RESEARCH AND APPLICATION OF U-BIT CONSTRUCTION METHOD IN SUBWAY STATION ENGINEERING LOCATED IN SATURATED SOFT SOIL AREA

Yan Guo[1], Yanfei Zhu[1], Weiqiang Pan[1] and Ye Jin[2]

1. *Shanghai Tunnel Engineering Construction Co., Ltd. No.1099 South Wanping Road, Shanghai 200032, China; guoyanyy@foxmail.com, zyflisp@163.com, pwq21@163.com*

2. *Shanghai Tunnel Engineering & Rail Transit Design and Research Institute, No.1999 West Zhongshan Road, Shanghai 200235, China; 47472837@qq.com*

ABSTRACT

In order to solve the problems existing in the construction of underground structures located in the downtown of saturated soft soil area, such as insufficient construction site, complex adjacent structures and great impact on the surrounding environment, the construction method of underground bundled integrate tunnel(U-BIT) is proposed. In this method, after steel pipes jacking completed, concrete is filled into the pipes, and prestress is tensioned to make each independent pipe combined to form a whole bearing structure, so as to achieve the purpose of reducing the size of structural components, improving the structural stiffness and bearing capacity. Based on the structural mechanical property test and the project of Wuding Road Station of Shanghai Metro Line 14, the failure mechanism of bundled integrate structure, the tension technology of prestressed tendons in narrow space and the variation rules of ground surface subsidence are systematically studied. The research shows that structural seam sections will be destroyed before pipe sections, so ensuring the mechanical performance of seam sections is very important to make sure the structural safety. Since each independent pipe is combined to form an overall stable structure under the prestress effect, the subsequent soil excavation has little influence on the tension of prestressed tendons and ground surface subsidence. Therefore, the above construction method can control the ground surface subsidence effectively and reduce the influence of underground engineering construction on the surrounding environment.

KEYWORDS

Underground excavation method, Underground bundled integrate tunnel, Saturated soft soil, Subway station, Prestressed tension, Ground surface subsidence

INTRODUCTION

With the rapid development of economy and urbanization process, the urban population increases with each passing day, which leads to the problems of land resource shortage and traffic congestion. The development and utilization of underground space is the most effective way to solve the above problems. And it is also the useful method to realize the sustainable development of society and economy. However, in the construction of underground structures in the urban central area, there are often problems such as insufficient construction sites and complex adjacent structures. If the open excavation method is adopted, traffic closure, pipeline relocation and demolition of surrounding buildings may be required, which not only has a long construction cycle and a high project cost, but also has a serious impact on the society. Shallow excavation method has been widely used in the construction of underground structures in the downtown because of its

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advantages of not affecting traffic pipelines, small construction area and light disturbance to the surrounding environment [1-2]. However, in the saturated soft soil area represented by Shanghai, because of the characteristics of weak foundation bearing capacity, high sensitivity coefficient, fast attenuation of thixotropic strength and difficult control of construction deformation, there are great risks in the application of shallow excavation method in these areas. Although the shield construction method and pipe jacking method can reduce the risk of digging in the saturated soft soil area, the above methods cannot meet the needs of large section and shallow covering soil of urban underground structures due to the limitation of equipment section size and the construction requirement of soil depth [3-5].

As a new type of underground excavation method, the pipe-roofing method uses a small pipe jacking machine to push steel pipes into soil between the starting shaft and the receiving shaft in turn. The pipes are connected with each other by a lock filled with sealing material to form an advanced support system, and then the box culvert is pushed or the soil is excavated under the pipe-roofing structure [6-7]. Therefore, the construction method does not need to reduce groundwater, and the land subsidence is controllable, so it can be applied to the saturated soft soil area, which has been paid attention to by scholars. According to the soil characteristics of above area, Zhu Yanfei et al. [8-9] carried out researches on the technology of steel pipe jacking with sealing grease lock, soil horizontal reinforcement and soil stratified excavation inside the pipe-roof. Based on the Shanghai Tianlin Road Tunnel project, Tang Zheng et al. [10] studied the change law of ground surface subsidence, and found that the value at the stage of pipe jacking is composed of the superposition of stratum loss settlement and surface uplift caused by grouting, while the value at the stage of suspended jacking is mainly consolidation settlement. Relying on the project of Guiqiao Road Station of Shanghai Metro Line 14, Pan Weiqiang [11] concluded that the influencing factors of ground surface subsidence in the process of pipe-roofing structure construction mainly include forebay pressure, pipe jacking speed, water sealing performance of tunnel portal, frictional force between pipe and soil and quality of synchronous grouting. Cheng Panpan et al. [12] accomplished numerical simulation of pipe jacking and soil excavation, and optimized related construction parameters, in order to reduce construction disturbance and speed up the application of this method in the downtown of saturated soft soil area.

However, through applying the pipe-roofing method, engineers found that with the increasing shortage of urban land supply, the construction site may not be able to provide space for making and pushing box culvert. In addition, in the pipe-roofing method, the steel pipes are connected by sealing grease lock, which cannot cooperatively bear loads. In order to overcome the influence of soil rheological properties, soil should be strengthened before excavation, and a large number of temporary steel supports should be installed after excavation, which results in low construction efficiency and high project cost. The above factors have seriously restricted the development of the pipe-roofing method, so it is urgent to study a new kind of pipe-roofing method with small construction space demand, high construction efficiency and adaptability to the geological conditions of saturated soft soil. Based on the PCR construction method [13], the construction method of underground bundled integrate tunnel (U-BIT) is proposed, which is a method that after steel pipes jacking completed, concrete is filled into the pipes, and prestress is tensioned to make each independent pipe combined to form a whole bearing structure. Compared with the traditional pipe-roofing structure, the shape of the pipe in the bundled integrate structure is updated from circular to rectangular, and the number of the sealing grease lock is updated from single to double, as well as the prestress is applied along the ring direction to form an overall structure. Therefore, this kind of structure has smaller pipe size, higher structural stiffness and bearing capacity. Prestressed technology has the advantages of good performance, easy construction and reasonable economy, which is widely used in foundation engineering, large-span structural engineering and bridge engineering. However, due to the large load borne by underground structures and the complex interaction between soil and structures, the application of prestressed technology in underground structures is not widespread at present, and it is only applied in underground large-span structures and shield tunnels. Tang Jian [14] adopted the composite frame system of prestressed beam and ordinary concrete longitudinal beam in the large-span underground structure, which can make the force distribution of the structure more reasonable and the economic benefit more remarkable. In order to solve the problems of heavy self-weight, obvious cracks and not being able to withstand tension of shield segment, Liu Fengjun [15] applied prestressed technology to shield tunnel, and studied its design theory and design method. For purpose of studying the response and performance of prefabricated prestressed underground pipe gallery with multi-cabin under earthquake action, Wang Jian et al. [16] conducted a finite-element analysis of soil-structure interaction. It is concluded that the setting of prestressed tendons can improve the structural integrity and reduce the structural relative displacement. As a new type of structure, the structural mechanical properties and construction technology of bundled integrate structure is still in the early research stage, and there are no similar projects for reference. In order to ensure the construction safety, based on the project of Wuding Road Station of Shanghai Metro Line 14, the engineering difficulties are studied, and the ground surface subsidence values are monitored and analysed, aiming to give an example for the future excavation project in the downtown of saturated soft soil area.

CONSTRUCTION METHOD OF U-BIT

Structural characteristics

The bundled integrate structure consists of standard steel pipes and working steel pipes, in which the working steel pipes are used for tensioning prestressed tendons. The construction method of the bundled integrate structure can improve the structural mechanical properties by applying prestress in ring direction to each steel pipe, so that the force form is upgraded from the longitudinal stress and transverse bracing to transverse prestress tensioning and cooperative bearing in longitudinal and transverse direction. Therefore, it can effectively control structural deflection, reduce ground surface subsidence, and realize underground excavation without soil reinforcement and support system, which has a significant advantage of construction period and project cost. In addition, the pipe of the above structure can be flexibly combined to form underground space with any different shape, and the construction has low demand for the site, so it can be widely used in underground engineering in complex environment of saturated soft soil area [17]. The bundled integrate structure is given in Figure 2-1.

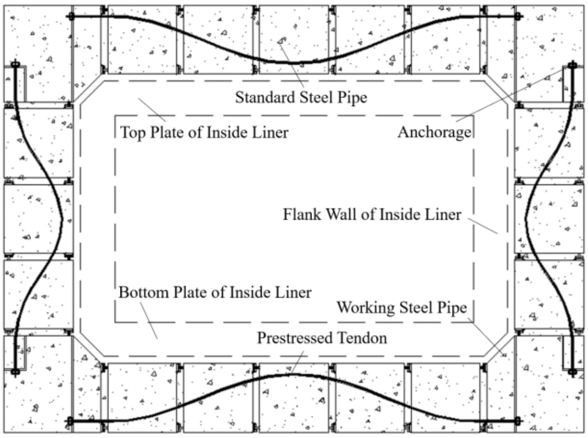

Fig.2-1 Bundled integrate structure

Construction process

Since prestress is needed to apply in each steel pipe of bundled integrate structure, the construction method is different from traditional pipe-roofing method. The specific process is as follows [18]:

(1) Pipe jacking. Between the starting shaft and the receiving shaft, standard steel pipes and working steel pipes are jacked sequentially into surrounding area of the underground structure to be built. The longitudinal direction of pipes is connected by welding, and the transverse direction of pipes is connected by sealing grease lock. Since prestress is applied to steel pipes in the later stage, each pipe has the perforation holes of prestressed tendons.
(2) Prestressed tendons installation. Install corrugated pipes into the perforation holes, and then install prestressed tendons into the corrugated pipes. After the installation of prestressed tendons is completed, concrete is poured into standard steel pipes and seam sections between the pipes.
(3) Tension and anchorage. When the concrete strength meets the design requirements, prestressed tendons are tensioned. After the tensioning force is stable, anchorages are installed to fix the prestressed tendons, so that the prestressed tendons will not retract after the tensioning equipment is withdrawn.
(4) Grout injection and anchor seal. Cement grout is injected into the gap between the corrugated pipes and the prestressed tendons. After the strength of the cement grout meets the design requirements, concrete is poured into the working steel pipes to encapsulate the anchorage.
(5) Soil excavation and structural construction. After completing the tension of prestressed tendons, the bundled integrate structure is formed. Then the soil excavation and structural construction are carried out under the bundled integrate structure.

MECHANICAL PROPERTY TESTS

Test scheme

In order to study the mechanical properties and weak points of the bundled integrate structure, the full-scale tests under design conditions and overload conditions are carried out. Considering the symmetry of the structure and the soil and water pressure load on the structure, one-quarter of bundled integrate structure is selected for the mechanical property tests. Dimensioned drawing of one-quarter of bundled integrate structure is drawn in Figure 3-1. The specimen is 4.2m wide, 3.1m high and 1.5m long. It is arranged in an inverted L shape and consists of working steel pipes, standard steel pipes and semi-standard steel pipes. The size of working steel pipe, standard steel pipe and semi-standard steel pipe are 1.4m×1.4m, 1.0m×1.0m and 0.5m×1.0m separately. And the width of the seam section is 0.1m. Along the longitudinal direction, three bundles of prestressed tendons are set in the width and height directions of the specimen, with a spacing of 500mm, and the designed tensile force is 439.425kN [19].

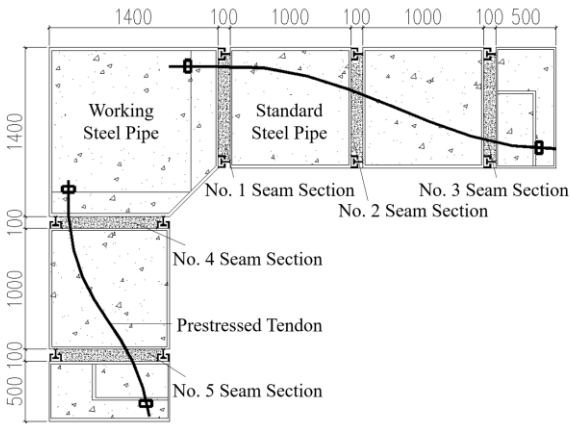

Fig.3-1 Dimensioned drawing of one-quarter of bundled integrate structure (unit: mm)

Loading equipment of structural mechanical property tests is given in Figure 3-2. In the tests, based on the actual load of structure at the service stage, the design of the test loading cases is carried out according to the principle of load equivalence that the total forces of the horizontal and vertical jacks are the same as the sum of actual water and soil pressures imposed on the one-quarter

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of bundled integrate structure. The vertical water and soil pressure applied to the structure is simulated by four jacks at the top of the loading equipment, and the horizontal water and soil load applied to the structure is simulated by three jacks on the side of the loading equipment. The right and bottom of the structure are constrained by sliding bearings. Table 3-1 is the loading cases of structural mechanical property tests.

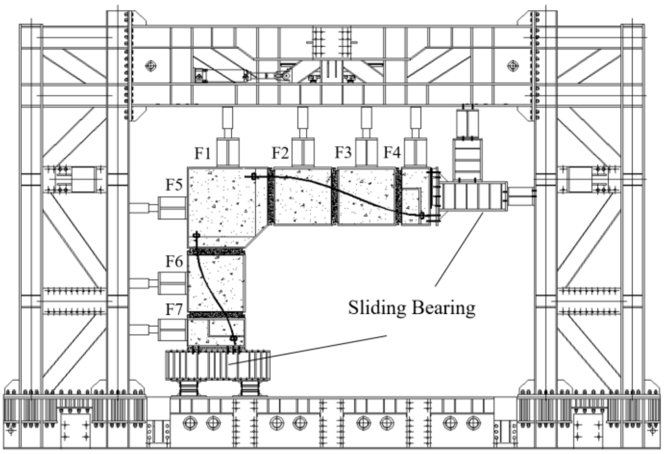

Fig.3-2 Loading equipment of structural mechanical property tests

Tab.3-1: Loading cases of structural mechanical property tests

Loading cases		Structural embedded depth/m	Lateral pressure coefficient	Load value/kN
Preload condition	1	1	0.8	F_1=53 F_2=42 F_3=42 F_4=23 F_5=105 F_6=83 F_7=45
	2	2		F_1=78 F_2=62 F_3=62 F_4=34 F_5=125 F_6=98 F_7=54
	3	3		F_1=104 F_2=81 F_3=81 F_4=44 F_5=145 F_6=114 F_7=62
Design condition	1	3.97	0.8	F_1=128 F_2=101 F_3=101 F_4=55 F_5=165 F_6=130 F_7=71
	2		0.6	F_1=128 F_2=101 F_3=101 F_4=55 F_5=124 F_6=97 F_7=53
	3		0.4	F_1=128 F_2=101 F_3=101 F_4=55 F_5=82 F_6=65 F_7=35
Overload condition	1	3.97	0.6	F_1=128 F_2=101 F_3=101 F_4=55 F_5=124 F_6=97 F_7=53
	2	5		F_1=154 F_2=121 F_3=121 F_4=66 F_5=139 F_6=109 F_7=60
	…	…		…
	13	16		F_1=431 F_2=339 F_3=339 F_4=185 F_5=306 F_6=240 F_7=131

Test result

Table 3-2 is the results of structural mechanical property tests. It can be seen from Table 3-2 that under the preload condition and the design condition, the maximum splaying value of seam section is less than 0.2mm, and the maximum deflection is less than 0.8mm. Initial state of No.2 seam section is given in Figure 3-3. Under the overload condition, when the corresponding structural embedded depth is less than 13m, there is no obvious separation phenomenon of seam section, the maximum splaying value fluctuates is less than 0.3mm, and the maximum deflection is 2.48mm. When the corresponding structural embedded depth increases to 13m, the concrete and the steel pipe are separated at the bottom of No.2 seam section, the maximum splaying value is 0.34mm, and the maximum deflection is 2.89mm. With the increasement of structural embedded depth, the range of seam section separates larger. When the corresponding structural embedded depth increases to

16m, the maximum splaying value of No.2 seam section is 0.43mm, and the maximum deflection is 3.98mm. Failure state of No.2 seam section is shown in Figure 3-4. According to the above mechanical property tests, it is found that structural seam sections will be destroyed before pipe sections. With the increase of structural embedded depth, seam sections are destroyed first, and the splaying value gradually increases, which leads to the increase of structural deflection and the decrease of structural stiffness. So, ensuring the mechanical performance of the seam section is very important to make sure the structural safety.

Tab.3-2: Results of structural mechanical property tests

Loading cases		Structural embedded depth/m	Maximum splaying value of seam section/mm	Maximum deflection/mm
Preload condition	1 2 3	1~3	＜0.2	＜0.5
Design condition	1	3.97	＜0.2	＜0.8
	2			
	3			
Overload condition	1-9	＜13	＜0.3	2.48
	10	13	0.34	2.89
	…	…		…
	13	16	0.43	3.98

Fig.3-3 Initial state of No.2 seam section

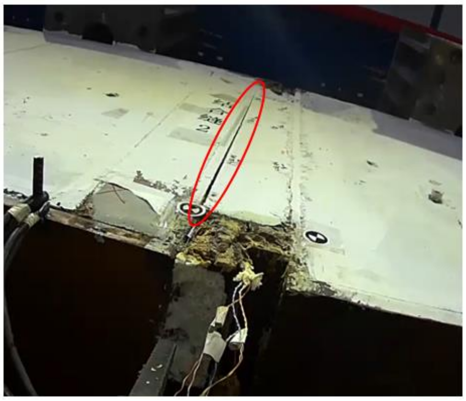

Fig.3-4 Failure state of No.2 seam section

ENGINEERING SITUATIONS

Wuding Road Station of Shanghai Metro Line 14 is located at the intersection of Wuding Road and Wuning South Road. It is an island-style station on the underground second floor. In the No.1 passageway of the station, there is a power pipe gallery that has an impact on the station construction and cannot be moved, so the construction method of bundled integrate structure is adopted. The width of the bundled integrate structure is 8.4m, the height is 6.2m, the length is 15.3m and the depth of covered soil is 3.97m. Plane graph and sectional graph of the underground bundled integrate tunnel are shown in Figure 4-1 and Figure 4-2. It can be seen from Figure 4-2 that steel pipes of the structure are mainly pushed in silty clay, muddy silty clay and muddy clay with high-water content, high compressibility and high sensitivity, which is difficult to construct. Table 4-1 is the physical properties of soils.

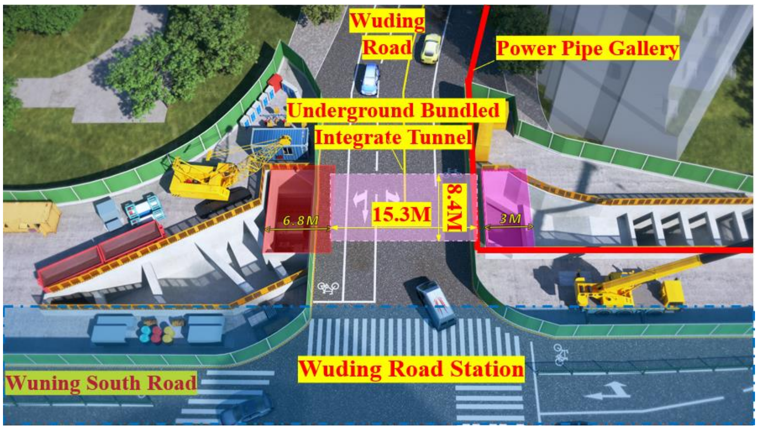

Fig.4-1 Plane graph of underground bundled integrate tunnel

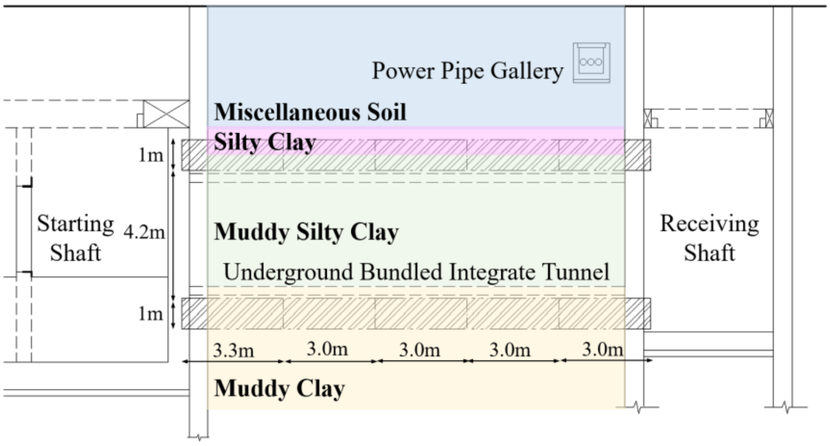

Fig.4-2 Sectional graph of underground bundled integrate tunnel

Tab.4-1: Physical properties of soils

Soil Unit	Name	Soil thickness/m	Unit weight/(kN·m^{-3})	Cohesion/kPa	Internal friction angle/°
1	Miscellaneous Soil	3.3	18.0	10	15
2	Silty Clay	0.5	18.0	18	16
3	Muddy Silty Clay	5.0	17.3	11	14
4	Muddy Clay	7.5	16.7	12	11

The bundled integrate structure is composed of four 1.4m×1.4m and sixteen 1m×1m rectangular steel pipes in the transverse direction, and four standard pipes with a length of 3m and a special pipe with a length of 3.3m are welded in the longitudinal direction. Considering the convenience of construction, prestressed tendons are changed from curve type to double-row linear type. And the model of prestressed tendons is 1×3Ø15.2, the spacing is 750mm, and the tension force is 580kN. In order to ensure the sealing effect of bundled integrate structure, the steel pipes are connected with C-T lock, which is filled with sealing grease. Schematic diagram of C-T lock is presented in Figure 4-3. Figure 4-4 introduces the cross-sectional profile of bundled integrate structure. In order to make steel pipes located in the top row can produce soil arching effect, steel pipes are pushed in the order of jacking steel pipes in the upper row first and then steel pipes in the lower row. In detail, the upper steel pipes are jacked from A0 pipe, then the left and right sides of steel pipes are jacked, and finally the lower steel pipes are closed at A15 pipe.

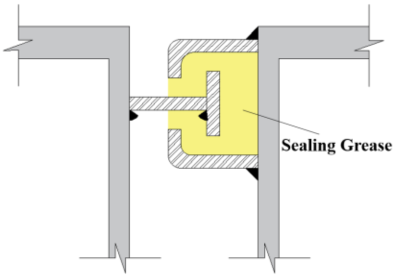

Fig.4-3 Schematic diagram of C-T lock

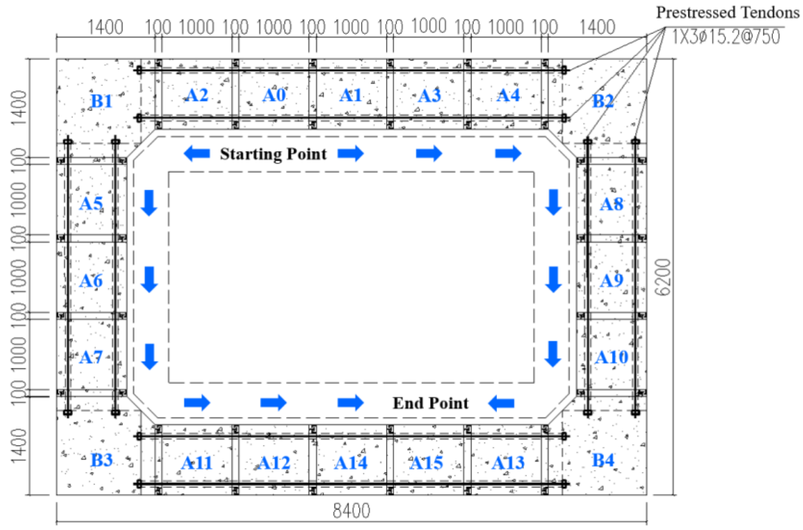

Fig.4-4 Cross-sectional profile of bundled integrate structure

As shown in Figure 4-5, based on the soil in the pipe needs to be cleaned completely, two kinds of earth-pressure balanced pipe jacking machines, which include a pipe jacking machine with three cutterheads and a pipe jacking machine with single cutterhead are adopted [20-21]. The main parameters of the earth-pressure balanced pipe jacking machines are shown in Table 4-2.

（a）*Pipe jacking machine with three cutterheads* （b）*Pipe jacking machine with single cutterhead*

Fig.4-5 Earth-pressure balanced pipe jacking machine

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Tab.4-2: Main parameters of the earth-pressure balanced pipe jacking machines

Item \ Type	Pipe jacking machine with three cutterheads	Pipe jacking machine with single cutterhead
Cutting size of cutterhead	1m×1m、1m×1.1m、1m×1.2m	1.4m×1.4m
Structural form of cutterhead	Three leaf-shaped cutterheads with four corner shovel teeth	Single spoke cutterhead with shovel blade
Cutting rate of cutterhead	97.8%	95.6%
Maximum soil excavation speed	3m/h	3m/h
Maximum revolution speed of cutterhead	2r/min	2r/min
Hinge form	Horizontal ±1.5° Vertical ±1.5°	Horizontal ±1.5° Vertical ±1.5° Rotation ±1.5°
Maximum torsional moment of cutterhead	30kN.m	80kN.m
Maximum jacking force of main jacking device	4000kN	

TECHNOLOGY OF TENSIONING PRESTRESSED TENDONS

Since the constraint effect of prestressed tendons is the key factor to ensure that the bundled integrate structure as a whole structure to bear the external load, it is particularly important to ensure the effective prestressing tension in construction. In this project, B1~B4 steel pipes are selected as the working steel pipe to tension prestressed tendons. As shown in Figure 5-1, the size of working steel pipe is 1.4m×1.4m, so the space is very narrow. Therefore, after all the steel pipes are jacked, prestressed tendons are installed and concrete is poured into the standard steel pipes and seam sections. After the concrete strength meets the design requirements, lightweight jack is used to tension prestressed tendons, and the tension force is 580kN. During the tensioning process, the prestressed tendons of same sections are tensioned according to the principle of first vertical, then horizontal and synchronous tensioning, and the prestressed tendons of different sections are tensioned according to the principle of symmetrical staggered tensioning from the middle to both sides. Since the prestressed tendons used in this project are very short, if the traditional anchor device is adopted, prestress loss caused by the retraction of anchorage is very large. Taking vertical prestressed tendons as an example, according to the code for design of concrete structures（GB 50010-2010）[22], the prestress loss of them due to anchor deformation and prestressed tendon shrinkage is 22.3%. Aiming at the above problems, the anchor with low retraction is selected to ensure the prestress tension is effective.

Fig.5-1 Picture of working steel pipe of bundled integrate structure

Variation curves of average tension of prestressed tendons with construction sequence are shown in Figure 5-2. As can be seen from Figure 5-2, the average tension of prestressed tendons is 466kN and the prestress loss is 19.7% after prestressed tendons are tensioned stability. When the concrete strength in the working steel pipes meets the design requirements, the relatively independent steel pipes under the constraint of prestressed tendons are combined into an overall structure, resulting in load redistribution. Part of the load is transferred from prestressed tendons to main structure, and the tension of prestressed tendons decreases by 10.0%. At the stage of soil excavation, the tension of prestressed tendons has been maintained at 410kN, indicating that after steel pipes form a stable structure, the soil excavation does not have a great impact on the structural force, and the tension of prestressed tendons is almost unchanged.

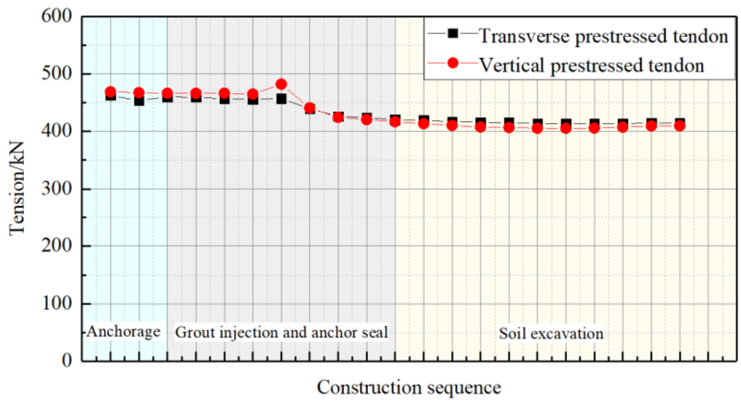


Fig.5-2 Variation curves of average tension of prestressed tendons with construction sequence

ANALYSIS OF GROUND SURFACE SUBSIDENCE

Since this project is the first underground bundled integrate tunnel in China, the influence of its construction on ground surface subsidence is still unclear. Therefore, the above values are monitored. Figure 6-1 is the measuring points layout of ground surface subsidence. A total of 28 ground surface subsidence measuring points of B1-1~14 and B2-1~14 are set up in the area of 3 times the width of bundled integrate structure. The measuring points of B1-1~14 and B2-1~14 are arranged along the fifth and half length of the structure, respectively. For the convenience of analysis, the average values of ground surface subsidence of B1-1~14 and B2-1~14 measuring points are respectively taken and plotted in Figure 6-2, indicating that the variation curves of average ground surface subsidence with construction sequence. It can be seen from Figure 6-2 that the ground surface subsidence shows a downward trend as a whole, and the subsidence mainly occurs at the stage of pipe jacking. After completing the jacking, the value of ground surface subsidence increases slightly. The above results show that steel pipes can form an overall support system under the constraint of prestressed tendons, which significantly reduces the ground surface subsidence caused by soil excavation. In addition, because the bundled integrate structure is fixedly connected with the starting shaft and the receiving shaft, the ground surface subsidence is small on both sides and large in the middle along the longitudinal direction of the structure. Ground surface subsidence curves after each construction sequence completed are given in Figure 6-3. According to Figure 6-3, the influence of structural construction on ground surface subsidence is about twice the width of the structure. After the completion of pipe jacking, the maximum ground surface subsidence of the cross section that the B1 and B2 measuring points located is 4.93mm and 9.66mm respectively. In the subsequent construction process, the values tend to be stable. After soil excavation is completed, the maximum ground surface subsidence of the cross section at B1 and B2 measuring points increases to 6.39mm and 10.16mm separately.

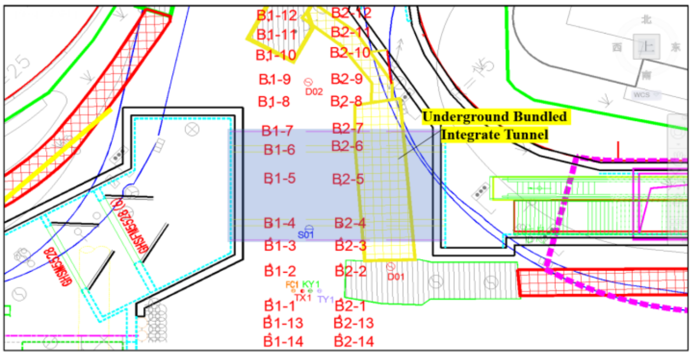


Fig.6-1 Measuring points layout of ground surface subsidence

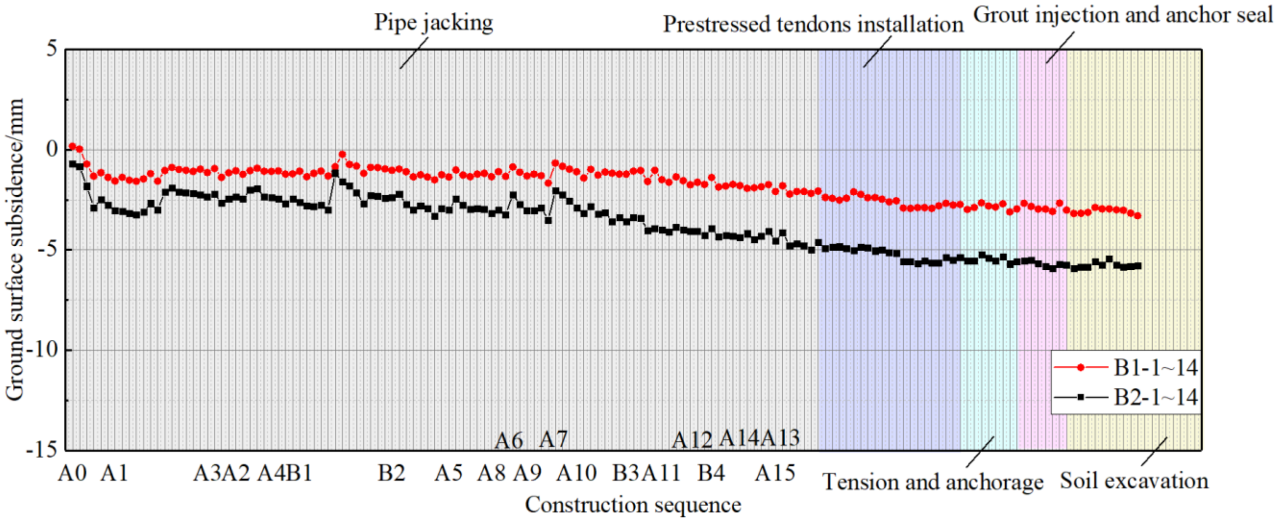
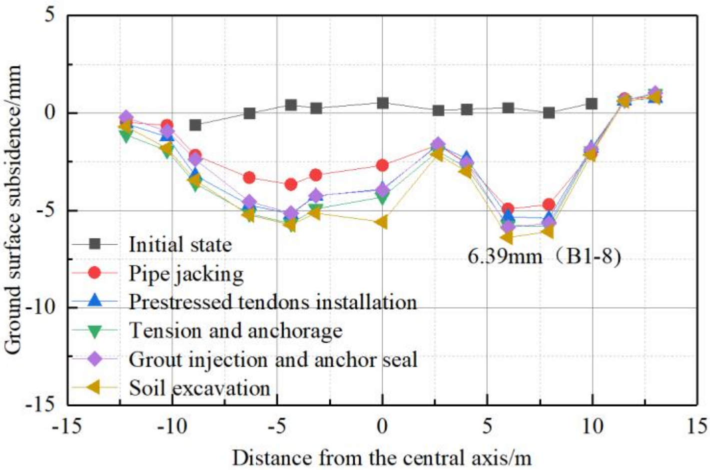
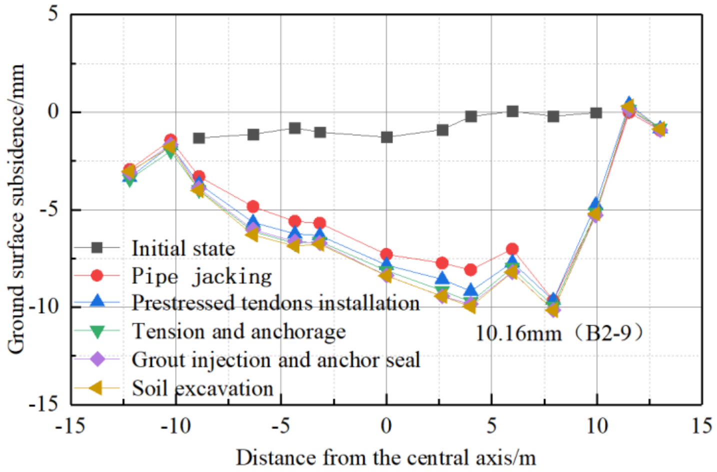


Fig.6-2 Variation curves of average ground surface subsidence with construction sequence



（a） *The cross section where the B1 measurement point is located*



（b）*The cross section where the B2 measurement point is located*

Fig.6-3 Ground surface subsidence curves after each construction sequence completed

CONCLUSION

Based on the project of Wuding Road Station of Shanghai Metro Line 14, the research on the construction method of bundled integrate structure is carried out in this paper, and the following conclusions are obtained.

(1) Compared with the traditional pipe-roofing method, the construction method of bundled integrate structure can improve the structural mechanical properties by applying prestress in ring direction to each steel pipe, so that the force form is upgraded from the longitudinal stress and transverse bracing to transverse prestress tensioning and cooperative bearing in longitudinal and transverse direction. In addition, the pipe of the structure can be flexibly combined to form underground space with any different shape, and the construction has low demand for the site, so it is suitable for underground engineering construction in complex environment.

(2) Seam sections of the bundled integrate structure will be destroyed before pipe sections, so ensuring the mechanical performance of seam sections is very important to make sure the structural safety.

(3) Due to the space of working steel pipe is very narrow, lightweight jack is used to tension prestressed tendons. In addition, in order to reduce the prestress loss caused by anchorage retraction, the anchor with low retraction is adopted to control the anchorage retraction with 1mm. In this project, the average tension of prestressed tendons is 466kN and the prestress loss is 19.7% after the prestressed tendons are tensioned stability.

(4) When the concrete strength in the working steel pipes meets the design requirements, the relatively independent steel pipes are combined into an overall structure, resulting in load redistribution. Part of the load is transferred from prestressed tendons to main structure, and the tension of prestressed tendons decreases slightly. At the stage of soil excavation, because of the steel pipes have already formed a stable structure, the soil excavation doesn’t have a great impact on the structural force, and the tension of prestressed tendons is almost unchanged.

(5) The influence of construction of bundled integrate structure on ground surface subsidence is about twice the width of the structure. In addition, the ground surface subsidence shows a downward trend as a whole, and the subsidence mainly occurs at the stage of pipe jacking. After completing the soil excavation, the value of ground surface subsidence increases slightly. In this project, the maximum ground surface subsidence is 9.66mm after finishing the pipe jacking, and the value increase to 10.16mm after soil excavation.

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