipe Provides Roof for Underground Construction in Busy Urban Area. Civ Eng 49(11):79-82.

[2] Hemerijckx E,1983. Tubular Thrust Jacking for Underground Roof Construction on the ANTWERP Metro Part 1.Tunn Tunn Int 15(5):13-16

[3] Lunardi P, 1991.Cellular Arch Technique for Large-span Station Cavern. Tunn Tunn Int 23:23-26.

[4] Kwak C W, Park I J, Kim S W, Kim J Y, 2007.Seismic behavior of Tubular Roof-Trench method(T.R.&T) by numerical analysis. 33rd ITA-AITES World Tunn Congr-Undergr Spac-The 4th Dim Metr 1: 513-518.

[5] Li YS, 2011.Research of the construction mechanics effect during large excavation to the subway station built by Pipe-roof Pre-construction Method.Dissertation. Central South University.

[6] Park IJ, Kwak C W, Kim S W, Kim J Y, Han S H ,2006. Verification and general behaviour of Tubular Roof & Trench method (TR&T) by numerical analysis in Korea.Tunn Undergr Sp Tech 21(3): 394-398.

[7] Yan S, Zhang ZJ, Jin CF, Jing L, 2011. Numerical analysis on inner forces of underground New Tubular Roof structure during excavation. J Shenyang Jianzhu U 27(6):1064-1069

[8] Li YS,Zhang KN,Huang CB ,2012. Monitoring of lining structure of tunnels built by using pipe-roof pre-construction method.Chin J Geotech Eng 34(8): 1541-1547.

[9] Li YS, Zhang KN, Huang CB, Li Zh, Deng ML, 2011b. Analysis of surface subsidence of tunnel built by pipe-roof pre-construction method. Rock Soil Mech 32(12): 3701-3707

[10] Yang X, Zhang KN, Li Z,2012a. Influence of steel pipe jacking on earth surface settlement in pipe roof pre-construction method[J]. J Shenyang U Tech 4: 469-473

[11] Yang X, 2012b. Reasearch of Large Diameter Jacking-Pipes with Small Space in Pipe-roof Pre-construction Method.Dissertation. Central South University.

[12] Yang X, Zhang K, Li Z, et al. Optimal design of distance between jacking pipes of new pre-construction method in Metro station[J]. China Railway Science, 2011, 32(2):61-66.