Optimization Of Curtain Grouting Range for Water-Rich Fault Tunnel

Shuai Wang¹, Hongbin Zhang¹, Shuai Ma¹, Jinqi Li, Wenbin Xie, Gao Liu¹, 2, *

¹School of Civil Engineering and Mechanics, Lanzhou University, Gansu Lanzhou, China
²Key Laboratory of Mechanics on Disaster and Environment in Western China of Ministry of Education, Lanzhou University, Gansu Lanzhou, China

*Corresponding author: liugaoef@lzu.edu.cn

Abstract. When the tunnel is excavated through the water-rich fault, it is easy to cause the problems of water surge and the instability of the face of the tunnel. The advanced curtain grouting can effectively improve the rock mass quality and water permeability of the fault broken zone, and ensure the safety of the construction. In view of this, MADIS-GTS finite element software is used to establish dynamic excavation models under the conditions of no curtain grouting and curtain grouting. The deformation and water seepage characteristics of the palm surface were compared and analysed to determine the fortification length, optimal grouting thickness and optimal grouting length of the curtain grouting before the fault. The results show that: (1) The timing of the connection between rock mass and fault plastic zone in front of the palm head is roughly the same as the timing of the deformation of the palm head face and the surge of seepage velocity. When the palm head face is about 0.5 times the tunnel diameter from the fault plane, the fortifications length of the curtain grouting should also be 0.5 times the tunnel diameter. (2) The increase of grouting length and thickness will reduce the risk of instability of the palm face. When the grouting length exceeds 12m and the grouting thickness exceeds 3m, the influence on the palm face is not obvious. The research results can provide reference for the curtain grouting design of tunnel through fault in the future.

Keywords: Water-rich fault, curtain grouting, fluid-structure coupling, deformation of heading face.

1. Introduction

Water and mud inrush are common disasters in the construction of tunnel through fault. At present, the prevention and control measures for water and mud inrush in tunnels mainly abide by the two principles of "mainly drainage" and "mainly plugging" [1]. For tunnels with different degrees of water and mud inrush, advanced pipe shed, radial grouting, drainage tunnel, curtain grouting and other treatment measures can be adopted [2]. Among them, curtain grouting method is widely used in water-rich fault zone to prevent outburst treatment, and the control effect is good. ZHAO et al. [3] determined the parameters of full-section curtain grouting through field test, completed the grouting
design through the fault, and achieved certain application in practical engineering. Through numerical simulation, WANG et al. [4] monitored the maximum seepage velocity of tunnel face with surrounding curtain grouting, and obtained the optimal thickness and grouting length of curtain grouting reinforcement ring. ZHANG [5] determined the initial fortification position of the supporting structure under different fault dip angles by analyzing the displacement changes of the roof when the tunnel passed through the fault. WANG et al. [6] used numerical calculation to compare and analyze five grouting ranges, including non-grouting excavation, half-section curtain grouting excavation and full-section curtain grouting, and selected the grouting range in the most suitable working condition. ZHANG [8] and FU et al. [9] respectively revealed the influence of curtain grouting on the seepage field and displacement field in surrounding rock through similar model test and numerical calculation model.

The above research has certain guiding significance for the prevention and control of water and mud inrush in tunnel through fault. However, most researches on curtain grouting only consider the selection of grouting thickness and grouting length. The fortification length of curtain grouting in front of the fault is rarely considered. In this paper, based on the mechanism of water and mud inrush in the fault fracture zone, relying on a diversion tunnel as the background, by analyzing the deformation and water seepage characteristics of the face of the tunnel, taking the practicability and safety of the project, the selection of grouting parameters such as the fortification length, grouting length and grouting thickness of the curtain grouting in front of the fault are determined. In the hope of providing some help for other similar projects.

2. Project Overview

A water diversion tunnel is a long-distance water diversion project, with diverse landforms and complex geological structures. The tunnel in the study area has a starting and ending course of ZK2 +000 ~ ZK2 +700 and a length of 700m. Pile No. ZK3+335 developed fault F1, the fault strike was almost perpendicular to the tunnel axis, the dip Angle was 85°, and the fault bandwidth was about 20m. The rock mass in the fault zone is broken, and the physical and mechanical properties are poor. The surrounding rock grade is V. The lithology of the upper and footwall of the fault is mainly composed of Cretaceous sandstone and conglomerate. The integrity of surrounding rock is poor, and the surrounding rock grade is IV. The buried depth of the tunnel is relatively large, about 495 ~ 750m. According to the geophysical exploration and drilling data, the depth of groundwater at the fault is about 50m, and the groundwater is relatively enriched, so there may be problems of water burst and gushing. TBM method is proposed to be used in the construction of the tunnel section where the fault is located. The excavation radius is 2.72m, and the supporting segments are C50 fiber concrete precast segments with a thickness of 32cm. In the range of 270° of the lateral arch and invert arch of the tunnel, the back of the segment is backfilled with d=5 ~ 10mm soya gravel with a thickness of 5 ~ 38cm; in the range of 90° of the bottom arch, the back of the segment is backfilled with M15 cement mortar with a thickness of 5cm. The whole section of the tunnel is consolidated grouting with φ32 hollow grouting bolts. The ring spacing is 1.6m, each ring has 8 holes, and the length of the bolts is 3.0m. In the fault affected area, the curtain grouting around the tunnel is used to reinforce the water-rich area in advance.

3. Numerical simulation study

3.1. Calculation model

According to the above engineering conditions, the fracture zone of the F1 fault has developed fissures, low rock strength and strong water permeability. The flow of groundwater in the pores of the fault fracture zone basically conforms to Darcy's law, so the finite element software MADIS-GTS was used to establish the fluid-structure coupling model. In order to eliminate the influence of boundary conditions on the calculation results, the spatial size of the three-dimensional calculation model was determined to be 100m×100m×60m (Fig.1), that is, the longitudinal boundary. The transverse
boundary was 5 times the diameter of the excavation tunnel, and the axial boundary was 1 time the width of the fault zone.

Figure 1: Model overview diagram

3.2. Calculation Parameters
It is assumed that the rock mass involved in this model and the rock mass reinforced by grouting are homogeneous and isotropic. Based on this assumption, the Mohr-Coulomb constitutive model is adopted for rock mass elements. For the primary lining and the secondary lining, the concrete material and the metal material involved adopt the elastic constitutive model. According to the field rock test and Code for Design of Concrete Structures, the calculation parameters of the model are shown in Table 1 below.

Table 1: Calculation model parameters

| category                | γ (kN·m⁻³) | E (GPa) | μ  | c (MPa) | ϕ (°) | K (m.s⁻¹) |
|-------------------------|------------|---------|----|---------|-------|------------|
| rock                    | 24.2       | 2.0     | 0.25 | 810     | 37    | 9.0×10⁸    |
| The fault zone          | 22.0       | 0.8     | 0.35 | 200     | 19    | 2.0×10⁷    |
| The first lining        | 23.6       | 30.0    | 0.2 | 6.0×10⁻⁹ |      |            |
| The secondary lining    | 23.8       | 34.5    | 0.2 | 6.0×10⁻⁹ |      |            |
| Grouting reinforcement area | 23.0   | 2.0     | 0.26 | 350     | 35    | 2.0×10⁹    |

3.3. Boundary conditions
Stress boundary, displacement boundary and seepage boundary need to be added to the 3D calculation model.

Stress boundary: According to the measured data of boreholes, the stress field in this section is mainly tectonic stress. Linear regression method is adopted to determine the stress boundary value of the model: σx = 15.8 MPa, the σy = 27.3 MPa, the σz = 16.7 MPa.

Displacement boundary: normal displacement constraints are added to the front and back sides of the model, left and right sides, and fixed end constraints are added to the bottom.

Seepage boundary: During seepage calculation, 500m water head boundary is added to the top, four sides and bottom of the model, and the tunnel excavation surface is set as the permeable boundary.

3.4. Calculation Condition
In order to determine the spatial arrangement of curtain grouting in the water-rich fault area, the following three working conditions were set respectively to determine the fortification length of curtain grouting, the thickness of grouting and the length of one grouting.

Working condition 1: Without curtain grouting, full section excavation is carried out by simulating TBM with 1m footage per cycle. Analyzing the deformation, seepage and plastic zone of wall rock when TBM passes through the fault, and determine the fortification length of curtain grouting.
Working condition 2: According to the fortification length determined in working condition 1, the grouting thickness is assumed to be 2m, and 6 types of primary grouting lengths, including 6m, 8m, 10m, 12m, 14m and 16m, are respectively set. The influence of different grouting lengths on supporting effect is compared and analyzed to determine the optimal length of primary grouting. Working condition 3: according to the fortification length determined in working condition 1 and the primary grouting length determined in working condition 2, six grouting thicknesses of 1m, 2m, 3m, 4m, 5m and 6m were set respectively to compare and analyze the changes of deformation and seepage velocity of the palm-face under different grouting thicknesses, and the optimal grouting thickness was selected.

4. Result analysis

4.1. Operating Condition 1 Fortification Length

4.1.1. Heading face deformation and seepage velocity. Due to the excavation and unloading of the tunnel and the role of high hydraulic pressure in the fault. The face of the tunnel will protrude and deform under the tunnel axis. In this model, when the distance between the tunnel excavation face and the fault zone is greater than 3m, the deformation of the tunnel face is small. The deformation law of the palm face of each cycle footage is basically the same, the deformation difference of the center of the palm face is about 0.5 cm, and the maximum deformation is less than 9cm.However, when the distance between the palm face and the fault zone is less than 3m, the deformation of the palm face begins to increase sharply. The deformation difference between the two cycles gradually increases with each 1m advance of construction. When the fault is exposed, the deformation of the hand face reaches its peak value, with the central deformation of about 15cm and the top and bottom deformation of about 6.4cm.

The seepage velocity of the face will increase gradually with the excavation. As shown in Fig. 3, three monitoring points are selected at the same position of different excavation face. When the distance between tunnel excavation face and fault zone is greater than 3 m, the seepage velocity of each monitoring point will increase slightly for each 1m advance of construction, but the overall range of change is not large, and the maximum value is not more than $1.5 \times 10^{-5}$ m/s. When the distance between the palm face and the fault zone is less than 3m, the seepage velocity at the monitoring point begins to increase, and the monitoring point 1 is larger than monitoring 3, until the fault zone was exposed, the seepage velocity at each monitoring point reached the average maximum value, and the maximum value of monitoring point 1 was $6.8 \times 10^{-5}$ m/s. Since then, due to the excavation pressure relief, the seepage velocity of the palm face will be reduced to a certain extent.

![Figure 2](image-url) heading face deformation at different positions
**Figure. 3** Variation of seepage velocity on the palm surface at different positions

4.1.2. *Distribution and development of plastic zone.* Under the influence of tunnel excavation, the stress of surrounding rock will be redistributed into a new equilibrium state. As shown in Fig. 4, the surrounding rock around the tunnel and in front of the tunnel face will undergo plastic deformation, forming an interconnected plastic zone. When the distance between the tunnel excavation face and the fault zone is 3m, the plastic zone of surrounding rock and the fault zone begin to form a connection zone. When the distance between the palm surface and the fault zone is 2m, the plastic zone of surrounding rock and the fault zone are completely connecting.

**Figure. 4** Plastic separation layout of surrounding rock at different excavation distances

(a) The heading face is 5m away from the fault  
(b) The heading face is 4m away from the fault zone  
(c) The heading face is 3m away from the fault  
(d) The heading face is 2m away from the fault
Constraints to sum up, the tunnel and fault zone are separated by 3m, the plastic zone of surrounding rock and the fault zone, constraints between the fault and surrounding rock under the action of high stress and high hydraulic pressure and damage can occur, between surrounding rock fissure filling, accompanied by a progressive loss of water, leads to the constraints of seepage velocity and deformation began to surge. Therefore, for safety reasons, the thickness of surrounding rock for preventing water and mud inrush in this tunnel is 4m in front of the fault zone, which is about 0.5 times the diameter of the tunnel. When the tunnel face is 4m away from the fault zone, advance curtain grouting should be used to reinforce the surrounding rock in front.

4.2. Grouting length in working condition 2

In the same geological conditions, due to the rig, grouting equipment power, the thickness of the wall and other factors are different. The length of grouting will also change when one grouting is used. In this section, other elements of numerical simulation are not changed. Grouting starts when the distance between the hand face and the fault zone is 4m, and only the influence of the length of one grouting in the surrounding rock in front of the hand face on the hand face is considered.

When tunnel construction begins to expose the fault zone, the deformation and seepage velocity of the tunnel face will increase significantly. After using curtain grouting, the deformation and seepage velocity of the palm face show a downward trend. When the grouting length is 6m, the maximum deformation of the palm face is 14.6 cm, and the maximum seepage velocity is 5.92×10⁻⁵ m/s. When the grouting length is 8cm, 10cm, 12cm, 14cm and 16cm, the maximum deformation of the palm face is 14.2 cm, 14 cm, 13.85 cm, 13.88 cm and 13.77 cm respectively, which decreases by 2.74%, 4.11%, 5.14%, 5.48% and 5.69% relative to the grouting length 6m. At the same time, the maximum seepage velocity of the palm face is 3.51×10⁻⁵ m/s, 3.01×10⁻⁵ m/s, 2.76×10⁻⁵ m/s, 2.62×10⁻⁵ m/s, 2.58×10⁻⁵ m/s, which decreases by 40.71%, 49.16%, 53.38%, 55.74% and 56.42% when the grouting length is 6m. When the grouting length increases from 6m to 12m, the maximum deformation and seepage velocity of the palm face decrease obviously. When the grouting length increases from 12 m to 14 m, the influence of the grouting length on the maximum deformation and maximum seepage velocity of the palm face begins to weaken, and its change curve gradually flattens.

![Deformation and velocity curves of the heading face of different grouting lengths](image_url)

**Figure. 5** Deformation and velocity curves of the heading face of different grouting lengths
According to working condition 2, set the grouting length as 10 m. Six conditions of grouting thickness of 1 m, 2 m, 3 m, 4 m, 5 m and 6 m were set. When the grouting thickness is 1m, the maximum deformation of the palm face is 14.25cm, and the maximum seepage velocity of the palm face is $7.71 \times 10^{-5}$ m/s. When the grouting thickness is 3 m, the maximum deformation of the palm face is 13.87 cm, and the maximum seepage velocity of the palm face is $2.89 \times 10^{-5}$ m/s. Compared with the grouting thickness of 1m, the two decrease by 2.67% and 62.52% respectively. When the grouting thickness is 6 m, the maximum deformation of the palm face is 13.83 cm, and the maximum seepage velocity of the palm face is $2.58 \times 10^{-5}$ m/s, which decrease by 0.03% and 3.46% respectively compared with the grouting thickness of 3 m. When the grouting thickness increases from 1 m to 3 m, the influence of the grouting thickness on the maximum seepage velocity of the maximum deformation of the palm face is greater. When the grouting thickness exceeds 3 m, the influence of the grouting thickness on the palm face becomes smaller and smaller.

5. Conclusion
(1) When the tunnel face is about 0.5 times the diameter of the tunnel face in front of the fault, the seepage velocity and deformation of the tunnel face will surge, and the surrounding rock plastic zone behind the tunnel face will connect with the fault zone. In order to ensure the construction safety, curtain reinforcement should be carried out in time to prevent water and mud inrush disasters.

(2) The larger the length of curtain grouting is, the better the supporting effect is. The deformation and seepage velocity of the palm face will gradually decrease with the increase of the grouting length. However, when the grouting thickness exceeds 10m, the reinforcement effect of curtain grouting will gradually weaken.

(3) The greater the thickness of curtain grouting is, the more obvious the supporting effect is. The deformation and seepage velocity of the palm face will decrease gradually with the increase of the grouting thickness. However, when the grouting thickness exceeds 3m, the reinforcement effect of curtain grouting is no longer obvious.

References
[1] Wei Zhou, Renhua Xu, Shuyi Huang, Ming Ye, Chufan Qi. Research on disposal measures of water and mud inrush disaster in karst tunnel based on hazard level [J]. China Equipment Engineering, 2021, 37(01): 260-26.
[2] Jizeng Zhao. Study of full-face curtain grouting on water-burst fault F4-4 subsea tunnel in Qingdao Jiaozhou bay [J]. Journal of Shandong University (Engineering Science), 2009,33 (6), 116-120.
[3] Wang Yufeng, Wu Li, Yuan Qing, Zhou Yuchun, Ma Chenyang. The Research of Grouting Scope in Longjinxi Water Tunnel through Fault Fracture Zone [J]. Science Technology and Engineering, 2016, 16(13): 257-261.

[4] Yufan Zhang, Jiamei Zhou, Shengbo Zhou, Yi Cheng, Le Yu. Study on Tunnel through Water-rich Fault Fracture Zone Based on Solid-fluid Coupling [J]. Railway Standard Design, 2018, 62(08): 111-116.

[5] Cong Wang, Yongquan Zhu. Reasonable Range of Advanced Curtain Grouting for Zhengpantai Tunnel [J]. Science Technology and Engineering, 2020, 20(22): 9196-9201.

[6] Weijie Zhang, Shucai Li, Jiuchuan Wei, Qingsong Zhang, Xiao Zhang, Daolei Xie. Model tests on curtain grouting in water-rich broken rock mass [J]. Chinese Journal of Geotechnical Engineering, 2015, 37(09): 1627-1634.

[7] Helin Fu, Pengtao An, Ka Li, Jie Li, Guowen Cheng, Jiabing Zhang. Modern Tunneling Technology, 2020, 57(S1): 458-465.