Experimental Study and Simulation Analysis of Slurry Filling Process of Shield Tail Synchronous Grouting

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1. Introduction

Simultaneous grouting at the end of the shield is an important way to control ground settlement and ground deformation during shield construction. When the shield tail gap is created, it needs to be filled with sufficient slurry through the synchronous grouting pipe in time to achieve the purpose of maintaining the stability of the pipe sheet and controlling the stress release and deformation of the strata. The study of the filling and diffusion process of synchronous slurry injection in the gap is of great significance to the determination of the construction process during the shield construction.

Model tests and numerical simulations are important ways to study the synchronous grouting process. Model tests are designed for real structures and can be used as auxiliary tests for large-scale structural tests, which are reproducible, intuitive, and economical. Many scholars have designed synchronous grouting model tests to analyze the slurry filling and diffusion patterns in the shield tail gap. Kannangara et al. [1] designed the on-site monitoring plan for shield construction with Earth pressure balance in silt strata, and discussed the effects of four parameters, namely shield working face pressure, tail grouting pressure, penetration rate, and pitching angle on the surface settlement during double tunnel excavation. Sharghi et al. [2] studied the effect of various components of the grout material on the mechanical properties through the field test method, and an appropriate amount of two-component grouting and compressive strength was introduced. Besides, they used FLAC3D to complete the numerical simulation of Tabriz Metro Line 2 and analyzed the effect of grouting performance on the ground surface subsidence effects. Zhao et al. [3] designed simultaneous grouting simulation tests for rectangular-like shield tunnels so as to study the effects of grouting pressure, slurry type, and tunnel shape on ground settlement. Liu et al. [4] designed a model to experimentally study the simultaneous grouting process of the URUP...
method of negative and shallow overburden construction, the qualitative relationship between shield tail grouting variables (grouting rate and grouting pressure), and soil response (pressure and settlement) were studied. Ding et al. [5] used a large-scale quasi-rectangular shield comprehensive simulation test platform to simulate the synchronous grouting process and designed different grouting ratios and positions of grouting holes to obtain the pressure distribution and slurry flow under different conditions to determine the optimal quasi-rectangular tunnel best grouting method. Duan et al. [6] conducted a large-scale model test of a quasi-rectangular tunnel for the construction of a rectangular shield tunnel to simulate the synchronous grouting process, measured the grouting pressure, and final grouting shape under different working conditions, and analyzed the circumferential pressure distribution and grouting variation law. Zhao et al. [7] designed a large-scale synchronous grouting simulation experiment to study the behavior of synchronous grouting in a quasi-rectangular shield tunnel and its influence on the surface movement. In addition, they emphasized and discussed the influence of grouting pressure and grouting type on the surface movement through sensitivity analysis. Wu et al. [8] analyzed tunnel settlement and ground settlement by field measurement method using stations as measurement points and verified the rationality of the measurement method by load transfer analysis.

Compared with the model test method, the numerical simulation method is based on the powerful calculation capacity of the computer, which can directly simulate and analyze large and complex structures with fast computing speed and low cost. There are also many scholars who simulate the synchronous grouting process, mainly by building models for simulation analysis and studying the influence of various factors on the synchronous grouting process. Zhang et al. [9] idealized the drainage conditions of the tunnel lining into three conditions: full drainage, partial drainage, and impermeable. Surface settlement and pressure distribution around the tunnel under the influence of lateral Earth pressure coefficient, shear modulus, and other factors were studied. Hu et al. [10] combined the ultra-shallow buried soft soil layer rectangular shield project to predict the pavement settlement based on the kriging spatiotemporal prediction model and verified the applicability of the settlement prediction model by monitoring the settlement data on-site, and analyzed the change law of the pavement settlement during the construction process. Shi et al. [11] calculated the interval of the free displacement field of soil around the pipeline caused by tunnel excavation based on the uniform ground motion model. Nikakhtar et al. [12] conducted numerical simulations based on the simultaneous grouting process, and used FLAC3D software to simulate the gradual hardening of the grout, the solid properties of the grout material, and the effects of grouting pressure on the surface subsidence of the shield segment, and carried out sensitivity analysis. Nagel et al. [13] conducted numerical simulations to analyze the pressure distribution in the gap and the effect on the surface subsidence of the slurry during the gap flow process. Oh et al. [14] carried out a three-dimensional finite element simulation of water-covered sand tunnel excavation, paying attention to the change of the stress and volume of the grouting in the tail gap with time and studied the effect of simultaneous grouting at the shield tail on the surface settlement. Do et al. [15] proposed a three-dimensional finite difference calculation method for double horizontal tunnels to study the influence of performance parameters such as shield face support pressure, shield tail grouting pressure, taper, and shield length on surface settlement and lining. Beghou et al. [16] established a finite difference (FD) model using Itasca FLAC3D and carried out a numerical simulation analysis of the whole process of shield TBM excavation. Kasper et al. [17] established a three-dimensional model to simulate the tunnel construction process considering the relevant components of the shield tunnel, soil layers, and gap grouting materials. Zhang et al. [18] developed a new neural network model to predict tunnel surface settlement and analyzed the effect of each parameter of shield operation on surface settlement. Lyu et al. [19] proposed a new analytical method to calculate the tunnel pressure generated by the surrounding rock of a double tunnel in a laminated stratum, and the applicability of the method was verified by engineering field pressure analysis data. Wu et al. [20] established a model based on ABAQUS to simulate the local leakage of shield tunnel lining and analyzed the effect of groundwater leakage on ground consolidation and tunnel deformation by parametric study. Peinan et al. [21, 22] simulated the synchronous grouting process of a rectangular-like shield with the help of the smooth particle hydrodynamics (SPH) method to analyze the slurry filling characteristics and pressure transfer and distribution under different slurry types and different grouting rate conditions. Liang et al. [23] established a time-space distribution model of the slurry pressure in the void considering the time-varying slurry viscosity to study the influence of the slurry pressure on the mechanical response of the lining segment and verified the slurry pressure data from field monitoring. Fu et al. [24] used Midas/GTS to carry out numerical analysis to study the effect of synchronous grouting on tunnel stability.

In general, the current research on the synchronous grouting process mainly focuses on the influence of factors such as grouting pressure and slurry nature on the surface settlement during synchronous grouting process, but there is a lack of research on the filling and diffusion mechanism of slurry in the gap when the synchronous grouting process is affected by groundwater, and the analysis of the influence of factors such as groundwater pressure and grouting pressure on the filling rate of slurry in the gap is not detailed enough. This study establishes a scaled-down model based on the shield tunnel project of Zhengzhou Metro Line 12 under Longzi Lake for numerical simulation and designs a corresponding synchronous grouting model for testing, verifies the applicability of the simulation through the test results, and then establishes an engineering equal-sized synchronous grouting model for simulation analysis to study the effects of groundwater pressure, grouting pressure and slurry density and viscosity on the interstitial pressure and slurry filling rate of the shield tail gap. The purpose is to provide...
guidance for the optimization of synchronous grouting process and parameter design.

2. Simultaneous Grouting Model Test and Simulation Analysis

2.1. Test Setup. The synchronous grouting model test setup mainly includes a model box, shield shell model, segment model, and grouting system, as shown in Figure 1.

2.1.1. Model Box. Model box size of $1 \times 0.75 \times 0.8$ m, welded with steel, a side with transparent acrylic panels, which is shown in Figure 2.

2.1.2. Shield Shell Model and Segment Model. The shield shell model is made of stainless steel tube, as shown in Figure 3, with an inner diameter of 210 mm and a thickness of 2 mm. The Segment model is shown in Figure 4, made of a transparent acrylic tube, with an outer diameter of 180 mm and a thickness of 10 mm.

2.1.3. Grouting System. A pressure drum was used as the grouting equipment, as shown in Figure 5. The grouting pressure was changed by adjusting the setting value of the regulator during the test. Plastic pipes of 8 mm diameter are installed at $45^\circ$, $135^\circ$, $225^\circ$, and $315^\circ$ on the inner wall of the shield shell to simulate four holes for grouting, and a rubber ring is installed at one end of the shield shell as a slurry stop ring. The grouting pipeline and the stop ring are shown in Figure 6.

2.2. Test Preparation

2.2.1. Fixing of the Segment Model. A circular hole with a diameter of 210 mm was opened on one side of the model box, and the segment model was placed on the acrylic
support on the inner wall of the model box through the circular hole and fixed with adhesive material, which is shown in Figure 7.

2.2.2. Shield Shell Model Assembly. The shield shell model is pushed into the model box by the round hole of the model box and was set on the outside of the pipe sheet model through the gap between the round hole and the pipe sheet model. Shield shell model assembling is shown in Figure 8.

2.2.3. Backfilling Sand Layer. Zhengzhou Metro Line 12 tunnel project under Longzi Lake is constructed by Earth pressure balance shield, and the construction interval mainly crosses the stratum: powder clay, fine sand, and clayey powder layer. Among them, the powder clay layer and the clayey powder layer are weakly permeable layers, and the sand layer is strongly permeable, which may cause loosening of the surrounding soil and soil loss during the shield construction, and may easily cause water gushing and sand gushing. Backfill the model box with fine sand collected from the construction site of Zhengzhou Metro Line 12 to a height of 100 mm above the shield shell model, and sufficient water was injected into the model box to saturate the sand and soil.

2.2.4. Cement Slurry Mixing. The slurry for synchronous injection of shield construction was mixed with silicate cement, a hydraulic cementitious material, and an appropriate amount of water, which has a certain early strength and later strength. The slurry for the synchronous grouting model test was also mixed with P.O42.5 silicate cement and water. Before the test, a sufficient amount of silicate cement and water were taken to mix the slurry in the ratio of 1 : 1, and the slurry was poured into the pressure drum after mixing.
2.3. Experimental Protocol and Process

2.3.1. Experimental Scheme. A single-factor test method was used to study the effects of grouting pressure and groundwater pressure on the slurry filling process. The specific test plan is shown in Table 1.

2.3.2. Test Process

(1) The shield shell model is pulled out at a uniform speed using a traction device, and the traction speed is 30 mm/min. When the shield is being excavated, the slurry is injected from the grouting hole and fills the shield tail gap along the tube sheet in a circular direction, and the time for complete filling of the gap in a circular direction usually does not exceed one minute. Adjust the pressure barrel grouting pressure and open the grouting valve when pulling out the shield shell model at a uniform speed, so that the slurry is injected into the shield tail gap through the grouting pipeline. The infrared camera is used to film the slurry filling process at the same time.

(2) After the synchronous grouting is finished, stop pulling the shield shell model and close the grouting valve, disconnect the grouting pipe, and the synchronous grouting process is finished. Since the slurry has not solidified and the pressure has not yet dissipated, it is necessary to block the grouting pipe when disconnecting the grouting pipe to prevent the slurry from flowing back through the grouting pipe.

(3) When the cement slurry is solidified, the sand layer in the model box is dug up and the distribution of solidified slurry around the tube piece model is observed to analyze the effect of the synchronous grouting model test slurry filling the shield tail gap.

2.4. Analysis of Test Results. The infrared camera was used to film the test process of the synchronous grouting model. After the slurry solidified at the end of the test, the sand layer was excavated to observe the slurry solidified around the pipe piece.

2.4.1. Analysis of Slurry Filling Process. Since the color of cement slurry and sand layer are close to each other in the photographed images, red lines are used to depict the contour of a slurry filling area at different moments and red arrows are used to indicate the direction of slurry flow to analyze the influence of different test conditions on the slurry filling rate.

When the grouting pressure of the upper and lower grouting holes are 0.2 MPa and 0.3 MPa (working condition 5) and the slurry filling rate is taken to be 0%, 50%, 80%, and 100%, the filling diffusion images and the corresponding grouting time are shown in Figure 9. It can be seen that during the synchronous grouting process, the slurry flows...
downward in the gap under the influence of gravity and fills the lower part of the gap first, after which the slurry level rises and the slurry fills the shield tail gap completely at 0.5s.

According to the slurry filling images, the slurry filling rate with time under the action of different grouting pressure and different sand overburden depth is shown in Figures 10 and 11. It can be seen that the slurry filling rate increases with the increase of grouting pressure under the same grouting time; when the grouting pressure is the same, the groundwater pressure gradually increases with the increase of sand overburden depth, and the slurry filling rate then decreases.

2.4.2. Morphology of Slurry-Filled Layer. After excavation of the sand layer at the end of grouting, the cured slurry filling layer formed around the pipe piece model is shown in Figure 12. As can be seen from the figure, during the synchronous grouting process, the shield tail gap is gradually filled completely with slurry, and the slurry wraps the pipe piece model after solidification, forming a filling structure with certain strength.

2.5. Simulation Analysis of Synchronous Grouting

2.5.1. Numerical Model. According to the model test, the corresponding simulation model is established for calculation and analysis. The outer diameter of the 3D model is 210 mm, the inner diameter is 180 mm, the thickness of the shield tail gap is 15 mm, the porous media area of the sand layer is set outside the gap, the thickness of the sand layer is 20 mm, and the negative direction of Y-axis is the direction of gravity.

The pressure inlet boundary is set at 45°, 135°, 225°, and 315° around the circumference of the model gap to simulate the simultaneous grouting of four holes at the end of the shield. The pressure inlet diameter is 8 mm, and the water pressure inlet boundary is set at the outer boundary of the porous medium in relation to the burial depth. Take the slurry density is 2000 kg/m³, the dynamic viscosity is $1.2 \times 10^{-3}$ Pa·s, and the soil porosity is 0.35. The multiphase flow VOF model is used to trace the position of the interface between different phases and analyze the diffusion pattern of the slurry in the shield tail gap at any moment.

2.5.2. Simulation Result Analysis of Synchronous Grouting. The slurry distribution when taking the grouting pressure of upper and lower grouting holes as 0.2 MPa and 0.3 MPa respectively is shown in Figure 14. The red area indicates slurry and the blue area indicates water. It can be seen that at the early stage of grouting, the slurry in the gap spreads up and down along the ring of grouting holes, the boundary between slurry and water is obvious, and the gap width direction is almost completely filled. After 0.2s of grouting, the upper and lower grouting holes are injected with slurry contact, and only part of the gap remains unfilled. The slurry completely fills the shield tail gap at 0.5s.

Simulation analysis of the synchronous grouting model test conditions was carried out separately, and the slurry filling rate versus time curves were obtained under different grouting pressure and different overburden depth conditions, which is shown in Figure 15. It can be seen that the calculated slurry filling rate trends with time are basically consistent with the test results, which proves the applicability of the numerical model.

3. Simulation Analysis of Synchronous Grouting for Metro Line 12

3.1. Numerical Model. Zhengzhou Metro Line 12 tunnel project under Longzi Lake is constructed by Earth pressure balance shield. A three-dimensional model of synchronous grouting was established for calculation and analysis based on engineering data. The outer diameter of the model is
6400 mm, the inner diameter is 6200 mm, and the thickness of the shield tail gap is 100 mm. A porous media area is set outside the gap with a sand layer thickness of 200 mm, and the negative direction of the Y-axis is gravity.

The pressure inlet boundary is set at 45°, 135°, 225°, and 315° around the circumference of the model gap to simulate the simultaneous grouting of four holes at the end of the shield. The pressure inlet diameter is 80 mm, and the water pressure inlet boundary is set at the outer boundary of the porous medium with respect to the burial depth. Take the 30 mm shield tail gap of the shield normal boring 1 min as the slurry filling area, as shown in Figure 16.

3.2. Simulation of Working Conditions. In order to analyze the influence of each factor on the filling efficiency of synchronous grouting slurry, different combinations of experimental parameters were set for synchronous grouting simulation, and the experimental parameter combinations are shown in Table 2.

3.3. Influence of Different Factors on Interstitial Pressure

3.3.1. Influence of Groundwater Pressure. The polar diagram of pressure distribution in the interstitial gap when the slurry fills the shield tail gap under the action of three kinds of groundwater pressure is shown in Figure 17. It can be seen
that in the process of synchronous grouting, the gap pressure distribution in the grout-filled area (near the grouting hole) is relatively uniform, and the pressure value is close to the grouting pressure value. The gap pressure distribution in the unfilled area (far away from the grouting hole) is controlled by the groundwater pressure, and the gap pressure value is positively correlated with the groundwater pressure. At the same location, the greater the groundwater pressure, the greater the gap pressure value. The pressure in the shield tail gap is evenly distributed after the slurry completely fills the gap.

3.3.2. Effect of Grouting Pressure. The gap pressure at different locations under different grouting pressure with time is shown in Figure 18, which shows that during the synchronous grouting process, the gap pressure value in the unfilled area of slurry is consistent with the groundwater pressure; the gap pressure value in the filled area increases with the increase of grouting pressure, and the maximum gap pressure is the grouting pressure. After the slurry completely fills the gap, the pressure in the shield tail gap is uniformly distributed, and the gap pressure distribution under different grouting pressure conditions is also different. During the grouting process, due to the high grouting pressure, it will lead to deformation around the tunnel. With the end of grouting, the grouting pressure decreases and the deformation around the tunnel turns into settlement. Finally, as the slurry solidifies, the settlement slowly stabilizes. The grouting pressure has a great influence on the surrounding settlement [7].

3.3.3. Effect of Slurry Density. Under different slurry density conditions, the polar plot of pressure distribution in the gap when the slurry fills the shield tail gap is shown in Figure 19. It can be seen that in the preinjection period, when the slurry is just injected into the shield tail gap, due to the small amount of slurry in the gap, the gap pressure is mainly soil and water pressure, and the maximum gap pressure is the slurry pressure near the injection hole; due to the flow of slurry in the shield tail gap after injection, for the upward flowing slurry, the work of gravity is negative and the slurry pressure decreases sharply, while for the downward flowing slurry, the work of gravity is positive and the slurry pressure increases sharply; when the slurry enters the gap through the

Figure 14: Contour of slurry distribution at different moments: (a) $t = 0$s, (b) $t = 0.1$s, (c) $t = 0.2$s, and (d) $t = 0.5$s.
Simulation results
Test results
0.0
0.2
0.4
0.6
0.8
1.0 Slurry filling rate (%)  
0.3 0.6 0.9 1.2 1.5
Grouting time (s)

(a)  
(b)  
(c)  
(d)  
(e)

**Figure 15:** Comparison of Simulation and test: (a) condition 1, (b) condition 2, (c) condition 3, (d) condition 4, and (e) condition 5.

![3D model](image)

**Figure 16:** 3D model.

<table>
<thead>
<tr>
<th>Condition no.</th>
<th>Groundwater pressure (MPa)</th>
<th>Upper grouting pressure (MPa)</th>
<th>Lower grouting pressure (MPa)</th>
<th>Slurry viscosity (Pa·s)</th>
<th>Slurry density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.15</td>
<td>0.2</td>
<td>0.3</td>
<td>0.012</td>
<td>2000</td>
</tr>
<tr>
<td>2</td>
<td>0.175</td>
<td>0.2</td>
<td>0.3</td>
<td>0.012</td>
<td>2000</td>
</tr>
<tr>
<td>3</td>
<td>0.20</td>
<td>0.2</td>
<td>0.3</td>
<td>0.012</td>
<td>2000</td>
</tr>
<tr>
<td>4</td>
<td>0.15</td>
<td>0.15</td>
<td>0.3</td>
<td>0.012</td>
<td>2000</td>
</tr>
<tr>
<td>5</td>
<td>0.15</td>
<td>0.25</td>
<td>0.3</td>
<td>0.012</td>
<td>2000</td>
</tr>
<tr>
<td>6</td>
<td>0.15</td>
<td>0.2</td>
<td>0.3</td>
<td>0.012</td>
<td>1500</td>
</tr>
<tr>
<td>7</td>
<td>0.15</td>
<td>0.2</td>
<td>0.3</td>
<td>0.012</td>
<td>2500</td>
</tr>
<tr>
<td>8</td>
<td>0.15</td>
<td>0.2</td>
<td>0.3</td>
<td>0.0012</td>
<td>2000</td>
</tr>
<tr>
<td>9</td>
<td>0.15</td>
<td>0.2</td>
<td>0.3</td>
<td>0.12</td>
<td>2000</td>
</tr>
</tbody>
</table>

**Table 2:** Combination of test parameters.
grouting hole and the slurry gradually contacts with the adjacent grouting holes, the gap pressure also gradually shows uniform distribution, and when the slurry completely fills the gap, the internal gap pressure all reachesthemaximum, and the maximum value is close to the grouting pressure; in general, when the slurry is first injected into the shield tail gap, due to the small yield strength of the slurry, the slurry density has a certain influence on the distribution of the initial value of the slurry pressure, and changing the slurry density has less effect on the gap pressure distribution [25].

3.3.4. Effect of Slurry Viscosity. The polar plots of pressure distribution of slurry-filled shield tail gap under different viscosity conditions are shown in Figure 20. It is not difficult to find that the slurry is just injected into the shield tail gap after diffusion in the gap, the gap pressure is mainly soil and water pressure, and the gap pressure in the area occupied by the slurry shows the uniform distribution, and when the slurry completely fills the gap, the internal gap pressure all reaches the maximum. Overall, changing the slurry viscosity has little effect on the pressure distribution inside the gap.

Figure 17: Interstitial pressure distribution under different groundwater pressure conditions: (a) $t = 0.5$ s, (b) $t = 3$ s, and (c) $t = 20$ s.
Considering the viscosity time variability, with the growth of slurry viscosity will lead to a sharp decrease in slurry pressure [25].

3.4. Influence of Different Factors on Slurry Filling Rate

3.4.1. Influence of Groundwater Pressure. The change of slurry filling rate with grouting time under different groundwater pressure is shown in Figure 21. It takes 4.5s, 8s, and 18s to select the appropriate grouting pressure according to the groundwater pressure to fill the shield tail gap as soon as possible to provide effective support and reduce the settlement.

The time required for the slurry to completely fill the gap under different groundwater pressures was obtained from the line graph, which is shown in Table 3.

3.4.2. Effect of Grouting Pressure. The change of slurry filling rate with grouting time under different grouting pressure is shown in Figure 22; the rate of slurry filling the shield tail gap increases with the increase of grouting pressure. When the grouting pressure is 0.15 MPa, 0.20 MPa, and 0.25 MPa, it takes...
17s, 4.5s, and 1.5s for the slurry to completely fill the shield tail gap respectively. Therefore, it can effectively improve the grouting efficiency and fill the gap as soon as possible to ensure the quality of synchronous grouting.

The time required for the slurry to completely fill the gap under different grouting pressures was obtained according to the line graph, which is shown in Table 4.

3.4.3. Effect of Slurry Density. The slurry filling rate with the change of grouting time under different slurry density conditions is shown in Figure 23. It is obvious that when the slurry density is 1500 kg/m³, 2000 kg/m³, and 2500 kg/m³, it takes 4s, 4.5s, and 5s for the slurry to completely fill the shield tail gap respectively. The slurry density has some influence on the efficiency of the slurry filling the shield tail gap, but the influence is not significant.

The time required for slurry to completely fill the gap under the action of different slurry densities was obtained according to the line graph, which is shown in Table 5.

3.4.4. Effect of Slurry Viscosity. The slurry filling rate with the change of grouting time under different slurry viscosity conditions is shown in Figure 24, which shows that when the slurry

Figure 19: Interstitial pressure distribution under different slurry density conditions: (a) $t = 0.5s$, (b) $t = 3s$, and (c) $t = 20s$. 

---

1500 kg/m³
2000 kg/m³
2500 kg/m³

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1500 kg/m³
2000 kg/m³
2500 kg/m³

---

1500 kg/m³
2000 kg/m³
2500 kg/m³
viscosity is 0.0012 Pa·s, 0.012 Pa·s, and 0.12 Pa·s, it takes 4.3s, 4.5s and 4.6s for the slurry to completely fill the gap respectively. The slurry viscosity has some influence on the efficiency of the slurry filling the shield tail gap, but the influence is not significant. The time required for slurry to completely fill the gap under the action of different slurry viscosities was obtained according to the line graph, which is shown in Table 6.

3.5. Sensitivity Analysis of Factors Influencing Synchronous Grouting at the End of the Shield. Sensitivity analysis is a method to analyze uncertainty. Single-factor influence analysis is used to analyze the degree of influence of factors such as grouting pressure, groundwater pressure, slurry density, and slurry viscosity on the rate of complete filling of the shield tail gap with slurry. The sensitivity coefficient is calculated by dividing the rate of change of the evaluation index by the rate of change of uncertain influence factors to express the sensitivity of the evaluation index to each influence factor, and the calculation formula is:

$$S_{AF} = \frac{\Delta A/A}{\Delta F/F}$$  \hspace{1cm} (1)
Figure 21: Groundwater pressure affects slurry filling effect curve.

Table 3: Time required for the slurry to fill the gap under the action of different groundwater pressure.

<table>
<thead>
<tr>
<th>Groundwater pressure (MPa)</th>
<th>0.15</th>
<th>0.175</th>
<th>0.20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filling gap time (s)</td>
<td>4.5</td>
<td>8</td>
<td>18</td>
</tr>
</tbody>
</table>

Figure 22: Grouting pressure affects slurry filling effect curve.

Table 4: Time required for slurry to fill the gap under the action of different grouting pressure.

<table>
<thead>
<tr>
<th>Grouting pressure (MPa)</th>
<th>0.15</th>
<th>0.20</th>
<th>0.25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filling gap time (s)</td>
<td>17</td>
<td>4.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Figure 23: Slurry density affects slurry filling effect curve.

Table 5: The time required for slurry to fill the gap under the action of different slurry densities.

<table>
<thead>
<tr>
<th>Slurry density (kg/m³)</th>
<th>1500</th>
<th>2000</th>
<th>2500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filling gap time (s)</td>
<td>4</td>
<td>4.5</td>
<td>5</td>
</tr>
</tbody>
</table>

Figure 24: Slurry viscosity affects slurry filling effect curve.

Table 6: The time required for slurry to fill the gap under the action of different slurry viscosities.

<table>
<thead>
<tr>
<th>Slurry viscosity (Pa·s)</th>
<th>0.0012</th>
<th>0.012</th>
<th>0.12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filling gap time (s)</td>
<td>4.3</td>
<td>4.5</td>
<td>4.6</td>
</tr>
</tbody>
</table>
Table 7: Sensitivity coefficient of influence factors.

<table>
<thead>
<tr>
<th>Influence factors</th>
<th>Groundwater pressure</th>
<th>Grouting pressure</th>
<th>Slurry density</th>
<th>Slurry viscosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity coefficient</td>
<td>6.834</td>
<td>-6.889</td>
<td>0.444</td>
<td>0.052</td>
</tr>
</tbody>
</table>

where \( A \) represents the evaluation index, \( \Delta A \) represents the rate of change of the evaluation index, \( F \) represents the influence factor, and \( \Delta F \) represents the rate of change of the influence \( S_{AF} > 0 \) means the evaluation index changes in the same direction as the uncertainty factor, and the larger \( |S_{AF}| \) indicates that the evaluation index is more sensitive to the uncertainty factor.

According to the relationship between the time required for slurry to completely fill the gap and each influencing factor obtained from Table 3–6, the sensitivity coefficient of the time required for slurry to completely fill the gap to each influencing factor is calculated by equation (1). The calculated sensitivity coefficient is shown in Table 7. It can be seen that the degree of influence of each influencing factor on the slurry filling gap is: grouting pressure > groundwater pressure > slurry density > slurry viscosity.

4. Conclusion

Relying on the Zhengzhou Metro Line 12 Shield Tunnel Project under Longzi Lake, the synchronous grouting model test and simulation were conducted respectively to study the influence law of groundwater pressure, grouting pressure, slurry density, viscosity, and other factors on the synchronous grouting slurry filling process at the end of the shield; the results show that:

1. The gap pressure distribution is mainly influenced by the grouting pressure and groundwater pressure, in the synchronous grouting process, the slurry-filled area mainly depends on the grouting pressure, and the pressure in the gap is positively related to the grouting pressure; the gap pressure distribution in the unfilled area is mainly controlled by the groundwater pressure, and the pressure in the gap is positively related to the groundwater pressure. After the slurry completely fills the gap, the overall pressure distribution in the gap at the end of the shield is more uniform.

2. With the increase of groundwater pressure, the rate of slurry filling the shield tail gap gradually decreases, the groundwater pressure increases from 0.15Mpa to 0.20Mpa, and the slurry filling gap time increases from 4.5s to 18s; with the increase of grouting pressure, the rate of slurry filling the shield tail gap increases, the grouting pressure increases from 0.15Mpa to 0.20Mpa, and the slurry filling gap time decreases from 17s to 4.5s. Compared with the grouting pressure and groundwater pressure, the effects of changing slurry density and slurry viscosity on the pressure distribution and slurry filling rate in the gap were smaller. The influence of each factor on the slurry filling rate was obtained by single-factor analysis: grouting pressure > groundwater pressure > slurry density > slurry viscosity.

Data Availability

No data were used to support the study.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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