Research on Deformation Control of Power Shield Tunnels Undercrossing Rivers Based on Orthogonal Experimental Method

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Abstract. When the shield tunnel is constructed under the river, the shield machine is excavated in the water-rich sand layer with rich water content and strong permeability, and it is difficult to control the stratum disturbance deformation during construction. In this paper, based on the project of Xi 'an 330kV power shield tunnel underpassing Bahe River, a three-dimensional fluid-solid coupling model of power shield tunnel underpassing Bahe River is established by using orthogonal test and numerical simulation. The sensitivity of soil pressure, grouting pressure and grouting layer thickness to stratum deformation is studied. The results show that the grouting pressure is the main influencing factor when the maximum ground settlement, the maximum vertical displacement and the maximum horizontal displacement of the stratum are taken as the evaluation indexes, while the sensitivity of grouting layer thickness and soil chamber pressure is small. Therefore, in the construction of river-crossing shield, the change of synchronous grouting pressure and grouting volume should be preferentially controlled according to the monitoring data and parameter feedback, and the parameters should be optimized and adjusted in time to control the deformation of the stratum.

Keywords: Power shield; Cross the river; Numerical simulation; Strata deformation.

1 Introduction

With more and more cities constructing underground tunnels for various purposes, the geological and geological conditions through which shield tunneling passes are becoming increasingly complex. It is inevitable that shield tunneling will penetrate buildings, existing tunnels, railway lines, and highways. When a shield tunnel passes through a river, due to the large soil disturbance caused by construction, the difficulty coefficient of controlling disturbance deformation and ground settlement is high, which can easily have a certain impact or even damage on the soil and buildings along the line. Therefore, it is necessary to conduct in-depth research on disturbance control caused by shield tunneling through rivers, and determine the main excavation parameters. Rankin [1]

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conducted in-depth research based on the conclusions of Peck et al. and revised the original Peck formula in combination with specific practical engineering, further improving the applicability and accuracy of the formula. Ahrens et al.[2] analyzed the changes in stress conditions of tunnel segments caused by underwater tunnel crossing through existing subway tunnel excavation construction by creating a finite element numerical model

At present, research on shield tunneling mostly focuses on the study of underpass structures, bridges, existing tunnels, and pipelines. However, there is a lack of systematic and comprehensive control of key excavation parameters and settlement control for small diameter shield tunneling underpass river construction. This article takes the Xi'an 330KV power tunnel crossing the Ba River as the engineering background, and comprehensively uses a combination of orthogonal experiments and numerical simulation methods to study the main excavation parameters that affect geological deformation and surface settlement during the process of crossing the river. It also provides some reference and guidance for the safe construction of the power shield tunnel crossing the rich water sand layer and the silty clay layer during the construction process of crossing the river.

2 Project overview

The 330kV underground power shield tunnel in the Ba River section of Xi'an City is located on the North Third Ring Road, Guang-yun -an Avenue, and Xing wei Road. The outer diameter of the interval shield tunnel is 4m, the inner diameter is 3.5m, the segment ring width is 1.2m, and the segment thickness is 0.25m;

3 Numerical simulation

3.1 Basic assumptions

In the establishment and calculation of numerical models, in order to ensure the practical feasibility of the model and the accuracy and reliability of the calculation, it is necessary to simplify the model appropriately. Therefore, the following assumptions are made:

(1) Each soil layer is evenly distributed in layers, with horizontal soil layer interfaces and ignoring small interlayer soil layers;

(2) Consider the soil as an ideal elastic-plastic body with homogeneous, isotropic, and nonlinear small deformation characteristics;

(3) The initial geostress is the initial self weight stress, ignoring the initial tectonic stress;

(4) Each step of the shield tunneling machine is completed instantaneously, and the lining segments are installed in one go;

3.2 Introduction to Finite Difference Models

This article uses FLAC3D finite difference numerical simulation software to establish a three-dimensional calculation model for small diameter shield tunneling through rivers. Consider the curved tunnel as a straight tunnel for simulation[3], with a diameter range of 5 times the lateral soil on both sides of the tunnel and 5 times the soil on the lower side of the tunnel, and the upper side up to the riverbed soil layer. The burial depth of this section of the tunnel is about 11m, so the model is taken as 48m along the longitudinal direction of the tunnel axis, 52m perpendicular to the transverse direction of the tunnel axis, and 35m in the soil layer below the river bottom. Therefore, the size of the calculated model is 48m × 52m × 35m (length × wide × High. The vertical clear distance between the left and right tunnels is 4m.

The upper surface of the model is a free surface, and a vertical uniformly distributed load of 40kPa is applied to the upper surface to simulate river water loads. The left and right sides of the model are constrained by X-axis displacement, the front and back sides are constrained by Y-axis displacement, and both vertical and horizontal constraints are set at the bottom horizontal plane[4,5]. The three-dimensional fluid structure coupling calculation model is shown in Figures 1.

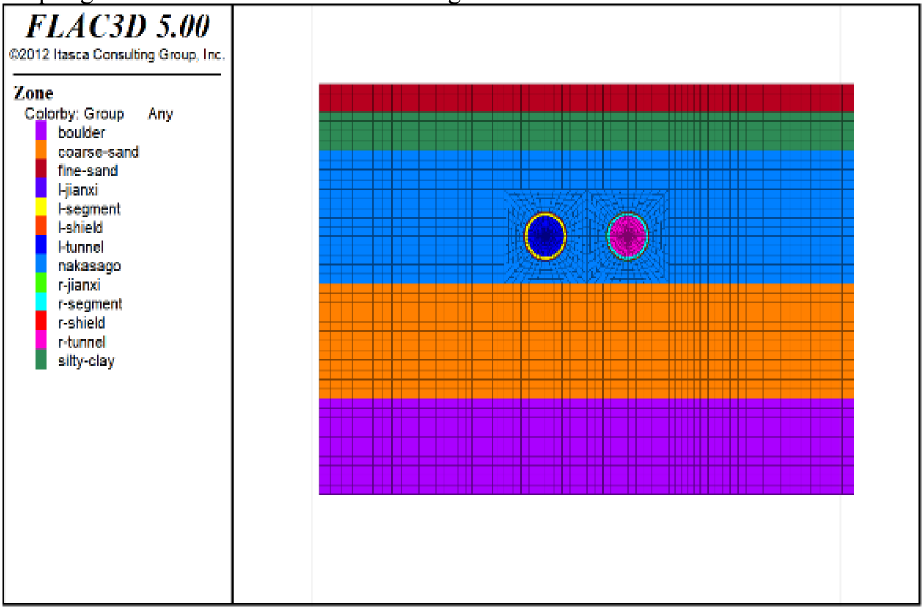


Fig. 1. Front view of 3D fluid-structure interaction model.

3.3 Strata and material parameters

The soil is a solid unit and adopts a Mohr Coulomb constitutive relationship[6]. The soil layers for crossing the Bahe River from top to bottom are fine sand, silty clay, medium sand, coarse sand, and round gravel. Based on engineering geological survey data, the physical and mechanical parameters of the soil layers are shown in Table 1

Table 1. Physical and mechanical parameters of soil layer.

name	thickness(m)	density(kg/m^3)	Bulk modulus(MPa)	internal friction angle(°)	coefficient of lateral pressure	Permeability coefficient(m/d)
fine sand	2	1940	9.33	29	0.39	25
Silty clay	4	1910	10	19.2	0.4	0.5
Medium sand	11	1960	10.9	31	0.38	30
coarse sand	10	1980	11.9	33	0.36	35
Round gravel	8	2010	25.64	34	0.33	45

Shield shell, pipe segments, grouting and other replacement layers are also solid units, using elastic constitutive relationships. The thickness of the equivalent layer can be taken as follows:

$$\delta = \eta \ddot{A} \quad (1)$$

In the formula: Ä—Shield tail gap, mm;

η—The coefficient ranges from 0.7 to 2.0, with an upper limit for extremely soft soil layers and a lower limit for hard soil layers. For shield tunnel construction in different soil types, the value can generally be taken as: hard clay, 0.7~0.9; Dense sand, 0.9~1.3; Loose sand, 1.3~1.8; Soft clay, 1.6~2.0.

The parameters of shield tunneling machine and lining materials are shown in Table 2.

Table 2. Shield machine and lining material parameters.

name	density (kg/m^3)	Bulk modulus (MPa)	shear modulus (MPa)
Shield shell	7800	1.11×10^5	8.33×10^4
Segment	2500	1.92×10^4	1.44×10^4
Grouting layer	1890	56.2	38.7

4 Design and result analysis of orthogonal experimental numerical simulation working conditions

In order to study the degree of influence of construction of electric shield tunneling under the Ba River on geological and ground deformation, and to analyze the sensitivity of various construction parameter factors to the geological environment, three influencing factors were selected: soil chamber pressure, grouting pressure, and grouting layer thickness[7,8], with four different levels for each factor. According to the actual engineering situation, the L16 (43) orthogonal test table was selected to simulate 16 working conditions[9]. The main quality evaluation indicators for small diameter shield tunnels crossing rivers include the maximum surface settlement value, the maximum vertical displacement value of the strata, and the maximum horizontal displacement value of the strata. The above evaluation indicators were numerically simulated and measured based on orthogonal experiments, and the results are shown in Table 3.

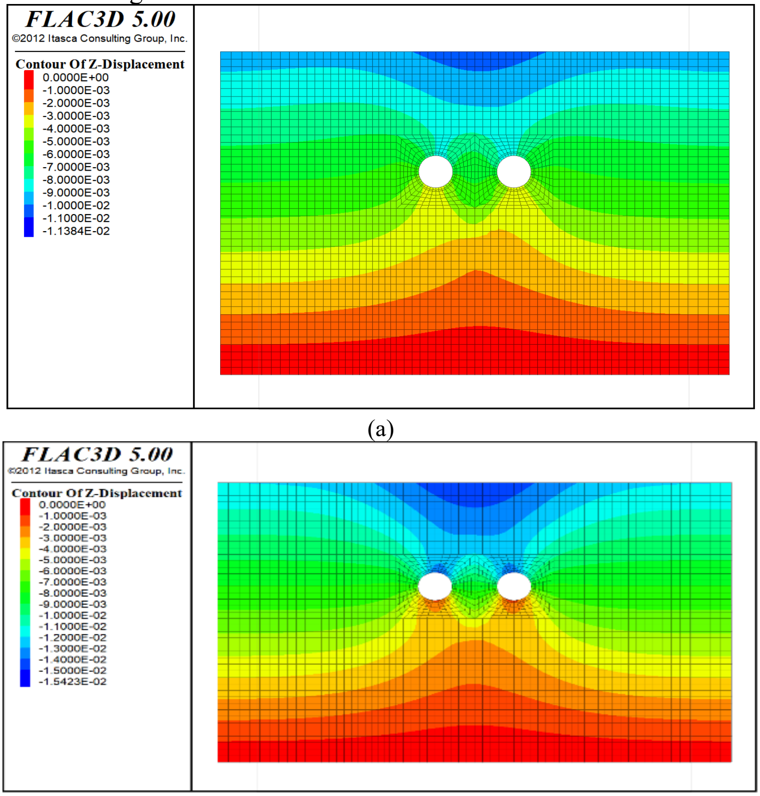
Table 3. Orthogonal test result.

Simulated working conditions	A Chamber pressure (MPa)	B Grouting pressure (MPa)	C Thickness of grouting layer (m)	Maximum surface subsidence value /m	Maximum vertical displacement value of strata /m	Maximum horizontal displacement value of strata /m
1	0.08	0.10	0.12	13.23	13.88	2.52
2	0.08	0.15	0.16	11.56	12.29	2.09
3	0.08	0.20	0.20	11.43	12.11	2.57
4	0.08	0.25	0.24	10.83	11.29	2.15
5	0.11	0.10	0.16	11.02	11.63	2.29
6	0.11	0.15	0.12	11.60	12.35	2.69
7	0.11	0.20	0.24	10.82	11.34	2.15
8	0.11	0.25	0.20	12.98	13.67	2.68
9	0.14	0.10	0.20	14.75	15.42	2.80
10	0.14	0.15	0.24	12.32	13.00	2.23
11	0.14	0.20	0.12	11.27	11.89	2.56
12	0.14	0.25	0.16	10.60	11.38	3.34
13	0.17	0.10	0.24	12.27	12.81	2.24
14	0.17	0.15	0.20	11.60	12.20	2.14
15	0.17	0.20	0.16	11.08	11.82	2.50
16	0.17	0.25	0.12	10.72	11.49	3.44

4.1 Analysis of surface subsidence value and vertical displacement of strata

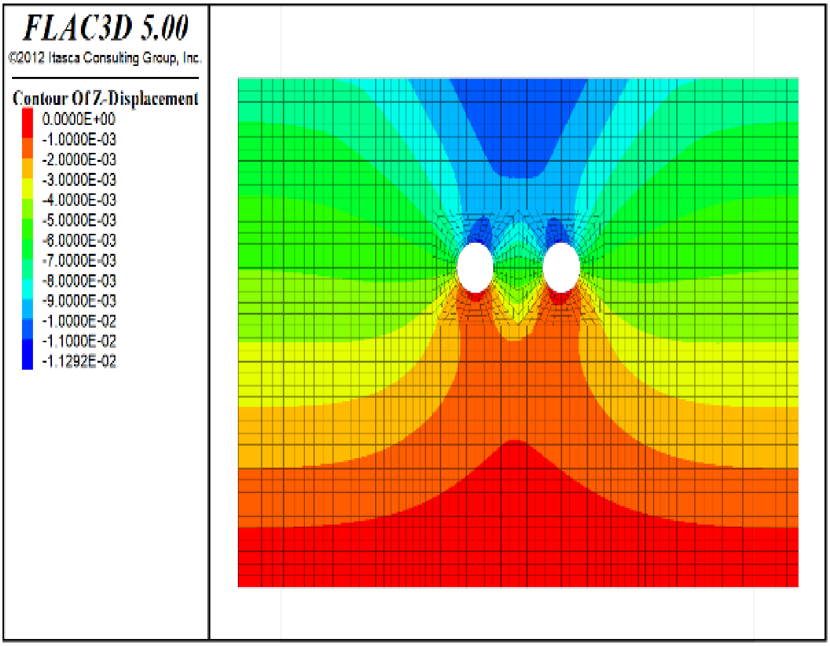
According to Table 3, the maximum surface settlement value is 14.75mm under condition 9, and the minimum value is 10.60mm under condition 12. The surface settlement obtained from all working conditions is within a range of more than ten millimeters, all within the allowable specification value of 30mm. However, during the construction of the shield tunneling through the Bahe River, it is still necessary to minimize surface deformation as much as possible to reduce construction safety risks. Due to space requirements, only partial cloud maps will be displayed. As shown in Figures 2.

From Figures 2, it can be seen that after the excavation of both the left and right lines of the shield tunnel is completed, the vertical deformation of the strata above the tunnel shows concave settlement grooves with large middle and small sides, which is consistent with the classic Peck empirical formula[10]. From Table 3 above, it can be seen that the maximum vertical displacement value of the stratum is 15.42mm under condition 9, and the minimum value is 11.29mm under condition 4. The maximum vertical displacement value of the stratum under other conditions is basically within this range, and the variation is not significant. The maximum vertical displacement value of the stratum mostly occurs at the top position of the two tunnel arches or the center of the concave settlement groove.



(a)

(b)

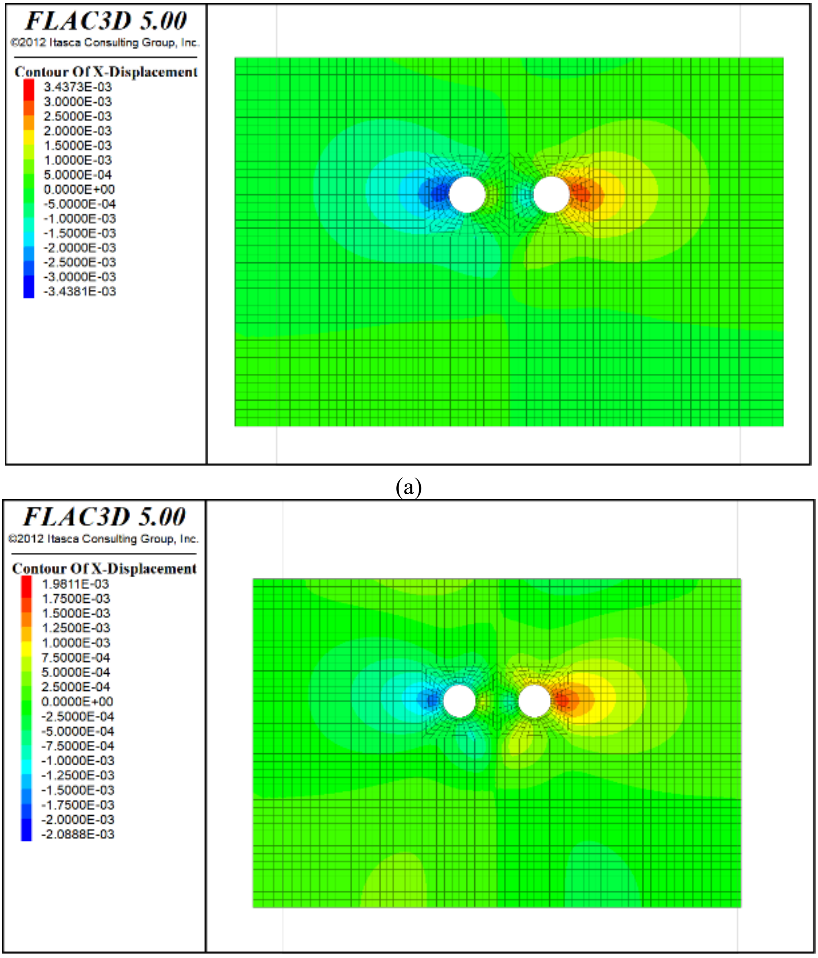


(c)

Fig. 2. Vertical displacement cloud map of strata in working conditions 12 (a), 9 (b), and 4 (c).

4.2 Horizontal displacement analysis of strata

According to Table 3, the maximum horizontal displacement of the stratum is 3.44mm under condition 16, and the minimum is 2.09mm under condition 2, with a difference of 1.35mm. From Figures 3, it can be seen that the maximum horizontal displacement value of the stratum basically occurs at the outer arch positions of the left and right tunnels, and the displacement amount at the outer arch positions of the two tunnels is almost the same. Due to the pressure of the upper river water, the left side of the arch waist of the left tunnel is displaced in the opposite direction of X, and the right side of the right tunnel is deformed in the positive direction of X, resulting in an elliptical trend in the left and right tunnels. Compared to the vertical displacement value of the stratum, the horizontal displacement value is smaller, which is because the shield tunnel segments and grouting materials have a certain degree of stiffness and are subjected to different forces. In the vertical direction, the shield tunnel segments and grouting need to bear the weight of the upper soil and water, as well as the construction load, resulting in significant displacement; In the horizontal direction, the pipe segments and grouting only bear the squeezing effect of the soil and water on both sides, and the displacement is relatively small.



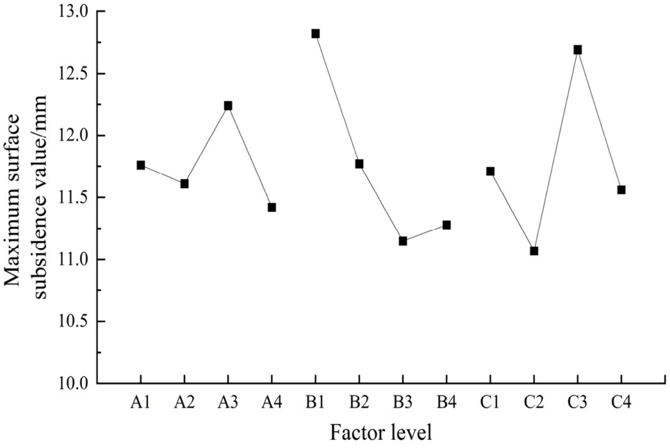
(a)

(b)

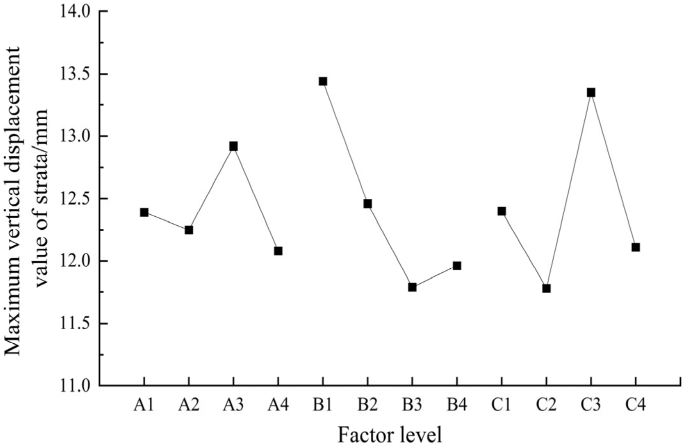
Fig. 3. Horizontal displacement cloud map of strata in working conditions 16 (a) and 2 (b).

4.3 Analysis of extreme test results

Table 4 and Figure 4 show that when the maximum surface settlement value, maximum vertical displacement value of the stratum, and horizontal displacement value of the stratum are used as evaluation indicators, grouting pressure is the main influencing factor, and grouting layer thickness and soil chamber pressure are secondary influencing factors. Perform range analysis on the numerical simulation results of orthogonal experimental method and obtain the optimal combination from it. When using the maximum surface settlement value as the indicator, the pressure of the soil silo is controlled at 0.17MPa, the grouting pressure is controlled at 0.20MPa, and the thickness of the grouting layer is taken as 0.16m, resulting in the smallest surface settlement[11]. When using the maximum vertical displacement value of the stratum as the indicator, the pressure of the soil silo is controlled at 0.17MPa, the grouting pressure is controlled at 0.20MPa, and the thickness of the grouting layer is taken as 0.16m, which has the smallest impact on the vertical displacement of the stratum. Surface subsidence refers to the vertical displacement that occurs on the surface of the stratum, so the optimal combination of the two evaluation indicators is consistent. When using the maximum horizontal displacement value of the stratum as the indicator, the pressure of the soil silo is controlled at 0.08MPa, the grouting pressure is controlled at 0.15MPa, and the thickness of the grouting layer is set to 0.24m, resulting in the minimum horizontal displacement of the stratum.



(a)



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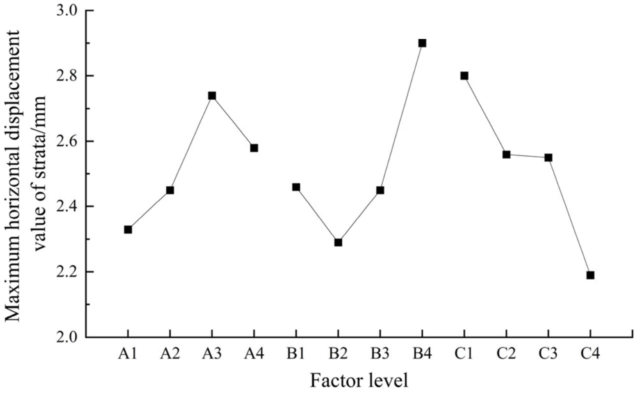

(c)

Fig. 4. Range analysis effect curve.

Table 4. Range analysis table.

Analysis items	Maximum surface subsidence value /m			Maximum vertical displacement value of strata /m			Maximum horizontal displacement value of strata /m		
	A	B	C	A	B	C	A	B	C
K_1	47.05	51.27	46.82	49.57	53.74	49.61	9.33	9.85	11.21
K_2	46.42	47.08	44.26	48.99	49.84	47.12	9.81	9.15	10.22
K_3	48.94	44.60	50.76	51.69	47.16	53.40	10.93	9.78	10.19
K_4	45.67	45.13	46.24	48.32	47.83	48.44	10.32	11.61	8.77
k_1	11.76	12.82	11.71	12.39	13.44	12.40	2.33	2.46	2.80
k_2	11.61	11.77	11.07	12.25	12.46	11.78	2.45	2.29	2.56
k_3	12.24	11.15	12.69	12.92	11.79	13.35	2.74	2.45	2.55
k_4	11.42	11.28	11.56	12.08	11.96	12.11	2.58	2.90	2.19
k_{max}	12.24	12.82	12.69	12.92	13.44	13.35	2.74	2.90	2.80
k_{min}	11.42	11.15	11.07	12.08	11.79	11.78	2.33	2.29	2.19
R	0.82	1.67	1.62	0.84	1.65	1.57	0.41	0.61	0.61
Sensitivity priority	B>C>A			B>C>A			B=C>A		
Preferred combination	$B_3C_2A_4$			$B_3C_2A_4$			$B_2C_4A_1$		

When the shield tunneling passes through the Bahe River, if too small soil pressure is used, the soil pressure is insufficient to resist the soil pressure and water and soil pressure in front of the tunnel face, which can cause the strata in front of the shield tunnel to collapse towards the tunnel face and cause significant surface settlement. Therefore, it is recommended to control the pressure of the soil silo at around 0.17MPa.

After shield tunneling excavation, timely synchronous grouting can effectively control surface settlement and surrounding soil deformation. Excessive grouting pressure may result in the grout not being able to effectively support the surrounding soil, making it difficult to achieve synchronous grouting. Excessive grouting pressure not only causes waste of grout, but also may cause pipe segments to float upwards, resulting in pipe misalignment and even cracking. Considering that the project is underwater and there is significant soil and water pressure, it is recommended to control the grouting pressure at around 0.20MPa.

The gap between the pipe segment and the surrounding soil is the main cause of geological deformation, so it is necessary to determine a reasonable amount of synchronous grouting (i.e. the thickness of the grouting layer) to control geological deformation. A smaller thickness of the grouting layer will not be able to completely fill the gaps and resist the displacement of the soil towards the tunnel direction; A larger thickness of the grouting layer will increase the amount of synchronous grouting and increase construction costs. Therefore, the recommended thickness of the grouting layer is around 0.16m.

5 Conclusion

This article comprehensively uses the orthogonal experimental method and numerical simulation method to establish a fluid structure coupling three-dimensional model, and studies the sensitivity of three factors: soil pressure, grouting pressure, and grouting thickness to the deformation of the underground strata of the electric shield tunneling through the Bahe River. Based on the range analysis of numerical simulation results, the shield tunneling parameters are determined. The following conclusion has been drawn:

(1)The maximum vertical displacement of the stratum generally occurs at the top of the two tunnel arches or the center of the concave settlement groove, and the maximum horizontal displacement generally occurs at the outer arch waist position of the left and right tunnels.When using the maximum surface settlement value, the maximum vertical displacement value of the stratum, and the maximum horizontal displacement value of the stratum as evaluation indicators, the sensitivity order of the three factors is grouting pressure, grouting layer thickness, and soil chamber pressure.

(2) Based on simulation results and construction experience, it has been determined that the control parameters for the excavation of the electric shield tunneling through the Bahe River are around 0.17MPa for the soil chamber pressure, 0.20MPa for grouting pressure, and 0.16m for grouting layer thickness. Priority should be given to controlling changes in synchronous grouting pressure and grouting volume based on surface deformation and convergence of pipe net clearance, and timely optimization and adjustment should be made.

(3)I hope that future readers can conduct a series of analysis supplements on the basis of range analysis, and attempt to use more working conditions in numerical simulation to study geological deformation.

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