Response Law of Shield Tunnel under Water-Rich Sand and Gravel Formation Based on Fluid-Solid Coupling Effect

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Abstract. Taking the water-rich pebble stratum under a subway tunnel as the engineering background, this paper explores the mechanical response characteristics of multi factor changes in shield tunnel construction to the tunnel stratum. Based on numerical simulation and combined with fluid structure coupling effect, the influence law of passive factors (buried depth and head height) on tunnel seepage field, stress field and displacement field are studied. At the same time, the influence of active factors (segment width, equivalent layer thickness and soil bin pressure) on tunnel safety evaluation index is studied combined with orthogonal test. The results show that the pore water pressure around the lining is positively correlated with the buried depth and head height, and the pore water pressure at each position of the outer wall of the lining is: arch waist > arch bottom > arch crown; the surrounding rock stress increases linearly with the buried depth and head height, and is symmetrical along the axial direction of the tunnel, and the stress growth rate of each position is more affected by the head height Large; at a single section, the stratum settlement and horizontal displacement are positively correlated with the head height, and the buried depth has little effect on the horizontal displacement, but the influence range extends to a certain extent; when taking the maximum surface settlement, maximum transverse displacement and maximum segment bending moment as the evaluation indexes, it is analyzed that the segment width and silo pressure are the main effects (significant) Factor, while the thickness of equivalent layer is a general (insignificant) factor.

Keywords: shield tunnel; orthogonal test; numerical analysis; sandy pebble stratum

1 Introduction

Domestic and foreign scholars have conducted extensive research on the response characteristics of strata under different construction parameters when tunneling through rich water-bearing formations. Wang Peiyong et al. [1] simulated the displacement and tensile stress distribution of tunnel roof under different overburden thickness based on

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finite element calculation results, and compared it with current specifications to determine a reasonable overburden thickness, which guided the shield tunnel construction of Chongqing Chaotianmen Liangjiang Tunnel. Kasper and Thomas [2] used numerical simulation methods to study the influence of overburden depth on ground settlement, lining loads, deformation, and tunneling operations during shield tunnel excavation. Cui [3] conducted 1g physical model tests to study the performance of segmented lining in shield tunnels under different earth pressure and external water pressure, and obtained the variations of water pressure and lining stress in highly permeable rich water sand and gravel formations. Wang et al. [4] investigated the relationship between excess pore water pressure in soil and tunnel depth under seepage effects based on the modified Cambridge model, and found that when H/D=1.5, they approximately showed a linear relationship. Lin et al. [5] used the Zhengpantai Tunnel project as an example to explore the effects of the three-step method on crown settlement, sidewall horizontal displacement, excavation face extrusion displacement, and plastic zone range based on a flow-solid coupling three-level orthogonal test, and obtained the optimal combination. Chen [6] compared and analyzed the response characteristics of tunnel roof and underlying reservoir area under different water depths using the flow-solid coupling effect and large finite element software ABAQUS, and found that the overlying water depth had little overall effect on the shape of the water bottom settlement trough, but the maximum settlement of the vault showed a linear increase with water depth. References [7-11] conducted optimal analysis on the thickness, depth, erosion conditions, and shield tunneling parameters of the pipe jacking through the sand and gravel formation of the Yellow River in Lanzhou Metro Line 1, providing guidance for similar engineering construction in the future.

2 Overview of the Project

The mileage marker of the tunnel under the Yellow River section is: YDK13+841 to DK14+245, with a total length of about 404m. The construction section is located in a fault basin, with very complex groundwater recharge conditions. The dynamic factors affecting the groundwater mainly vary with the seasons, and the highest water level reaches 11.66m. The shield tunneling method with slurry balance is used to pass through the 2-10 and 3-11 gravel layers, with a large difference in the size of gravel particles ranging from 20mm to 500mm, and the maximum uniaxial compressive strength reaching 163MPa, the permeability coefficient of the soil layer is 6.37×10-4m/s.

3 Establishment of Numerical Models

3.1 Dimension of Model Establishment

The section of the tunnel passing under the Yellow River has a large variation in the riverbed elevation, with a minimum burial depth of 15m and a maximum burial depth of 30m. The minimum depth of the Yellow River is 0.25m, and the maximum water depth is 6.33m. According to the Lagrangian continuous medium method, based on the FLAC3D software, in order to reduce the simulation result error caused by boundary condition constraints, the model length is taken as 3 to 5 times the outer diameter of the tunnel, and the model height is taken as 2 to 3 times the burial depth of the tunnel. The model dimensions are 60m x 60m x 42m.

3.2 Boundary Conditions and Material Parameters

To ensure the accuracy of tunnel excavation under the simulation of fluid-structure coupling, displacement constraints are set at the front, back, left, right, and bottom boundaries of the model, with impermeable boundaries set at the left, right, and bottom boundaries. The pore water pressure is equal to the hydrostatic pressure and varies with depth in a gradient manner. The tunnel face is set as a permeable boundary, zero water pressure boundary is set on the inner side of the pipe, and the soil water content is set to the saturated water content.

4 Tunnel Construction Active Influencing Factor Simulation Analysis

4.1 Orthogonal Experiment

When studying the effects of different active factors on experiments, in order to ensure the accuracy and feasibility of the experimental results, a three-factor four-level orthogonal experiment is selected. The selection of factor levels should be based on engineering considerations, combined with the experimental results for numerical simulation. The experimental design is shown in Table 1 and Table 2.

Table 1. Factors and levels of safety influences on shield tunneling under the Yellow River orthogonal test

Level	Factors		
	Segment width A (m)	Equivalent layer thickness B (cm)	Earth pressure C (kPa)
1	1.2	10	200
2	1.5	15	300
3	1.8	20	400
4	2.0	25	500

According to the experimental results, the experimental design table can be obtained, as shown in Table 2.

Table 2. Orthogonal experimental design table

Test No.	Level Combi-nation	Test Condition			Sur-face Settle-ment max (mm)	Hori-zontl Dis-place-ment max (mm)	Bending Moment max(kN·m)
		A (m)	B (cm)	C (kPa)			
1	A1B1C1	1.2	10	200	16.15	42.60	8.51
2	A1B2C2	1.2	15	300	13.58	34.43	18.39
3	A1B3C3	1.2	20	400	12.00	29.90	16.10
4	A1B4C4	1.2	25	500	10.82	26.68	19.93
5	A2B1C2	1.5	10	300	11.93	29.31	19.53
6	A2B2C1	1.5	15	200	12.86	32.37	18.84
7	A2B3C4	1.5	20	500	8.65	25.15	31.90
8	A2B4C3	1.5	25	400	9.33	26.86	25.46
9	A3B1C3	1.8	10	400	9.51	21.84	21.99
10	A3B2C4	1.8	15	500	7.92	21.77	34.75
11	A3B3C1	1.8	20	200	10.97	32.18	18.68
12	A3B4C2	1.8	25	300	9.46	25.78	26.55
13	A4B1C4	2.0	10	500	7.82	19.09	35.13
14	A4B2C3	2.0	15	400	7.40	22.58	32.38
15	A4B3C2	2.0	20	300	8.18	26.92	33.86
16	A4B4C1	2.0	25	200	9.35	30.86	26.71

4.2 Analysis of Orthogonal Experiment Results

Using the maximum surface subsidence, maximum horizontal displacement of strata, and maximum bending moment of tunnel segments as the analysis indicators, a method combining range analysis and variance analysis is adopted to explore the influence of the three factors on the safety of shield tunneling under rivers.

Cluster Analysis. Factor analysis should be carried out in the following steps:

(1) Assuming no interaction among factors A, B, and C, calculate the value of K_i, where K_i represents the sum of the corresponding experimental results for any level i in a column.

(2) Calculate the ki value, where ki represents the arithmetic mean of the experimental results obtained when a factor takes level i in any column, $k_i = K_i/s$, where s is the number of occurrences of each level in each column.

(3) Calculate the range R, R=max$\{k_i\}$- min$\{k_i\}$.

(4) Analyze the priority order of factors based on the calculated range. The larger the range R, the greater the impact on the safety of tunneling under the river section for shield tunneling.

5 Conclusion

The goal is to ensure the safe construction of shield tunneling and the following conclusions are mainly drawn:

(1) The pore water pressure around the lining is positively correlated with the burial depth and hydraulic head. With the increase of burial depth, the rate of increase of pore water pressure at the arch waist of the lining is slightly higher than that at the arch bottom and arch top. However, with the increase of hydraulic head, the rate of increase of pore water pressure at various positions outside the lining is basically the same. In addition, the pore water pressure at various positions on the outer wall of the lining decreases from high to low in the following order: arch waist > arch bottom > arch top.

(2) The stress in the surrounding rock increases linearly with burial depth and water head height, and is symmetric along the tunnel axis. The rate of stress increase at the lining arch crown tends to decrease first and then increase with burial depth, while it continues to increase with water head height. The growth rate at the arch bottom and the arch waist increases first and then decreases with burial depth, and tends to decrease first and then increase with increasing water head.

(3) With the increase in tunnel depth and water head, at a single cross-section, the vertical displacement curve of the ground is horizontally symmetrical along the tunnel centerline, presenting a "V" distribution, while the horizontal displacement of the ground presents a "double-arch" distribution. The settlement and horizontal displacement of the strata are positively correlated with the water head height, and the depth of burial has a minor influence on horizontal displacement, but with a certain degree of extension in its range of influence.

(4) When using the maximum surface subsidence, maximum lateral displacement, and maximum bending moment of the shield tunnel segment as evaluation indicators, combined with variance and range analysis methods for mutual verification, it is analyzed that the segment width and Earth pressure are the main influencing (significant) factors, while the equivalent layer thickness is a general (insignificant) factor. For the maximum lateral displacement indicator of the stratum, the Earth pressure has the greatest influence, while the segment width has the greatest impact on the maximum surface subsidence and maximum bending moment of the shield tunnel segment.

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