Research Article

Parameters Optimization of Curtain Grouting Reinforcement Cycle in Yonglian Tunnel and Its Application

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For practical purposes, the curtain grouting method is an effective method to treat geological disasters and can be used to improve the strength and permeability resistance of surrounding rock. Selection of the optimal parameters of grouting reinforcement cycle especially reinforcement cycle thickness is one of the most interesting areas of research in curtain grouting designs. Based on the fluid-structure interaction theory and orthogonal analysis method, the influence of reinforcement cycle thickness, elastic modulus, and permeability on water inflow of tunnel after grouting and stability of surrounding rock was analyzed. As to the water inflow of tunnel after grouting used as performance evaluation index of grouting reinforcement cycle, it can be concluded that the permeability was the most important factor followed by reinforcement cycle thickness and elastic modulus. Furthermore, pore water pressure field, stress field, and plastic zone of surrounding rock were calculated by using COMSOL software under different conditions of reinforcement cycle thickness. It also can be concluded that the optimal thickness of reinforcement cycle and permeability can be adopted as 8 m and 1/100 of the surrounding rock permeability in the curtain grouting reinforcement cycle. The engineering case provides a reference for similar engineering.

1. Introduction

With the rapid development of highways, more and more tunnels are to be constructed in China. Unfavorable geology such as fault and karst which is easy to induce geological disasters is often exposed by excavation during the construction of tunnels. Casualties and economic loss caused by geological disasters are very serious at present [1–3].

For practical purposes, curtain grouting method is an effective method to manage geological disasters and can be used to improve the strength and permeability resistance of surrounding rock [4]. Related to the economy and safety, selection of the optimal parameters of grouting reinforcement cycle especially thickness of reinforcement cycle is one of the most interesting areas of research in curtain grouting designs.

Some studies on the behavior of the selection of the optimal parameters of grouting reinforcement cycle have been conducted with experimental and numerical methods.

Considering stability of surrounding rock, He [5] presented the reasonable parameters of grouting cycle by using the FLAC software. Based on the theoretical calculation and numerical simulation, Li et al. [6] proposed the parameters of grouting cycle of XiangAn subsea tunnel. Zhang et al. [7] analyzed the relationship between hydraulic pressure outside the lining and tunnel drainage. Wang [8] analyzed the influence of reinforcement cycle thickness on stress and displacement of the JiaoZhouWan subsea tunnel, China.

However, few studies have been concerned with the details of the influence of reinforcement cycle thickness on water inflow. To get a better understanding of a key performance index of grouting reinforcement cycle, there is a need to analyze the water inflow of tunnel after grouting.

In this paper, based on the fluid-structure interaction theory [9–13] and orthogonal analysis method, the influence of reinforcement cycle thickness on water inflow of tunnel after grouting and stability of surrounding rock was analyzed. The optimal parameters especially reinforcement cycle

FIGURE 1: Cross section of the tunnel.

FIGURE 2: Geological map of grouting area.

thickness were therefore selected and applied in Yonglian tunnel successfully, which provides a reference for similar engineering.

2. Engineering Situation

Yonglian tunnel with a length of 2500 m was located on expressway from Ji'an City to Lianhua City, in Jiangxi Province, China. Because of complex geological conditions, the tunnel was the key engineering of the expressway.

2.1. Geological Conditions. There were a large number of regional faults and secondary faults with rich water such as fault-2 (see Figure 1) in tunnel. The rock quality designation (RQD) of surrounding rock of tunnel was smaller than 5%.

The geological prospecting (see Table 1) was assessed based on the boreholes information. A proper geological

FIGURE 3: Large-scale inrush of mud and water.

TABLE 1: Parameters of boreholes.

Label	Declination (°)	Dip (°)	Length (m)
L1	−16	−15	36.9
L2	−6	10	35.5
M1	0	0	33
M2	0	7	33.2
R1	17	−17	34.3
R2	7	12	32.9

map of grouting area from ZK91+330 to ZK91+355 was then described in Figure 2.

It can be concluded from Figure 2 that the lithology of grouting area was mainly strong weathered sandstone, strong weathered shale, fault breccia, and fault gouge. Besides, many water inflow points were exposed through boreholes with the maximum velocity of $65 \text{ m}^3/\text{h}$.

2.2. Geological Disasters. From July 2 to August 19, 2012, 8 times inrush of mud and water with large scale occurred in the left tunnel, and the volume of gushing mud and water was more than $50,000 \text{ m}^3$ in total (see Figure 3). A large number of construction machines were damaged during the inrush of mud and water, which hindered the normal construction seriously.

3. Calculation Model

3.1. Brief Introduction to COMSOL Software. Based on the finite element theory, the COMSOL software was designed to describe and simulate various physical phenomena. Based on the COMSOL software, the multiphysical field coupling can be better simulated and the various mathematical models can be used to describe the physical phenomena. In the present paper, porous media flow module and rock and soil mechanics module were used for numerical analysis.

3.2. Calculation Model and Boundary Conditions. According to the actual working conditions of Yonglian tunnel, the calculation model was composed by lining, grouting reinforcement cycle, and surrounding rock. As shown in Figure 4, the sizes of the calculation model, the tunnel, and the chamber section were adopted as $200 \text{ m} \times 180 \text{ m}$, $15.58 \text{ m} \times 12.39 \text{ m}$, and $13.98 \text{ m} \times 10.79 \text{ m}$, respectively. The distances

FIGURE 4: Calculation model.

FIGURE 5: Grid of model.

from the center position of the tunnel to the left boundary, the right boundary, the upper boundary, and the lower boundary of the calculation model were taken as 100 m, 100 m, 110 m, and 70 m, respectively. The model was set for steady state with ignoring the influence of time.

The left and right boundary were set for roller support boundary with $u = 0$. The lower boundary was fixed with $u, v = 0$, and the upper boundary was free. Water was free to permeate outside the lining with $p = 0$. The upper boundary was set for a free surface, and the left boundary, right boundary, and lower boundary were impermeable.

3.3. Basic Assumptions

3.3.1. Seepage Field. The groundwater flow was assumed to follow Darcy's law, and tunnel drainage was assumed to be achieved through seepage upon the lining. The surrounding rock was taken as homogeneous and isotropic medium. Rock mass below the surface of water was assumed to be saturated.

Pore water was in still state before excavation and was in stable seepage state after excavation.

3.3.2. Stress Field. The grouting reinforcement cycle, surrounding rock, and lining were simulated by using the Mohr-Coulomb elastic-plastic constitutive model. The gravity stress field was regarded as initial stress field with ignoring tectonic stress field.

3.4. Grid Generation. The freedom triangular grid with special elaboration was used (see Figure 5). To improve calculation accuracy, the grid around the lining was densified.

The largest and smallest cell sizes were 4 m and 0.015 m, respectively, and the curvature resolution was 0.25. Basic parameters of grid are shown in Table 2.

4. Parameters Optimization of Curtain Grouting Reinforcement Cycle

4.1. Orthogonal Analysis of Influencing Factors. The improvement of the performance of grouting reinforcement cycle mainly shows as the improvement of strength, stiffness, and permeability [14]. Based on the orthogonal analysis method, the influence of reinforcement cycle thickness, elastic modulus, and permeability on the performance of grouting reinforcement cycle was analyzed.

4.1.1. Performance Evaluation Index. According to the actual working conditions of Yonglian tunnel, the parameter of water inflow per linear meter of tunnel after grouting, q , was regarded as the performance evaluation index of grouting reinforcement cycle.

4.1.2. Basic Parameters. According to related specifications [15, 16], the basic parameters of grouting reinforcement cycle, surrounding rock, and lining are shown in Table 3.

4.1.3. Values of Affecting Factors. The reinforcement cycle thickness, elastic modulus, and permeability are the three most important factors. The thickness of d was regarded as a key research object with six levels. The elastic modulus and permeability were characterized by the variation coefficient of M and N with three levels. One obtains

$$\begin{aligned} M &= \frac{E_g}{E_w}, \\ N &= \frac{k_w}{k_g}, \end{aligned} \quad (1)$$

where E_w and E_g are the elastic modulus of surrounding rock and grouting reinforcement cycle, respectively, and k_w and k_g are the permeability of surrounding rock and grouting reinforcement cycle, respectively.

Parameters of reinforcement cycle thickness, elastic modulus, and permeability are shown in Table 4.

4.1.4. Design of Orthogonal Table and Calculation Results. As shown in Table 5, orthogonal table was selected to be the mixed level table $L_{18}(6 \times 3^6)$. The calculation results are listed as in Table 5.

(a) $d = 2$ m (b) $d = 4$ m (c) $d = 6$ m

FIGURE 6: Continued.

FIGURE 6: Pore water pressure field under different conditions of reinforcement cycle thickness.

TABLE 2: Parameters of grid.

Parameters	Values	Parameters	Values
The smallest quality of unit	0.7396	The largest cell size	4
The average quality of unit	0.9726	The smallest cell size	0.015
Triangle unit	15503	Curvature resolution	0.25
Edge unit	699	The largest cell growth velocity	1.2
Endpoint element	26		

TABLE 3: Basic parameters.

Name	Size (m)	Elastic modulus (GPa)	Gravity (KN/m^3)	Poisson's ratio	Internal friction angle ($^\circ$)	Cohesion (MPa)	Permeability (m^2)
The fourth grade surrounding rock	200×180	1.5	18.5	0.40	24	0.13	5.0×10^{-11}
Grouting reinforcement cycle	d	1.5 M	19	0.21	45	0.65	NK_w
Lining	0.8 (thickness)	25	25	0.25	50	1.5	5.0×10^{-13}

FIGURE 7: Variation of pore water pressure.

TABLE 4: Parameters of factors.

Level	d (m)	Factors	
		M	N
1	2	2	20
2	4	5	50
3	6	10	100
4	8	—	—
5	10	—	—
6	12	—	—

4.1.5. Calculation of Range. The average value of performance evaluation index under different levels of factors was calculated as follows:

$$\begin{aligned}
 k_{11} &= \frac{(1340.1 + 996.2 + 699)}{3} = 1011.8, \\
 k_{12} &= (1340.1 + 1136.2 + 609.1 + 311 \\
 &\quad + 500.3 + 273.9) \frac{1}{6} \\
 &= 695.1, \\
 k_{13} &= (1340.1 + 1136.2 + 1013.5 + 922.8 \\
 &\quad + 889.9 + 857.1) \frac{1}{6} \\
 &= 1026.6.
 \end{aligned} \tag{2}$$

The calculation values of $k_{21}, k_{22}, k_{23}, k_{31}, k_{32}, k_{33}, k_{41}, k_{51}$, and k_{61} are shown in Table 5.

The range of performance evaluation index under different factors was calculated as follows:

$$\begin{aligned}
 R_1 &= k_{11} - k_{61} = 1011.8 - 537.4 = 474.4, \\
 R_2 &= k_{12} - k_{31} = 695.1 - 682.1 = 13, \\
 R_3 &= k_{13} - k_{33} = 1026.6 - 403.8 = 622.8.
 \end{aligned} \tag{3}$$

4.1.6. Analysis of Results. Regarding water inflow of tunnel after grouting as performance evaluation index of grouting reinforcement cycle ($R_3 > R_1 > R_2$), the permeability was assumed to be the most important factor followed by reinforcement cycle thickness and elastic modulus.

4.2. Variation Characteristics of Pore Water Pressure Field, Stress Field, and Plastic Zone

4.2.1. Pore Water Pressure Field. The pore water pressure field under the conditions of different reinforcement cycle thickness is shown in Figure 6.

It can be concluded from Figure 6 that the pore water pressure field varies significantly under different conditions of reinforcement cycle thickness, showing the funnel shape around the chamber section. As the thickness of grouting reinforcement cycle increases from 2 m to 10 m, the funnel shape area gradually decreases from 3.6 times to 1 times hole diameter. Figure 7 shows that the pore water pressure outside the grouting reinforcement cycle increases from 0.57 MPa to 1.01 MPa, whereas the pore water pressure of the surrounding rock increases from 1.45 MPa to 1.67 MPa. The pore water pressure outside the lining decreases from 0.21 MPa to 0.14 MPa.

4.2.2. Stress. The stress under different conditions of reinforcement cycle thickness is shown in Figure 8.

(a) $d = 2$ m (b) $d = 4$ m (c) $d = 6$ m

FIGURE 8: Continued.

FIGURE 8: Stress under different conditions of reinforcement cycle thickness.

FIGURE 9: Variation of maximum stress around chamber section.

FIGURE 10: Plastic zone under different conditions of reinforcement cycle thickness.

TABLE 5: Orthogonal table design and calculation results.

Label	Factors			Performance evaluation index of q L/(d·m)
	Grouting reinforcement cycle d	M	N	
1	1 (2)	1 (2)	1 (20)	1340.1
2	1	2 (5)	2 (50)	996.2
3	1	3 (10)	3 (100)	699
4	2 (4)	1	1	1136.2
5	2	2	2	743.9
6	2	3	3	473.5
7	3 (6)	1	2	609.1
8	3	2	3	371.5
9	3	3	1	1013.5
10	4 (8)	1	3	311
11	4	2	1	922.8
12	4	3	2	535.7
13	5 (10)	1	2	500.3
14	5	2	3	293.8
15	5	3	1	889.9
16	6 (12)	1	3	273.9
17	6	2	1	857.1
18	6	3	2	481.2
K_{1j}	1011.8	695.1	1026.6	
k_{2j}	784.5	697.6	644.4	
k_{3j}	664.7	682.1	403.8	
k_{4j}	589.8			
k_{5j}	561.3			
k_{6j}	537.4			
R_j	474.4	13	622.8	

It can be concluded from Figure 8 that the stress field varies significantly under different conditions of reinforcement cycle thickness, showing a butterfly shape around the chamber section. As the thickness of grouting reinforcement cycle increases from 2 m to 10 m, the maximum stress around the chamber section gradually decreases from 11.47 MPa to 8.54 MPa (see Figure 9).

4.2.3. Plastic Zone. The plastic zone under different conditions of reinforcement cycle thickness is shown in Figure 10.

It can be concluded from Figure 10 that the plastic zone varies significantly under different conditions of reinforcement cycle thickness, showing a butterfly shape around the chamber section. As the thickness of grouting reinforcement cycle increases from 2 m to 10 m, the butterfly shape area around the chamber section decreases gradually.

4.2.4. Conclusions. As the thickness of grouting reinforcement cycle increases from 2 m to 10 m, the maximum stress,

pore water pressure, and plastic zone outside the lining all decrease, indicating that the strength, stiffness, and permeability of surrounding rock are improved significantly.

4.3. Parameters Optimization of Curtain Grouting Reinforcement Cycle. As previously described, the water inflow of tunnel after grouting was regarded as the performance evaluation index of grouting reinforcement cycle, and the thickness of reinforcement cycle and permeability have a significant influence on the water inflow. Considering the dual requirements for economy and safety, there is a need to select the minimum safe thickness and permeability of grouting reinforcement cycle.

The curves of water inflow per linear meter of tunnel after grouting are shown in Figure 11.

It can be seen from Figure 11 that the water inflow per linear meter of tunnel is 1757.4 L/(d·m) when the thickness of reinforcement cycle is 0 m, indicating a serious threat to the tunnel safety. According to the curve, under the

FIGURE 11: Curves of water inflow per linear meter after grouting.

FIGURE 12: Design of curtain grouting.

conditions of the same permeability variation coefficient N , the water inflow per linear meter decreases gradually with increasing grouting reinforcement cycle thickness. However, when the grouting reinforcement cycle thickness is more than 8 m, the water inflow is steady approximately. Under the conditions of same reinforcement cycle thickness, the water inflow per linear meter decreases gradually with an increase in permeability variation coefficient N . However, when the permeability variation coefficient N is more than 100, the water inflow is steady approximately.

It can be concluded that the thickness of 8 m and the permeability variation coefficient N of 100 are the optimal parameters of grouting reinforcement cycle.

5. Field Test of Curtain Grouting in Yonglian Tunnel

5.1. Design Scheme of Curtain Grouting. The key parameters of curtain grouting were designed as follows.

- (1) According to the results of numerical simulation, the thickness of reinforcement cycle was adopted as 8 m. Based on field tests, the terminal distance between grouting holes, diffusion radius of grouting were designed to be 8 m, 3.5 m, and 2 m, respectively.
- (2) Because of stress concentration, the grouting holes were densified near the foot arch and arch wall to

FIGURE 13: Construction of curtain grouting.

FIGURE 14: P-Q-t curve during grouting.

strengthen the reinforcement, and 153 grouting holes including 124 curtain grouting holes, 21 vault grouting holes, and 8 supplement grouting holes were designed in total (see Figures 12 and 13).

- (3) The cement-GT grouting material was used in curtain grouting which had the advantages of controllable gel time, high strength, and good permeability resistance performance [17, 18].

5.1.1. P-Q-t Curve during Grouting. Injection pressure and velocity which can reflect the diffusion characteristics of slurry were recorded during grouting.

It can be seen from Figure 14 that the maximum of injection pressure and velocity can reach 4.1 MPa and 83 L/min, respectively.

Fault gouge was reinforced by filling, compaction, and splitting effect of the injected slurry. Initially, the slurry played a compaction role, and the injection pressure needed to increase to overcome the initial stress of the medium. Due to low porosity, the injection velocity was relatively low at this stage. When the injection pressure was enough to overcome the initial stress, the medium was split by slurry with the formation of a large space. Therefore, the injection pressure

FIGURE 15: Monitoring points.

decreased rapidly, whereas the injection velocity increased rapidly.

In a word, the injection pressure and velocity show a wavelike law, indicating that fault gouge was reinforced by filling, compaction, and splitting effect of the injected slurry.

5.2. Examination of Reinforcement Effect. Reinforcement effect for unfavorable geology area was examined by examination holes, P-Q-t curve, surrounding rock deformation monitoring, and excavation.

5.2.1. Examination Holes. According to relevant standards and engineering cases [19, 20], the design of examination holes must be representative and comprehensive. 21 examination holes were then designed to evaluate reinforcement effect. For example, lithology and water inflow exposed by JC-13 hole and JC-16 hole are shown in Table 6.

Note that a lot of mixed solidification bodies of slurry and rock were exposed by examination holes, indicating that the unfavorable geology area was reinforced effectively.

The velocity of water inflow of JC-13 hole and JC-16 hole was $144 \text{ L/d}\cdot\text{m}^{-1}$ and $72 \text{ L/d}\cdot\text{m}^{-1}$, respectively, which were less than that of relevant engineering cases, indicating that the thickness of reinforcement cycle designed by results of numerical simulation is suitable.

5.3. Surrounding Rock Deformation Monitoring. Two monitoring sections were designed at ZK91+333 and ZK91+341 to monitor the vault settlement and peripheral convergence of primary support during the excavation of tunnel, and the monitoring points were arranged as shown in Figure 15. The monitoring results are shown in Figure 16.

Figure 16 shows that the maximum velocity of vault settlement and peripheral convergence is smaller than 2 mm/d and the average velocity is smaller than 0.5 mm/d . The accumulative value is relatively stable. It can be concluded that the self-stability of surrounding rock can be improved greatly by curtain grouting, which can ensure the safety of tunnel construction. In other words, the thickness of reinforcement cycle can be adopted as 8 m.

(a) Vault settlement curve of ZK91+333

(b) Peripheral convergence curve of ZK91+333

(c) Vault settlement curve of ZK91+341

(d) Peripheral convergence curve of ZK91+341

FIGURE 16: Monitoring data.

5.4. Slurry Veins Exposed by Excavation. As shown in Figure 17, two representative regions are selected to illustrate the distribution of slurry veins. Fault medium is tightly combined with consolidation body of slurry.

The sizes of slurry veins are shown in Table 7. There are 16 slurry veins including primary and secondary veins in two regions with the maximum width of 460 mm.

It can be concluded from Figure 17 and Table 7 that the strength of rock was improved significantly by curtain grouting, indicating the reliable reinforcement cycle thickness of 8 m.

6. Conclusions

- (1) Regarding water inflow of tunnel after grouting as performance evaluation index of grouting reinforcement cycle, it was found that permeability was the

most important factor followed by reinforcement cycle thickness and elastic modulus.

- (2) Pore water pressure field showed the funnel shape, and the stress field and plastic zone showed the butterfly shape around the chamber section under the conditions of different reinforcement cycle thickness. With the increase of thickness, the pore water pressure upon lining, stress, and plastic zone decreased with different levels.
- (3) According to the results of numerical simulation, the thickness of reinforcement cycle and permeability were, respectively, selected to be 8 m and 1/100 of the surrounding rock permeability as the optimal parameters of curtain grouting reinforcement cycle. After application in Yonglian tunnel, it was proved to be effective, reliable, and suitable by means of

TABLE 6: Lithology and water inflow exposed by JC-13 and JC-16.

Label	Lithology	Velocity of water inflow ($L/d \cdot m^{-1}$)
JC-13	3 m–6 m: solidification body of slurry; 7 m–16 m: mixed solidification body of slurry and fault gouge; 17 m–25 m: mixed solidification body of slurry and fault breccia; 26 m–31 m: mixed solidification body of slurry and fault gouge.	144
JC-16	3 m–9 m: mixed solidification body of slurry and fault gouge; 10 m–21 m: mixed solidification body of slurry and fault breccia; 22 m–31 m: mixed solidification body of slurry and fault gouge; 32 m–35 m: solidification body of slurry.	72

FIGURE 17: Slurry veins exposed by excavation.

TABLE 7: Sizes of slurry veins.

Region	Label	Width (mm)	Classes
1	Vein-1	13	Secondary
	Vein-2	122	Primary
	Vein-3	9	Secondary
	Vein-4	11	Secondary
	Vein-5	460	Primary
	Vein-6	14	Secondary
	Vein-7	27	Secondary
	Vein-8	12	Secondary
2	Vein-1	8	Secondary
	Vein-2	9	Secondary
	Vein-3	17	Secondary
	Vein-4	33	Secondary
	Vein-5	62	Primary
	Vein-6	26	Secondary
	Vein-7	15	Secondary
	Vein-8	23	Secondary

examination holes, P - Q - t curve, surrounding rock deformation monitoring, and excavation, providing a reference for similar engineering to some extent.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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