Model experimental test and numerical analysis of the influence of a strike-slip fault on a tunnel project

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Abstract: Many active faults exist in the west of China, especially strike-slip faults; thus, passing through active faults is inevitable during tunnel construction, and the stability problem of tunnels becomes an important research topic. To investigate pivotal issues caused by active faults, such as the failure modes of tunnels, considering Xianglushan tunnel as a backing project, this study examined the response law of a tunnel under a strike-slip fault in virtue of model experimental test and numerical analysis, which is a comprehensive method. On the basis of the prototype tunnel, a numerical analysis model was established to acquire the failure mode of deformation, the distribution of stress, and the internal force of lining under the dislocation of the strike-slip fault. Meanwhile, a model experimental test was performed under the strike-slip fault to monitor tunnel deformation and failure, strain distribution, ground deformation, and crack caused by the fault. First, the results of the model test were in good agreement with the numerical analysis, indicating that the liner maintains high stress state near the fracture surface but low stress state in its ends. The west haunch of the hanging wall and the east haunch of the footwall presented a tensile failure. Moreover, the east haunch of the hanging wall and the west haunch of the footwall reaching fault trace suffered in press condition lightly. According to the result of the numerical analysis, the tensioned zone of the lining was distributed along the longitudinal direction of the tunnel, which mainly focused on the longitudinal position of the wall on both sides of the tunnel in the range from 0.5 D (D is the diameter of the tunnel) to 2 D away from the fracture surface in the footwall and in the same range in the hanging wall. Second, the wrinkling range of ground was from ~2.4 D to 1.3 D in the model size according to the model test. Furthermore, the failure form of lining under the strike-slip fault is a kind of combined failure, including tensile failure and direct shear failure, but shear failure is the main failure form. Last, the affected zone of lining was wider within the hanging wall than the footwall. Therefore, the footwall under the fault dislocation is the control point to resist such dislocation. This research provides a reference for the fortified range of the tunnel crossing a strike-slip fault with certain practical significance.

1. Introduction
Fault zones are widely distributed in China, especially in the west region, making the investigation of tunnels at fault crossings inevitable; therefore, scholars pay further attention to the issue of fault dislocation increasingly.¹
Majid K. et al. investigated the effects of the burial depth and dip angle of a fault on a tunnel under a normal fault by conducting a model test [2]. The primarily potential shear zone can be divided into two secondary shear zones, owing to the existence of tunnels in the shear zone; under the reverse fault, the soil stiffness and dip angle of the fault are the mainly affected factors for structure stability [3]. By measuring the coefficient of ellipticity, the maximum force and relative distribution of the buried steel pipe were determined through experimental simulation method, and the result showed that the deformations of the sections of the pipe are more serious than its fixed parts. [4] Liu et al. obtained the response law and affected range of highway tunnels under the reverse fault at stick-slip dislocation by considering different dip angles [5-7]. In terms of strike-slip faults, finite element analysis was established by analyzing the mechanism of deformation and failure of underground pipelines under different conditions, including wall thickness, pipeline length, ratio of pipeline diameter to thickness, fault displacement, and width [8-9].

Existing studies are mainly thorough on the structural failure relationship of tunnels crossing normal and reverse faults. However, less work on tunnels that cross strike-slip faults is acquired. At present, numerical analysis is the main method to research on strike-slip faults, which make it inaccurate in results, and the model test method seems more important than the numerical analysis. According to statistics, the main type of dislocation in China is strike-slip type during earthquake [10]. Therefore, investigating the response characteristics of tunnels under strike-slip faults is of great significance.

The Xianglushan tunnel starts from Shigu in the north and ends at the east coast of Erhai Lake, Dali, with a total length of 62.596 km. The geological condition is complex, and 13 large faults exist in which Longpan-Qiaohou (F-1), Lijiang-Jianchuan (F-2), and Heqing-Eryuan (F-3) faults are regional active faults of the Holocene with northwest direction. Nowadays, the activity is mainly manifested by the nature of strike-slip faults with creep- and strike-slip dislocations. The horizontal dislocation rate of faults is 2.2–3.5 mm on average (Figure 1). The diversion project for water on central Yunnan is a large-scale main livelihood item in the southwestern part of China. However, the geological conditions are overwhelmingly complex and thus have been a concern in engineering geology.

![Figure 1. Position relationship between the tunnel and faults](image)

Based on domestic and foreign works and combined with the project, this paper mainly used numerical analysis method to study the response laws of deformation, distribution of stress, and internal force of liner under a strike-slip fault. On the basis of the results of the numerical analysis, a model experimental test with a scaling ratio of 1:100 was performed to verify the validity of the numerical analysis. According to the results of the model experimental test, the response laws of distribution of strain, ground deformation, and cracks of liner under the strike-slip fault were obtained.

2. Numerical analysis

2.1. Model
To eliminate the boundary effect, the tunnel is extended to twice of the original length at the fault plane along the longitudinal distance. The numerical model, which consists of a hanging wall and a footwall, is constructed with a length of 120 m. The maximum distance, which ranges from the boundary of the hanging wall to the fault plane, is 70 m; the maximum distance, which ranges from the boundary of the footwall to the fault plane, is 50 m. Meanwhile, considering three to five times of the diameter of the liner, the model is built with a width of 50 m and a depth of 40 m in total by using the Flac3D analysis software, which adopts the fast Lagrangian difference method. The liner zone crosses the strike-slip fault and is oriented perpendicularly to the fault plane. The fault zone was simplified as a fault plane with mechanical parameters due to its narrowness.

In the numerical model, the tunnel depth is 15 m. The interfaces are set between fault plane (Interface-1) and between the lining and the rock mass (Interface-2). The numerical model is shown in Figure 2a. To simulate the movement of the strike-slip fault, the boundary conditions of the model are set to adopt free boundaries in the upper part of the rock mass, and the other faces of the footwall are fixed. Considering the loading features of the strike-slip fault, an initial velocity is applied on the surrounding rock. An initial velocity along the x-axis direction is also applied at the hanging wall boundary, and the deformation diagram is displayed in Figure 2b.

Figure 2. Layout and deformation diagram of the numerical model

Figure 3 shows the size and measurement point layout of the lining in which the radius is 4 m, and its height reaches 1.05 m according to the measurement data form field. To obtain visual optimization in the result, sections of measurement points are selected every five meters along the longitudinal direction of the tunnel within four measurement points per section, including the vault (V-1–V-25), foot (F-1–F-25), west (W-1–W-25), and east (E-1–E-25) haunch of the tunnel.

Figure 3. Size and measurement point layout of the lining

According to the report of geotechnical investigation, the physical and mechanical parameters of the rock mass and liner are presented in Table 1, where $\gamma$ is the bulk density; $E$ is the Young’s modulus; $\nu$ is the Poisson’s ratio; and $c$ and $\phi$ are the cohesion and friction coefficient, respectively. To obtain the response characteristics of the tunnel under fault conditions accurately, homogeneous materials, including rock mass and lining, are adopted.
Table 1. Mechanical properties of rock mass and liner

| Type        | $\gamma$ (kN m$^{-3}$) | $E$ (GPa) | $\nu$ | $c$ (MPa) | $\phi$ ($^\circ$) |
|-------------|------------------------|-----------|-------|-----------|------------------|
| Rock mass   | 27.0                   | 0.3       | 0.3   | 0.55      | 65               |
| Liner       | 23.8                   | 28.0      | 0.2   | -         | -                |

Through the mechanical property test of the contact surface, the interface parameters are shown in Table 2, where $k_n$ and $k_s$ are the normal and shear stiffness, respectively; $R_t$ is the tensile strength.

Table 2. Mechanical properties of interfaces

| Number | $k_n$ (GPa) | $k_s$ (GPa) | $R_t$ (GPa) | Bonded slip on/off |
|--------|-------------|-------------|-------------|--------------------|
| 1      | 16.0        | 6.0         | 0.5         | on                 |
| 2      | 18.0        | 12.0        | 1.3         | off                |

2.2. Result analysis

In this study, the maximum displacement of the fault is 50 cm, and the fault displacements are set to 10, 20, 30, 40, and 50 cm in order. The deformation of the tunnel, longitudinal stress, and the distribution of the internal force under different displacements are simulated and analyzed.

2.2.1. Displacement distribution

Figure 4 illustrates the displacement distribution curves of the tunnel axis along the longitudinal direction under different displacements.

![Figure 4. Distribution curve of horizontal displacement along the axis of the tunnel at different distances](image)

2.2.2. Longitudinal stress

The distribution of longitudinal stress at the top, bottom, left, and right walls of the tunnel is shown in Figure 5, and the top and bottom of the tunnel exhibit a consistent stress law. Supposed that the coordinate value at the fracture surface is 0. The longitudinal stresses at the left and right sides of the fracture surface are extremely small out of the coordinate range of $\pm$ 20 m. However, longitudinal stress generally changes sharply within the $\pm$ 20 m of the fault plane and reaches the maximum value at the fault trace. Furthermore, the longitudinal stresses of the west and east side are symmetrically distributed along the fault trace. The longitudinal stresses, which change within a range of $\pm$10 m on the west and east haunches, are significant, presenting a tensile failure on the west haunch of the hanging wall and east haunch of the footwall. However, the east haunch of the hanging wall and west haunch of the footwall, both of which reach fault trace, suffer in press condition lightly.

2.2.3. Internal force
Figure 6 shows the changes in internal forces when the liner is viewed as an elastic beam, including the characteristics of shear forces, bending moments, and thrust along the horizontal direction. The shear and thrust are the largest near the fracture surface, and the change trend is inversely related to the distance from the tunnel to the fracture surface. However, the bending moment in the horizontal plane reaches a maximum value of ±16 m on both sides of the fracture surface, and the bending moment value on the fault plane is 0.

![Figure 5. Longitudinal stress with longitudinal distance](image1)

![Figure 6. Internal force along longitudinal distance](image2)
3. Experiment model test

3.1 Equipment

The equipment (Figure 7) used in this demonstrative test is an independently designed test model equipment that can consider the form of a strike-slip fault. The loading system is realized by the jack acting on the outside of the hanging wall. The geometric similarity ratio used in this experiment is $C_L = 1:100$, bulk density similarity is $C_V = 1:100$, and other parameters are obtained on the basis of similarity theory, including buried depth ratio $C_H = 1:100$, elastic modulus $C_E = 1:100$, lining radius $C_r = 1:100$, lining strain, stress ratio $C_ε = 1:100$, and $C_σ = 1:100$. The design size of the box is $72 \text{ cm} \times 50 \text{ cm} \times 40 \text{ cm}$. The maximum distance, which ranges from the boundary of the hanging wall to the fault plane, is $42 \text{ cm}$; the maximum distance, which ranges from the boundary of the footwall to the fault plane, is $30 \text{ cm}$.

![Figure 7. Equipment for the experiment](image)

3.2 Test scheme

After trial and error and tests of mechanical properties are performed, the mixture ratio of materials for the lining is determined to be gypsum: water: barite powder: diatomaceous earth: fiber = 1: 1.2: 0.6: 0.25: 0.004. The size of the liner model is $600 \text{ mm}$ in length, $100 \text{ mm}$ in width and height, and $10 \text{ mm}$ in thickness. According to the obtained mix ratio, the tunnel model is shown in Figure 8a, and the corresponding cross-sectional dimensions are illustrated in Figure 8b. The mixture ratio of the same materials of the rock mass is sand: barite powder: sodium silicate: water = 1: 0.5: 0.1: 0.1.

![Figure 8. Tunnel model and section sizes](image)

3.3. Result analysis

3.3.1 Rock mass displacement

Figure 9 shows the ground initial and final deformation result. When the displacement reaches $36 \text{ mm}$, the ground cracks penetrate. In addition, when the final displacement is $50 \text{ mm}$, the maximum horizontal relative dislocation of the rock mass is $30 \text{ m}$ by measuring the dislocation value of the grid line on the rock mass. The range of crack extension is from $-240 \text{ mm}$ to $130 \text{ mm}$.
3.3.2 Longitudinal strain

The longitudinal strains of #3–#6 sections of the top, bottom, west, and east haunches are shown in Figure 10. The longitudinal strains on the west haunch of the hanging wall and the east haunch of the footwall are negative in value consistently. Therefore, the west haunch of the hanging wall and the east haunch of the footwall present a tensile failure mode. Huge changes in the longitudinal strains of #4 and #5 sections also exist. Moreover, the maximum change rate of strain occurs when the displacement reaches 40 mm, especially the longitudinal strain at the bottom of the tunnel.

3.3.3 Cracks

According to the distribution and development of cracks, circumferential cracks are evident between #4 and #5 sections; the longitudinal cracks between #3 and #4 sections and between #6 and #7 sections are triggered, as illustrated in Figure 11. Clearly, the longitudinal cracks on the right wall between #6 and #7 sections gradually develop into diagonal cracks and extend to the top of the tunnel. The longitudinal cracks between #3 and #4 sections develop into oblique cracks and extend from the right wall to the left wall gradually, which has the tendency to develop into circumferential cracks.
4. Conclusion
The results of the model test are consistent with the results of the numerical analysis that are as follows:
First, the liner maintains high stress state near the fracture surface but low stress state in the ends. Second, according to the panorama of liner cracks, the circumferential cracks in the model test appear at the peak of the longitudinal stress, as revealed in the results of the numerical analysis. Last, the stress states on both sides near the fault plane are complicated; the hanging wall and footwall, both of which are 1.0 \( D \) away from the fracture surface, also evidently show tensile and compression characteristics, respectively.
The wrinkling range of ground is from \(-2.4 \ D\) to \(1.3 \ D\) in the model size. Moreover, when the displacement reaches 0.5 \( D\), the peak of the displacement of the ground becomes 0.3 \( D\), which indicates that a certain amount of ground compression occurs during the process of dislocation. The failure mode of the tunnel structure is a combined failure, including bending tensile and direct shear failure. However, shear failure is the main failure mode under the compression–bending–shear force.
The hanging wall is affected by the strike-slip fault in a smaller scope and intensity than the footwall. Thus, the footwall is the control point of the resisting dislocation of the tunnel.

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