Study On Ground Deformation and Reinforcement Induced By the Construction of Rectangular-Like Shield without Columns

Bo Li, Yishuo Wei

Abstract— **For the purpose of investigating the influence of certain construction factors on the deformation of the stratum of rectangular shield pillarless tunnels, this paper combines the first case of rectangular shield pillarless tunnels in China with the use of the finite element software to establish a three-dimensional numerical simulation model of the soil body, tunnel tubes, grouting and other substitutes, and the simulation calculates and analyzes the influence of the construction factors such as the pressure of the grouting pressure, the pressure of the earth silo, and the conditions of the soil stratum on the deformation of the stratum. Based on the phenomenon of ground deformation and settlement, the problem of soil reinforcement for controlling the ground deformation caused by shield tunneling is proposed. The study results show that the morphing and subsidence: of the deformation and settlement curve of the ground layer of a rectangular shield pillarless tunnel conforms to the general law of the peck formula, As the grouting pressure was increased, the distortion and sedimentation of the strata decreased; as the pressure of the soil bin increased, the distortion and sedimentation of the strata increased; the larger the modulus of elasticity of the soil body is, the smaller the deformation and settlement of the ground layer is; after the reinforcement of the soil, the deformation and settlement of the ground layer in the corresponding working conditions decrease by about 75.3%, 72.5%, and the reinforcement effect is The effect of reinforcement is obvious. In the actual construction, each construction parameter should be reasonably adjusted to control the deformation of the ground layer, and the study's results may provide a reference for subsequent research.**

Index Terms—**Rectangular shields without columns；Construction factors； numerical simulation；Stratigraphic deformation； soil reinforcement**

I. Introduction

In the 19th century, the world's first rectangular shield tunnel appeared in London, but the project was mainly hand-dug, and the efficiency was not high. It was gradually phased out. With the development of society and the progress of science and technology, the circular shield has become the main type of shield in construction because of its convenient mechanized construction. In recent years, China has vigorously developed the construction of urban rail transit, according to statistics, as of the end of 2023, according to relevant statistical reports, the total operating mileage of rail transit lines reached 10,165 kilometers. In the construction of urban rail transit, shield method is a common construction method in the construction process, because of its safety, reliability, advanced technology and economic benefits, it has been widely used in the construction of soft soil areas. In recent years, with the increase of the development intensity of urban underground space in China, the construction of various types of tunnels continues to grow, which leads to less and less underground space available. Therefore, rectangular shield tunnels with high space utilization have been developed and manufactured.

In the early 21st century, Japan built the world's first rectangular shield tunnel. In 2015, the construction of a rectangular shield tunnel in a shield section of Line 3 in Ningbo, Zhejiang Province, began, marking that China's rectangular shield has entered a new stage. At present, the rectangular shield construction has also gone out of Ningbo and applied to the urban rail transit construction in Hangzhou, Zhengzhou and other places. At the same time, in view of the construction requirements of the rectangular shield section of rail transit, China also innovated the column-free structure of the rectangular shield tunnel. Compared with the traditional column structure, the outer diameter, segment thickness and width of the column-free structure remain unchanged, but the middle column structure is eliminated. Compared with the original reinforced concrete segment, the segment material is steel structure. The construction of this structure has no application experience in China, and the formation deformation caused by the construction has no precedent. The soil layer passed by the shield machine is mostly clay and silt soil, and it passes through the built-up area. Therefore, it is necessary to carry out three-dimensional numerical simulation of the construction of rectangular shield tunnel without pillar to guide the actual construction.

For the formation deformation caused by shield construction, the research on circular shield tunnel technology is relatively mature, and a large number of relevant numerical simulation research results have been obtained [2,3]. Sun Tongli et al. [4] studied and analyzed the surface settlement phenomenon of double-circle shield tunnel by means of numerical simulation calculation, and obtained the impact characteristics of environmental geotechnical engineering during the construction process of double-circle shield. Based on the existing research results, in order to study and explore the formation deformation rule during the excavation of column-free rectangular shield tunnel [5-7], the finite element software ABAQUS was used to build a three-dimensional numerical model of the entire construction process of the column-free rectangular shield tunnel, and the

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soil deformation around the tunnel caused by the excavation was analyzed. The influence law between soil deformation and construction factors is studied, and the results can provide a certain reference for the construction of rectangular shield without column.

II. PROJECT OVERVIEW

The design of rectangular shield tunnel without pillar structure is based on a certain section of Ningbo Rail Transit Line 2 project. The line is laid along the main road of urban area, and the surrounding land is mainly residential land and commercial land. The section of the designed crossing is located in front of Zhaobaoshan Station, and there are residential areas, squares, banks and other buildings around the line. The situation of pipelines and underground structures at the location is complicated. The existing buildings on both sides have more restrictions on the construction of the section, and the space is small. According to the detailed geological survey data, the soil layers involved in the influence range of tunnel shield tunneling are mainly silty clay and silty silty clay. The tunnel section of the crossing section is located in the silty clay stratum. The thickness of soil covering the tunnel is about 16m. The central depth of the tunnel is 19m.

This project is a two-line subway tunnel, as shown in Figure 1. The rectangular shield machine used is developed and produced by our country, as shown in Figure 2.

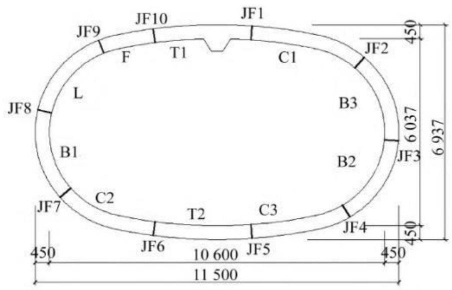


Figure 1 Section of column-free structure of class rectangular tunnel (mm)

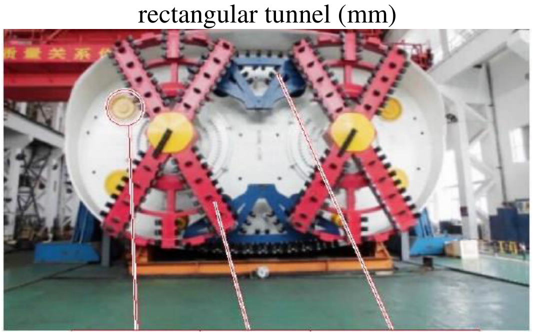


Figure 2 Shield machine cutter plate diagram

III. THREE-DIMENSIONAL NUMERICAL SIMULATION OF RECTANGULAR SHIELD TUNNEL WITHOUT PILLAR

A. Constitutive model and basic assumption

Three-dimensional finite element simulation was used in this calculation. There were 27,900 solid elements and 30,732 nodes in the model. More-coulomb plasticity criterion was used for model soil, linear elastic model was used for lining segments and grouting layers.

It is assumed that the simplified conditions are as follows: the soil layer is evenly distributed horizontally and the soil layer under study is isotropic material; The pipe segment and grouting layer adopt linear elastic constitutive structure. The effect of seepage coupling is not considered, and the effect of reinforcement inside the concrete segments is ignored.

B. Computational model and boundary conditions

The axis direction of the model tunnel is y direction in the software, that is, the tunnel excavation direction. The horizontal direction perpendicular to the tunnel axis is x direction; The vertical direction perpendicular to the tunnel axis is the z direction; As shown in Figure 3.

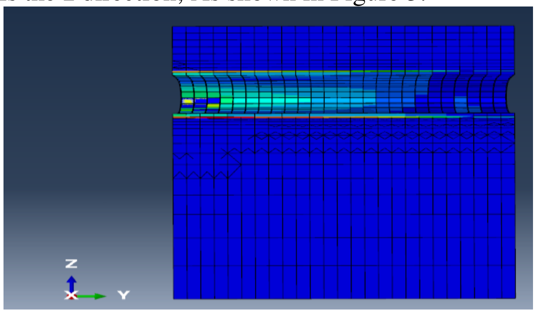


Figure 3 Finite element calculation model section

Calculation range: the transverse length (x direction) is 70m, the longitudinal length (y direction) is 30m, and the depth (z direction) is 40m. The buried depth of the tunnel is 10m, the height and width of the tunnel is 11.5x6.9m, the thickness of the steel lining segment is 0.45m, the ring width is 1.2m, and the steel type is Q345, as shown in Figure 1.

Boundary conditions and grid unit Settings: the upper part of the model is free constraint, no constraint conditions are set, the lower part of the model is full constraint, and horizontal normal constraints are applied around the model. The element type was selected by C3D8R reduction integration method, and hexahedral elements were used to finely divide the model. In order to facilitate calculation, the structural mesh of surrounding rock mass gradually became thinner from the center point of the lining to the outside.

C. Material parameter selection

According to the engineering geological survey report and relevant data, the parameters of each soil layer are determined as shown in Table 1. The grouting layer adopts the waiting layer model with a thickness of 0.25m. The material parameters of shield shell, grouting layer and segment are shown in Table 2.

Table 1 Geophysical parameters

Soil types	Natural densities(kg/m^3)	cohesive force（KPa）	angle of internal friction（°）	modulus of elasticity（KPa）	Poisson's ratio
silty clay	1730	53	27.8	23000	0.42
ooze	1670	18	25	18000	0.38
loam	1840	13.3	24.2	14000	0.39
silty chalky clay	1790	45	26.6	24500	0.4

Table 2 Parameters of tube sheet, grouting layer and shield shell for class 2 rectangular tunnels

designation	Selected Models	modulus of elasticity （Mpa）	densities （kg/m^3）	Poisson's ratio
Pipe Lining	resilient	206000	7580	0.2
grouting layer	resilient	30	2000	0.2
shield	resilient	210000	7500	0.22

D. Calculation process

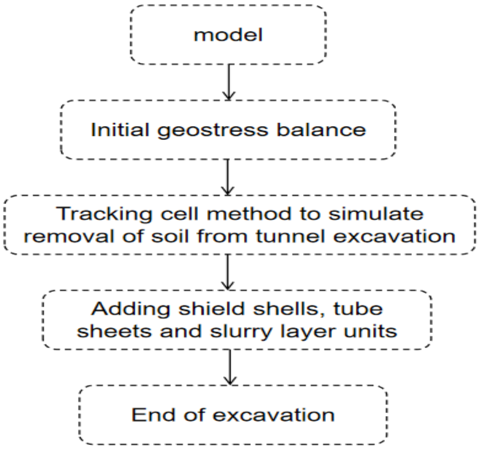


Figure 4 Simulation steps

By using the single factor control variable method, a variety of conditions are set in the process of rectangular shield tunnel without pillar, and the influence of grouting pressure, soil bin pressure and soil conditions on formation deformation is considered. According to the above working conditions, the main research object of Ningbo rectangular shield tunnel without pillar is formation deformation. According to the model simulation results, the horizontal displacement of soil mass and structure is small, and the vertical displacement is large, which is consistent with the actual construction situation. Vertical displacement is one of the most concerned control indicators, so the vertical displacement of formation deformation is studied and analyzed. As can be seen from FIG. 5, FIG. 6 and FIG. 7, due to the existence of ground stress around the tunnel, the deformation of the upper and lower parts of the tunnel is relatively large under the action of ground stress, and the soil displacement in the upper part of the tunnel is the largest.

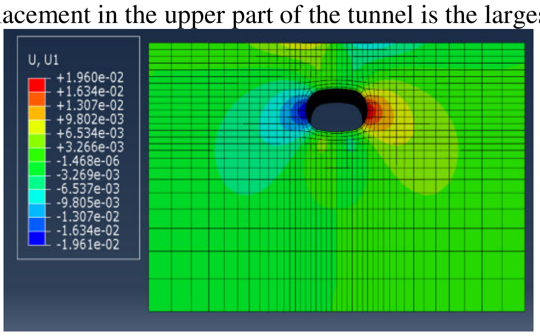


Figure 5 Cloud view of lateral displacement of modeled soils

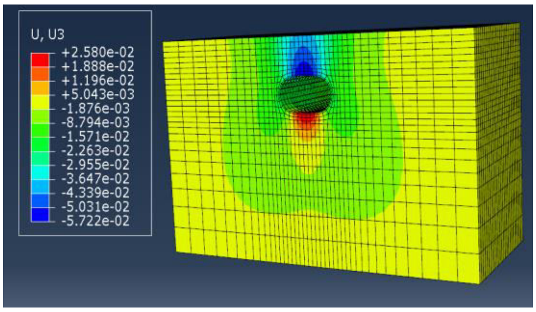


Figure 6 Vertical displacement cloud of modeled soil body

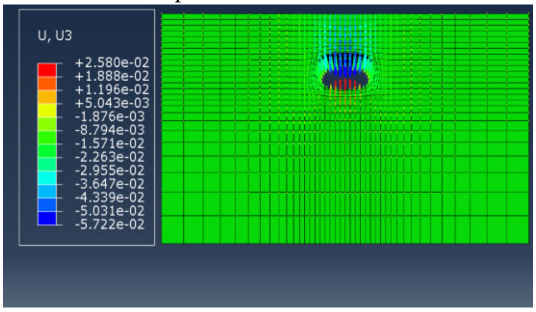


Figure 7 Vector map of soil displacement

As can be seen from FIG. 8, the formation deformation of a similar rectangular shield tunnel without pillar shows settlement, and the curve presents an approximate normal distribution, consistent with the shape of the surface settlement curve predicted in peck's formula. The maximum settlement is 57.23mm, and 35m in the figure is the location of the tunnel's central axis, and the maximum settlement occurs near the tunnel's central axis. The numerical model meets the construction requirements [9] and can be used for subsequent calculations.

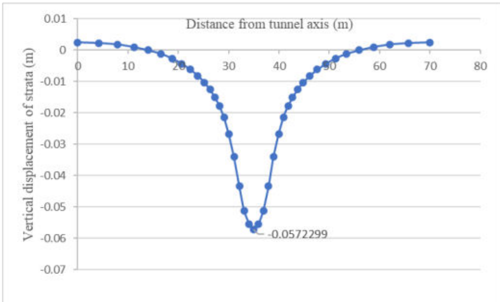


Figure8 Stratigraphic deformation curve

IV. ANALYSIS OF THE INFLUENCE OF DIFFERENT INFLUENCING FACTORS ON FORMATION DEFORMATION

There are many influencing factors on formation deformation of rectangular shield tunnel. Sensitivity analysis is carried out on three factors: synchronous grouting pressure, soil bin pressure and soil layer condition. According to the obtained results, various construction factors are reasonably adjusted.

A. Influence of simultaneous grouting pressure on formation deformation

In numerical simulation of rectangular shield tunnel without column, grouting amount, grouting pressure and grouting slurry density are closely related to formation deformation. In order to ensure the accuracy of numerical simulation, grouting pressure is selected for research and analysis. Three different grouting pressure conditions of 0.1MPa, 0.2MPa and 0.3MPa were selected for analysis, and other construction parameters remained unchanged. Figure 9 shows the vertical displacement curve of different grouting pressures on formation deformation. It can be seen from Figure 9 that formation deformation is manifested as settlement. When grouting pressure is 0.1MPa, formation settlement is 57.22mm. When the grouting pressure is 0.2MPa, the formation settlement is 53.90mm. When the grouting pressure is 0.3Mpa, the formation settlement is 50.58mm. The formation settlement decreases with the increase of grouting pressure. The reason for this phenomenon is that the grouting pressure acts on the inner surface of the soil of the excavation face, and the direction of the acting force deviates from the center of the pipe segment, which plays a certain supporting role on the upper stratum of the tunnel, thus reducing the formation settlement. Every 0.1Mpa increase of grouting pressure, the formation settlement decreases by about 3mm. Therefore, in the actual construction process, in order to control the formation deformation, the grouting pressure can be properly adjusted.

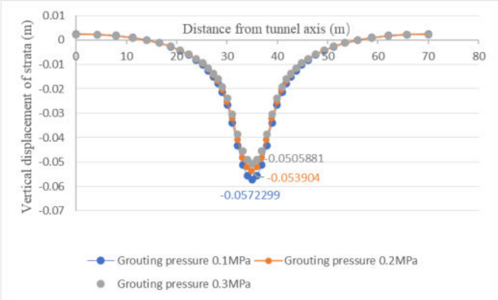


Figure 9 Formation deformation curves at different grouting pressures

B. *Effect of soil bin pressure on formation deformation*

The formation deformation is not only related to the properties of the grouting slurry, but also the soil bin pressure (palm surface pressure) is an important factor. The excavation of the rectangular shield machine is the soil pressure balance. When the shield machine is excavating, it relies on the rotation of the blade to cut the soil in front and then continues to push forward. At this time, the shield will exert a driving force on the excavated soil in front to maintain the stability of the excavated face. Therefore, the uniform pressure of soil in the tunnel excavation face is modeled in this paper. Based on the analysis of relevant data of subway projects at home and abroad, and according to the soil condition of Ningbo City and existing engineering practice, the soil bin pressure of Ningbo subway shield tunneling machine is usually 0.1-0.3MPa. Three different working conditions of soil bin pressure are set respectively as 0.1MPa, 0.2MPa and 0.3MPa for simulation analysis, and other construction parameters remain unchanged. Figure 10 shows the vertical displacement curve of different bin pressures on formation deformation. It can be seen from Figure 10 that with the gradual increase of bin pressure, formation settlement shows an increasing trend, and the two present a positive correlation trend. When the bin pressure is 0.3MPa, formation settlement is the largest and the formation settlement value is 66.89mm. When the soil bin pressure increases, the disturbance ability of the shield machine to the formation will be enhanced, resulting in the formation deformation and settlement increase. In the actual construction process, the soil bin pressure should be controlled reasonably to avoid excessive formation deformation.

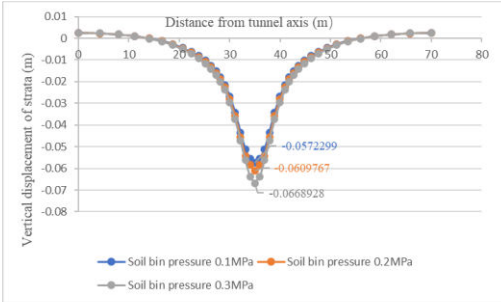
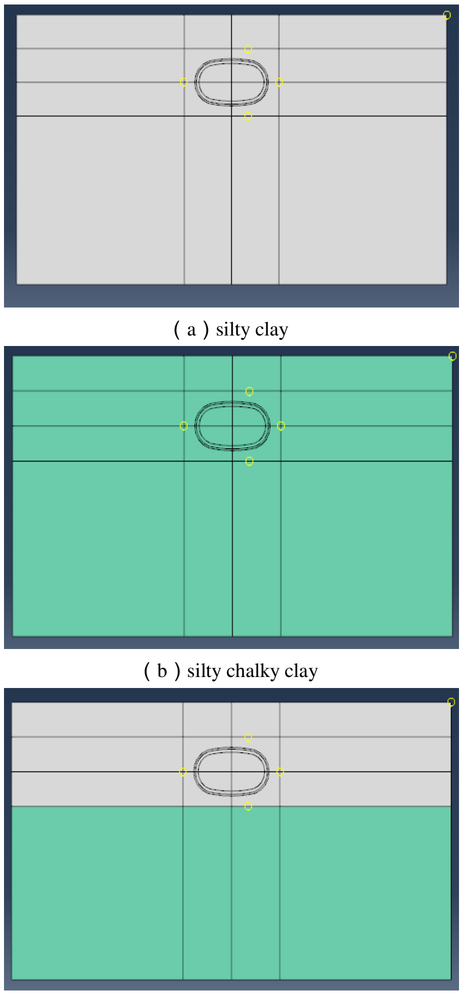


Figure10 Ground deformation curves at different soil bin pressures

C. *Influence of soil layer condition on formation deformation*

Considering the influence of rectangular shield tunneling machine through different soil layers on formation deformation, the shield tunneling construction models of different soil layers are established, as shown in Figure 11. The first type of soil layer is all silt clay, the second type is silt silty clay, and the third type of composite soil layer is covered with 15m silt clay and 25m silt silty clay. Other relevant parameters such as grouting pressure and soil bin pressure are the same.



(a) silty clay

(b) silty chalky clay

(c) composite layer of soil

Figure11 Construction drawing model of different soil layers

As can be seen from the vertical displacement curve of formation deformation under different soil layers in FIG. 12, the influence of soil layer condition on surface deformation is more obvious. When soil layer condition is silt clay, the formation settlement displacement is 57.23mm. When the soil layer is silty clay, the settlement displacement is 53.29mm. When the soil layer is composite soil layer, the stratum settlement displacement is 56.67mm. Because the elastic modulus of silty clay is smaller than that of silty clay, the formation deformation and settlement are most obvious. The silt silt clay has higher elastic modulus, and the silt silt clay has the smallest settlement displacement. When the composite soil layer of muddy clay and muddy silty clay is used in rectangular tunnel construction, the peak value of formation settlement lies between the condition of muddy clay and the condition of muddy silty clay, which is obviously caused by the proportional relationship between the upper and lower muddy silty clay in the model. Different soil layers have different physical properties, and the properties of silty clay are complementary to those of silty silty clay.

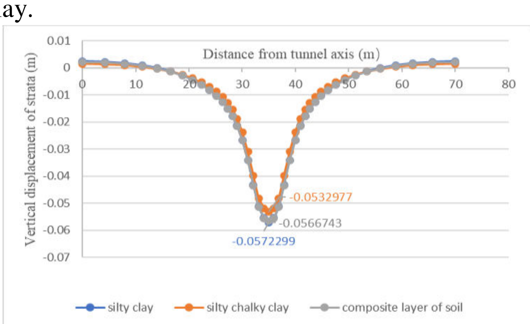


Figure 12 Ground deformation curves for different soil conditions

D. Influence of soil reinforcement on formation deformation

In order to control formation deformation, the soil around the rectangular shield tunnel without pillar is reinforced, and the reinforcement range is shown in Figure 13.The white area in the center is the excavation area,the rest of the red part is the soil reinforcement area, and the soil reinforcement area adopts the molar Coulomb criterion. The parameters selected are mainly based on relevant literature [21], and the specific values are as follows: the cement reinforcement layer with the soil reinforcement density of 2200kg/m3, Poisson's ratio of 0.30, elastic modulus of 400MPa, cohesion force of 52Kpa, and internal friction Angle of 30°. The strengthening research is carried out in the condition of silt clay and soil bin pressure 0.3MPa. Figure 14 shows the vertical displacement influence curve on formation deformation after soil reinforcement. It can be seen from Figure 14 that before soil reinforcement, the maximum settlement displacement of formation deformation is 57.23mm. Under the condition of silt clay reinforced soil layer, the maximum settlement displacement of formation deformation is 14.11mm, which is about 75.3% less than that before reinforcement. When the bin pressure is 0.3Mpa, the maximum settlement displacement of formation deformation is 66.89mm. When the soil layer is strengthened under the soil bin pressure of 0.3MPa, the maximum settlement displacement of the formation deformation is 18.40mm, which is about 72.5% less than that before the reinforcement. It can be seen that the soft soil layer can effectively reduce the influence of tunnel excavation on formation deformation after being treated by the reinforced soil layer. In actual construction, the reinforced soil layer can be considered to control formation deformation.

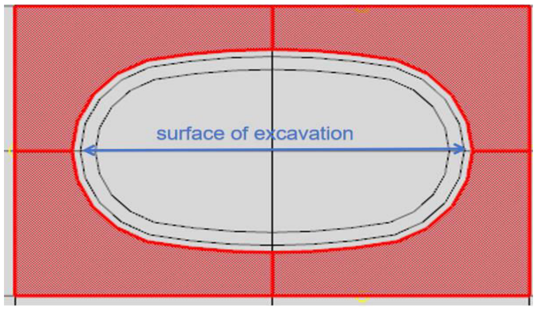


Figure 13 Soil Reinforcement Zone

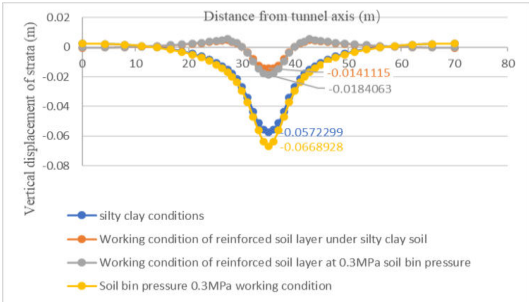


Figure 14 Ground deformation curves for reinforced soil conditions

CONCLUSION

Combined with a certain section of Ningbo Rail Transit Line 2 project, a three-dimensional tunnel excavation calculation model was established by using finite element software, and the construction process of a similar rectangular shield tunnel without pillar was simulated numerically. The calculation considered the whole process of shield tunneling construction, and the following conclusions were drawn:

(1) The numerical simulation of the construction process of rectangular shield bolleless tunnel is carried out, and the formation deformation curve of bolleless tunnel is similar to that predicted by peck formula. The maximum settlement is 57.23mm, which is located near the central axis of the tunnel.

(2) The numerical simulation of the construction process of rectangular shield bolleless tunnel is carried out, and the formation deformation curve of bolleless tunnel is similar to that predicted by peck formula. The maximum settlement is 57.23mm, which is located near the central axis of the tunnel.

(3) The formation deformation and settlement amount of rectangular, pillar-free shield tunnel increases with the increase of soil bin pressure. When the soil bin pressure increases, the disturbance ability of the shield tunnel to the formation will be enhanced, resulting in the formation deformation and settlement increase. In the actual construction process, the soil bin pressure should be adjusted in time to control formation deformation.

(4) According to the analysis of formation deformation and settlement under different soil layers, soil with larger elastic modulus will have smaller surface deformation and settlement. In order to control formation deformation, control measures for soil reinforcement are proposed. After finite

element numerical simulation, the maximum formation deformation and settlement displacement under the condition of silt clay reinforced soil layer is 14.11mm. After the soil layer is strengthened at 0.3MPa, the maximum settlement displacement of formation deformation is 18.40mm, which is about 72.5% less than that before reinforcement. The formation deformation and settlement can be reduced effectively in the soft soil area of Ningbo.

(5) There are many factors affecting the construction of rectangular shield tunneling. At present, the corresponding analysis can only be given through numerical calculation. After the corresponding monitoring data are obtained in subsequent tunnel construction, the further research on rectangular shield tunneling without pillar can be done.

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