Study of the Thickness of Curtain Grouting Ring for the lifecycle of Tunnel in Water-rich Fault Fracture Zone

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Abstract. Junchang Tunnel passes through fault fracture zone where joints and fracture developed, the water-rich zone is wide and the geological condition is extremely complex, which is likely to induce the water gushing and mud gushing. Based on the project, the proper thickness of curtain grouting ring for the lifecycle of tunnel in water-rich fault fracture zone is analyzed, and the main conclusions are as follows: (1) Comprehensive advance geological forecast including ultra-high density resistance method, land sonar method, transient electromagnetic method and drilling method are adopted to achieve good prediction results in the fault fracture zone of DK7+812 to DK7+862; (2) The full-face curtain grouting method can effectively reduce the formation deformation caused by tunnel excavation in the tunnel construction in water-rich fault fracture zone, and the effect of water plugging is great; (3) According to the formula of thick wall tube, the experience of grouting and water plugging in existing tunnels, and the comparison of finite element method, the thickness of curtain grouting ring should be greater than 5m to meet the safety requirements. Considering the safety requirements and the reduction of curtain grouting ring in the operation period, the thickness of curtain grouting ring needs to be increased to 7m.

1. Introduction

Against the backdrop of the Western Development in China and the expansion of transportation networks, more highway and railway tunnels inevitably have to pass across the water-rich fault fracture zones [1–3] with poor self-stability, high water pressure, and large water volume. This kind of zone is difficult to block, and the tunnel lining structure is often cracked with water and mud gushing, even leading to landslide disasters [4–6], thereby causing a huge threat for tunnel construction and operation. In recent years, domestic and foreign scholars have been carrying out research on the tunnels in the water-rich layer, mainly focusing on value rationalization and stability analysis of grouting reinforcement ring parameters of the tunnel curtain [1] [2], prevention and treatment of water and mud gushing during tunnel construction [3–6], key techniques of construction in unfavorable geological sections [8] [9], and assumption of external water pressure value of the rich-water lining [9–12]. The research has played an active role in the aspect of tunnel construction.
However, the current research focuses mainly on the stability analysis during tunnel construction, but less on geological prediction before construction and lining safety analysis during life-cycle operation of the water-rich fault fracture zone. For example, in the early stage of tunnel construction, it is often found that the geological conditions are inconsistent with the proven ones, resulting in construction difficulties; during tunnel operation, the curtain grouting ring gradually fails, and the external water pressure behind the lining structure increases, causing lining crack and water leakage. Therefore, it is necessary to conduct an in-depth study on the life-cycle stability and safety of the tunnel curtain grouting. In view of this, this paper takes on the Baomao Expressway Junchang Tunnel Project as the case to study the stability of lining curtain grouting before, during and after tunnel construction based on comprehensive advanced geological prediction and numerical calculation. This study meets the reasonable value of life-cycle curtain grouting, and is expected to provide reference for the design, construction and operation of tunnels in the water-rich fault fracture zone.

2. Overview of tunnel engineering

The Junchang Tunnel from Cenxi to Shuiwen section of Baotou-Maoming Expressway is located between the Caledonian fold group (consisting of Fuqing syncline, Baishidong syncline and Tangdong syncline) and Shuiwen syncline during Yanshan period. The Rongxian-Cenxi fault and Dalong-Shuiwen fault pass through the northeast and southeast of the tunnel, respectively. The tunnel is a separate small clear-distance tunnel. The left line is 4270m long, while the right line is 4288m long, and the left and right tunnels are 17m apart. The water-rich soft layer of the Junchang tunnel is about 150m long. The survey data reveals that it is located in the tectonic development area with relatively developed rock joints and fractures, relatively broken local rock mass and high groundwater level. In addition, the tunnel passes through the residential area of Shanxin Village, posing great difficulty for construction.

3. Comprehensive advanced geological forecast

The Junchang Tunnel was constructed to the weak water-rich stratum in March 2013, but failed to achieve any footage in the face for two and a half years until August 2015, witnessing the occurrence of three large-scale water and mud disasters with the maximum water inflow of 1200 m³/h and the maximum mud volume of 2900 m³. Water and mush gushing caused deformation and cracking of the initial branch and partial cracks of the second lining.

![Figure 1. Water gushing and mud gushing in Junchang Tunnel](image)

Due to the multi-solution of geophysical exploration, a single geological prediction method cannot fully reflect the actual formation. Therefore, after the occurrence of a sudden water disaster in the Junchang Tunnel, the ultra-high-density resistivity method, terrestrial sonar method, transient electromagnetic method and drilling method are used to conduct comprehensive advanced geological prediction analysis of the rich-water weak layer so as to find out the geological and hydrogeological conditions of the unfavorable geological section.
**Table 1. Synthetic advance geology forecast results in water-rich fault fracture zone**

| Forecast method                  | Function                                                                 | Conclusion                                                                 |
|----------------------------------|--------------------------------------------------------------------------|---------------------------------------------------------------------------|
| High density resistivity method   | Proving detailed geological structure information and distribution of groundwater resources | DK7+814 and DK7+960 are the lithostatigraphic boundary of left line tunnel. DK7+814~ DK7+960 are the water-bearing fault belt. CK7+950 is the lithostatigraphic boundary of right line tunnel. CK7+838~CK7+950 water-bearing fault belt. |
| Land-sonar method                | Exploration of cavity, Flow channel and fault distribution location in rock Layer | DK7+850~DK8+040 of left line and CK7+840~CK8+020 of right line are fault fracture zone, the joints and crack development, wide water-rich. |
| Transient electromagnetic method | Prove hydrogeology such as aquifer geology, Hydraulic passage, Deep irregular water body, et.al | 30~50m in front of the working face of the left tunnel, there may be a large crushing zone on the left side, and a large volume of water on the right side of the left tunnel. |
| Drilling method                  | Explore the formation lithology, Rock strength and water content in front of tunnel working face | The tunnel working face is mainly medium-weathered migmatite with grey-brown color, developed joints and fissures, fragmentary structure, fragmented rock mass and hard rock. |

**Table 2. Verification of actual excavation in water-rich fault fracture zone**

| Mileage                           | Synthetic advance geology forecast                                      | Verification of actual excavation                                                                                  |
|-----------------------------------|------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------|
| DK7+812~DK7+815                   | Medium weathered migmatite, Joints and fissures are well-developed, Surrounding rock is relatively fragmented, Presenting massive structure. | The weathered migmatite is mainly characterized by well-developed joints and fissures, mostly in a closed state, presenting massive structure, wet rock mass (local dripping effluent), hard rock and poor self-stabilization ability. Strong weathered migmatite is dominant, joints and fissures are developed, yellowish brown sandy clay is filled and cemented, presenting fragmentary structure, hard rock, seepage in many places, poor self-stabilization ability. |
| DK7+815~DK7+828.8                 | Strongly weathered migmatite, Joints and fissures are well-developed, Surrounding rock is partially fragmented, Presenting fragmentary structure, Large water content. | Strong weathered migmatite is dominant, joints and fissures are well-developed, presenting fragmentary structure. Grouting veins are found in DK7+839. The predicted results are basically consistent with the fault fracture zone. |
| DK7+828.8~DK7+846                 | Strongly weathered migmatite, Joints and fissures are well-developed, Presenting fragmentary structure, Large water content. There is a large fault near DK7+839 with an inclination of about 69 degrees and inclination to the direction of import. | Totally weathered migmatite is dominant, presenting fragmentation-loose structure, seepage in many places, no self-stabilization ability. A large area of grouting veins are found in the arch, agree with the predicted results. There is a large wave of water in the right arch waist, and the waer body is turbid, extremely unfavorable geological conditions and large water inflow. |
| DK7+846~DK7+862                   | Totally weathered migmatite, Joints and fissures are well-developed, Surrounding rock is extremely fragmented, Presenting loose structure, located in the water-rich permeability zone. There is a large fault near DK7+847 with a dip angle of 90 degrees. | |

It can be seen from Table 1 to Table 2 that the water-rich soft layer of the Junchang Tunnel is dominated by fully weathered granite with fractured rock mass, developed fractures, multiple well-connected water guiding channels, large water pressure, complex and varied geological conditions. The comprehensive advanced geological prediction method is used to provide a basis for the full-section curtain grouting method in the water-rich fault fracture zone, and has achieved good results in practice.
4. Fluid-structure coupling calculation during tunnel construction

This section uses midas GTS NX to establish a two-dimensional fluid-structure coupling analysis model to analyze the effect of groundwater in the water-rich stratum on the stability of surrounding rock of the tunnel. The calculation satisfies the following basic assumptions: (1) The surrounding rock of the tunnel is made of a continuous, homogeneous, and isotropic material; (2) The water flow in the surrounding rock is small and can satisfies Darcy's law; (3) The groundwater level at the boundary of the model is constant. The stratum and curtain grouting reinforcement circle adopts the Mohr-Coulomb constitutive model commonly used in geotechnical engineering, and is simulated by plane strain element. Its lining structure adopts elastic constitutive model, the primary lining adopts beam element simulation, and the secondary lining adopts plane element simulation.

The mapping grid is used to divide the model into 4728 units and 4624 nodes. The tunnel calculation model is shown in figure 2 and figure 3. The model size is set to be 150m (width) × 108m (height), while the depth of tunnel is 50 m. The horizontal constraint is applied to the left and right sides of the model and the vertical constraint is applied to the bottom, while the top is the free boundary. In order to simulate the seepage field characteristics of the tunnel under water-rich conditions, the hydrostatic pressure boundary is set around the model boundary, with the water pressure increasing linearly with depth.

![Figure 2. The calculation model of tunnel](image_url)

According to Code for Design of Road Tunnel (JTG D70-2004), geological survey reports and related engineering experience, this paper sets the physical and mechanical parameters of the surrounding rock and supporting structure of the tunnel, as shown in Table 3.
Table 3. Mechanics parameter of model

| Material              | Unit weight (kN·m⁻³) | Elastic modulus (GPa) | Poisson ratio | Porosity | Cohesive forces (MPa) | The angle of internal friction(°) |
|-----------------------|----------------------|-----------------------|---------------|----------|-----------------------|----------------------------------|
| Totally weathered rock| 19.5                 | 0.02                  | 0.36          | 0.43     | 20                    | 20                               |
| Slightly weathered rock| 21                  | 1.3                   | 0.3           | 0.3      | 100                   | 25                               |
| Curtain grouting ring | 22                   | 1                     | 0.35          | 0.36     | 150                   | 27                               |
| Shotcrete             | 25                   | 28                    | 0.2           | -        | -                     | -                                |
| Secondary lining      | 25                   | 33.5                  | 0.2           | -        | -                     | -                                |

During the analysis process, the curtain grouting reinforcement ring mainly bears the external hydrostatic pressure. According to the actual measurement data of the Junchang Tunnel, the allowable compressive strength of curtain grouting reinforcement ring is 2.5 MPa and the maximum hydrostatic pressure is 1.0 MPa. The equivalent diameter of tunnel excavation is 12.0m. According to the fourth strength theory of thick-walled cylinder formula, the required curtain thickness is calculated to be 4.8m. Based on the experience of tunnel grouting reinforcement and water blocking construction [5], this section sets the reference thickness of curtain grouting to be 5m. Based on this, it is determined that the numerical simulation schemes are all full-section advanced curtain grouting. A total of 8 schemes are used so as to determine the optimal curtain grouting thickness. The calculation results of the full-section curtain grouting reinforcement using the finite element model are shown in Table 4.

Table 4. Comparison of numerical results of full-section curtain grouting ring

| Analysis case | Crown settlement (mm) | Ground settlement (mm) | Bottom uplift (mm) | Water inflow of working face (m³·h) |
|---------------|------------------------|------------------------|--------------------|-----------------------------------|
| 1(no grouting)| 55.35                  | 26.42                  | 43.89              | 14.71                             |
| 2(1m grouting)| 42.66                  | 21.09                  | 46.41              | 9.60                              |
| 3(2m grouting)| 31.68                  | 16.06                  | 40.67              | 7.46                              |
| 4(3m grouting)| 24.83                  | 12.76                  | 31.43              | 6.20                              |
| 5(4m grouting)| 20.81                  | 10.65                  | 24.88              | 5.38                              |
| 6(5m grouting)| 17.95                  | 9.16                   | 20.67              | 4.78                              |
| 7(6m grouting)| 15.88                  | 8.07                   | 17.97              | 4.36                              |
| 8(7m grouting)| 14.33                  | 7.25                   | 15.97              | 3.99                              |

Figure 4 and Figure 5 are the comparison of case1 and case6. The calculation results show that:

1. The full-weathered granite is treated using full-section advanced curtain grouting method, thus achieving relatively satisfactory water blocking and reinforcement effects. As the curtain thickness increases, the tunnel water inflow gradually decreases. When the curtain grouting reinforcement reaches 5m+ thick, the tunnel water inflow can be controlled within 5m³/h, thereby effectively reducing the risk of water and mud gushing during tunnel construction.

2. The full-section curtain grouting method can effectively reduce the ground deformation caused by tunnel excavation. When the curtain grouting thickness reaches 5m, the vault settlement and surface subsidence are only 32.4% and 34.7% of that under non-grouted situation, respectively.

3. From the main stress distribution cloud diagram, it can be seen that the bottom lining may crack when it is not grouted. But when the curtain grouting thickness reaches 5m, the lining tensile stress value reaches 1.39MPa<1.43MPa, at which point the lining structure is basically safe.

Based on guideposts of surrounding rock deformation, water inflow, and lining stress during construction, it can be judged using the thick-walled formula, experience of existing tunnel engineering grouting reinforcement and water blocking construction and finite element comparison that the 5m-thick full-section curtain grouting for reinforcement in the Junchang Tunnel section can meet the structural stability requirements.
Based on the above analysis and actual construction, the 5m-thick full-section curtain grouting can meet the safety requirements during construction. The Junchang Tunnel was successfully completed on October 18, 2016 and was officially opened to traffic on January 5, 2017. However, for more than two years of operation, there have been problems such as lining cracks, water seepage, and water gushing in different sections of the water-rich fault fracture zone. The main reasons include: 1) The lining is thicker than 50cm, and the construction joints and uncompacted vibration occurred during construction lead to water seepage; 2) Under the joint influence of hydrodynamic pressure and overload vehicle disturbance, the water-repellent and bearing capacities of the curtain grouting layer are gradually reduced, leading to greater water pressure on the lining, thereby resulting in the occurrence and development of lining cracks and water seepage.

Therefore, it is necessary to consider the failure possibility of curtain grouting reinforcement ring during operation. In addition, it is worth analyzing the decrease of elastic modulus, cohesion force, internal friction angle of the reinforcement ring layer, the increase of permeability coefficient, the increase of water pressure, the uneven layer settlement, the crack of secondary lining, water leakage and water gushing.

5.1 Determination of external water pressure of lining during operation
Before tunnel excavation, the water pressure at each point of the surrounding rock increases linearly with depth. After excavation, the contour is related to the drainage rate of the tunnel lining structure. The extreme working conditions are drainage rate=0% (impermeable, figure6(a)) and drainage rate=100% (water permeable, figure6(b)). Based on the head analysis under the above two working conditions, it can be seen that: (1) 0% drainage rate of the lining structure is equivalent to the adoption of full sealing waterproof measures. After the seepage field of the surrounding rock becomes stable, the pore water pressure at each point of the surrounding rock is basically equal to that of the initial seepage field, and the head height behind the lining structure is almost equal to the initial head height. (2) When the drainage rate of the lining structure is 100%, the pore water pressure is distributed in the shape of the precipitation funnel along the outer contour of the left and right tunnels. This is mainly
because the water in the water-rich fault continues to leak into the face after excavation, leading to smaller pore water pressure near the tunnel face. In addition, the head value on the model boundary is not affected because the head boundary is applied around the model. In the fluid-structure coupling analysis model during operation, the head setting is analyzed under the 100% drainage rate condition so as to characterize the safety of the tunnel lining structure under the most unfavorable condition.

Figure 6. Pore water pressure contour of surrounding rock under different drainage rate after tunnel excavation

5.2 Analysis of fluid-structure coupling calculation results during tunnel operation

Based on the two-dimensional fluid-structure coupling analysis model established in Chapter 4 and the head determination method of the surrounding rock nodes described in Section 4.1, this paper sets the calculation conditions under different failure degrees of reinforcement rings, as shown in Table 5.

Table 5. Failure reduction parameter of curtain grouting ring

| Analysis case | Parameter reduction | Unit weight (kN·m⁻³) | Elastic modulus (GPa) | Cohesive forces (MPa) | The angle of internal friction(°) |
|---------------|---------------------|-----------------------|-----------------------|-----------------------|----------------------------------|
| 1             | 90%                 | 21.8                  | 0.92                  | 137                   | 26.3                             |
| 2             | 80%                 | 21.6                  | 0.84                  | 124                   | 25.6                             |
| 3             | 70%                 | 21.4                  | 0.76                  | 111                   | 24.9                             |
| 4             | 60%                 | 21.2                  | 0.68                  | 98                    | 24.2                             |
| 5             | 50%                 | 21.0                  | 0.60                  | 85                    | 23.5                             |

Figure 7. Deformation of 5m curtain grouting ring
Figure 8. Deformation of 7m curtain grouting ring
Figure 9. Principal stress contour of 5m curtain grouting ring in case 1
Figure 10. Principal stress contour of 5m curtain grouting ring in case 3
It can be seen from Figure 7 to Figure 12 that:

When the thickness of the full-section grouting reinforcement ring reaches 5m and the parameter is reduced to 90%, the curtain grouting reinforcement ring reaches its critical compressive strength of 2.5MPa; when the parameter is reduced to 50%, the maximum compressive stress value is 3.23 MPa > 2.5 MPa, leading to higher failure possibility and further lining problems.

When the thickness of the full-section grouting reinforcement ring is increased to 7m and the parameters are reduced to 50%, the corresponding grouting ring stress value is 2.35MPa, still less than the compressive strength value. It can be seen that the increase of the curtain grouting ring thickness can ensure its safety during operation in consideration of the possible material failures.

In summary, 5m-thick full-section curtain grouting can meet the requirements of construction. However, from the perspective of long-term operation, as the grouting effect gradually weakens and the layer penetration increases, there may be confined groundwater after lining, which will have a negative influence on the structure. Therefore, it is feasible to adopt 7m-thick curtain grouting ring, which can effectively ensure the normal working condition of the curtain grouting ring and reduce the possibility of problem occurrence, thereby ensuring the safe operation of the tunnel and greatly reducing the operating expenses.

6. Conclusion and suggestions

Based on the practice of Junchang Tunnel and the fluid-structure coupling calculation model, this paper analyzes the impact of the thickness of the curtain grouting reinforcement ring on the structural safety of the tunnel. The main conclusions are as follows:

1) The comprehensive advanced geological prediction method combining ultra-high density electric resistance method, terrestrial sonar method, transient electromagnetic method and drilling method can accurately predict the geological conditions of Junchang Tunnel and provide a basis for the construction of curtain grouting construction section. Therefore, it can be applied in similar engineering practices.

2) Full-section curtain grouting method can effectively reduce the layer deformation caused by tunnel construction. When the thickness of curtain grouting is 5m, the crown settlement and surface subsidence are only 35.5% and 39.5% of that under the non-grouted situation. Based on the thick-walled cylinder formula, the experience of grouting reinforcement and water blocking construction of existing tunnel projects, and finite element comparison, it can be concluded that the 5m-thick full-section curtain grouting reinforcement can meet the structural stability requirements during tunnel construction. This is basically consistent with the existing research results.

3) During tunnel operation, when the full-section grouting reinforcement ring of the tunnel is 5m thick and the parameters are reduced to 90%, the failure probability of the curtain grouting reinforcement ring significantly increases, leading to shorter service life of the tunnel. When the thickness of the full-section grouting reinforcement ring is increased to 7m and the parameters are reduced to 50%, the safety of tunnel operation can be effectively guaranteed. It can be seen that for the
operation period, the increase of curtain grouting ring thickness can ensure the safety of the tunnel project throughout its life-cycle in consideration of the gradual failure of the grouting curtain.

(4) With the whole life-cycle of the tunnel taken into consideration, the 7m-thick curtain grouting ring is obviously better than the 5m-thick one, as it can more effectively guarantee its normal operation. However, it should be noted that the control from a single index of increasing the curtain grouting thickness has certain limitations. Further research is needed to consider the comprehensive influence of other factors so as to propose corresponding countermeasures.

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