Experimental and numerical investigation for the rupture problem of a tunnel subjected to strike-slip fault

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Abstract. In this study, a model test and a DEM-FDM coupling numerical analysis were conducted to investigate the response and mechanism of a tunnel subjected to strike-slip fault rupture. The interaction of the tunnel with the fault rupture, the deformation pattern, and the strain evolution and crack propagation in the tunnel liner were observed in the test. With the experimental data, a DEM-FDM coupling model was constructed and calibrated. With this model, the response and mechanism of the tunnel subjected to strike-slip fault rupture were numerically investigated, to provide a deep insight into the design factors of the tunnel liner.

1. Introduction

Active faults can cause unfavourable effects on tunnels in two different forms: ground shakes, or commonly referred to as earthquakes; and fault ruptures. A fault rupture can cause strong impacts on the tunnel liner due to the dislocation of the opposite parts of an active fault [1-4]. Literature reviews suggest that the majority of the existing studies have been focused on the ground shake problems of tunnels, i.e., the aseismic issues of the tunnel. However, major seismic events are associated with notable permeant fault displacements. Previous reconnaissance reports of major seismic events have shown that tunnels are vulnerable to dislocated faults. Typical cases of the seismic damage of tunnels across active faults can be found in the works of [5-9]. These cases highlight the importance of the design of tunnel liners against fault ruptures. Limited results have been reported for problems of the strike-slip faults, especially for tunnel projects. However, for regions such as western China, strike-slip faults account for a considerable proportion of active faults. From 1900 to 2015, 29 major seismic events with surface ruptures were recorded in China, 52% of which were triggered by strike-slip faults [10]. Thus, it is of sufficient practical significance to study the response and failure mechanism of a tunnel subjected to a strike-slip fault rupture.

This paper presents a model test and DEM-FDM coupling numerical analysis to investigate the response and mechanism of a tunnel subjected to a strike-slip fault rupture. The interaction of the tunnel with the fault rupture, the deformation pattern of the model, and the strain and crack propagation in the tunnel liner were observed in the test. With the experimental data, a DEM-FDM coupling model was constructed and calibrated, to provide deep insight into the design factors of the tunnel liner.
2. The model test
A water diversion tunnel crossing an active strike-slip fault in southwest China was chosen as the prototype project. The cross section of the tunnel is circular, with an outer diameter of 10 m. The prototype dimensions were chosen to be 100 times greater than the physical model. The diameter of the prototype tunnel is 10 m, which leads to a 10 cm diameter of the model tunnel.

The test machine used in this study is a self-developed model test apparatus. The main component of the apparatus is an open-top steel shear box that is vertically divided into two sides. The ‘active’ side could offset in parallel to represent the strike-slip fault, with the ‘passive’ side remaining stationary. The offset is driven by an electrohydraulic jack whose loading velocity is controllable. The maximum stroke of the jack is 10 cm, and the dimensions of the model container (shear box) are 72 cm×50 cm×45 cm (L×W×H), as shown in Fig. 1.

The outer diameter of the prototype tunnel is 10 m, and the thickness of the prototype liner is approximately 1 m (25 cm shotcrete + 80 cm concrete liner). Considering the dimensions of the shear box, the dimensions of the test model were set to 72 cm×50 cm×40 cm (L×W×H). A 1:100 scaling law was adopted for the geometric similarity, which led to a 1 cm-thick model liner (D=1 cm). Notice that the scaling law for the density is 1; we then have 1: 100 scaling laws for the tunnel depth, stress and strain.

The tunnel model was made according to a patented formula. The ingredients of the tunnel model are plaster, diatomite, barite powder, and polypropylene fiber, at an approximate ratio of 1: 0.6: 0.25: 0.004. Additionally, the rebars in the prototype tunnel liner were modeled with a steel mesh. The length of the model tunnel is 60 cm. This length was verified with a trial numerical simulation [11] to have a negligible influence on the model test.

The rock mass model was also prepared according to a patented formula. The main contents are fine sand, barite powder, and sodium silicate. Sodium silicate is the key element of the formula, which can provide cohesion to the model rock mass.

The deformation pattern of the model, strain, and crack propagation in the tunnel liner were observed in the test. To capture the strain evolution in the liner, 40 strain gauges were installed on the liner surface. The positions of the strain gauges were determined based on the experience learned in the trial numerical simulation. Seven monitoring sections were planned, as shown in Fig. 2. The far-end sections, #1 and #7, verify whether the length of the tunnel model was sufficient. The central sections, #2~#6, are the main monitoring sections since the trial numerical simulation predicts that the damage of the tunnel liner is localized in the vicinity of the intersection of the tunnel and fault plane. Strain gauges were attached to the top arch, floor, left and right sidewalls and were identified as T, F, L, and R, respectively. According to the trial numerical simulation, the strain of the sidewalls is meaningful and subsequently complex. For these positions, strain gauge rosettes were attached with which the full strain tensor could be obtained. All the strain gauges were calibrated to check the functionality before the performance of the test. Temperature compensation was conducted by connecting a block of tunnel material outside the shear box.

The deformation or the strain inside the rock mass model is difficult to measure considering the limit size of the current model. As an alternative, the surface deformation pattern of the rock mass model was
observed by marking the model surface with grids of white sand. A camera was placed right above the shear box to obtain a top view of the model surface.

The observation of crack propagation in the tunnel liner is the highlight of this test. To continuously observe the development and evolution of cracks in the model tunnel liner, especially the crack on the inner surface of the tunnel, an endoscope was used. The probe of the endoscope was inserted in one end of the model tunnel. Video footage and photographs were taken from various internal perspectives throughout the test, as shown in Fig. 2.

![Figure 2. Plan view of the instrumentation of the model test](image)

The development of the deformation pattern of the model surface in the test is given in Fig. 3. The cracks started to emerge when the offset was 12 mm and gradually propagated to the middle of the shear box from both ends. The propagation rates of both sides were basically the same. As the offset reached 36 mm, a penetrated shear band formed.

![Figure 3. Plan view of the instrumentation of the model test](image)

Crack propagation in the tunnel liner was captured with the endoscope during the test, as shown in Fig. 4 and 5. No obvious crack growth was observed on the inner surface of the liner until the offset reached 28 mm. As the displacement reached 28 mm, a minute circumferential crack first appeared between sections #4 and #5 and extended to the right sidewall to induce a diagonal crack toward section #3. At an offset of 32 mm, the circumferential crack between sections #4 and #5 developed to the left sidewall and combined with two longitudinal cracks. The circumferential crack between sections #4 and #5 gradually widens as the offset magnitude increases and propagates to the invert of the tunnel. As the offset finally reached 50 mm, serious damage can be observed between #4 and #5, and conjugate cracks can be found. The longitudinal cracks at both sidewalls have propagated to section #7.

To summarize the crack pattern, liner cracks induced by faulting are mainly circular cracks concentrated in the vicinity of the shear zone, while the liner cracks at the footwall portion are basically longitudinal.
cracks. Compared to the footwall portion, tunnel liner damage at the hanging wall portion is relatively minor, and the cracks are localized beyond section #3.

![Image 1](image1.png)

**Figure 4.** Plan view of the instrumentation of the model test

![Image 2](image2.png)

**Figure 5.** Panorama view of liner cracks

3. The DEM-FDM coupling modelling and verification

The coupling method used in the present paper is the built-in discrete/continuous coupled approach in the PFC3D code, which is derived from the method proposed by Xiao and Belytschko [12]. This method takes advantage of the continuous and discrete approaches used (fast Lagrangian analysis of continua in 3 dimensions (FLAC3D) and particle flow code in 3 dimensions (PFC3D)), which are both based on the resolution at each time step of Newton’s second law. To allow the exchange of data between the particles in PFC3D and the zones in FLAC3D, the time step was imposed at the same value for both the continuous and discrete models.

Newton’s second law (used by both algorithms) is for the determination of the motion (velocity) of each particle/gridpoint by the applied unbalanced force. For this reason, the term ‘equation of motion’ was used. With the updated velocity, the incremental displacement and the induced contact forces of each particle/gridpoint can be updated. The differential form of the equations of motion for a particle/gridpoint are as follows:

\[
\begin{align*}
\Delta x_i^{(t+\Delta t)} &= \Delta x_i^{(t)} + \frac{\Delta t}{m} \Delta \dot{x}_i^{(t+\Delta t/2)} \\
\Delta \dot{x}_i^{(t+\Delta t/2)} &= \Delta \dot{x}_i^{(t-\Delta t/2)} + \frac{\dot{p}(t)}{m} \Delta t
\end{align*}
\]

where \(\Delta t\) is the time step, \(x_i^{(t)}\) is the component of the particle/gridpoint’s position in the direction \(i\) at the moment of \(t\), \(m\) is the mass of the particle or the concentrated mass of the gridpoint, and \(\dot{p}(t)\) is the unbalanced force.

The unbalanced force update of the particle in the PFC3D framework follows the following formula:

\[
F_i^{(t)} = F_{i\text{unb}}^{(t)} = mg - Ku_i^{(t)} - c\dot{x}_i^{(t)} - m\ddot{x}_i^{(t)}
\]
in which \( F^{(e)} \) is the applied force that acts on the particle, \( g \) is gravity, \( K \) is the stiffness of the particle’s contact, \( c \) stands for the damping factor, and \( u^{(e)}_i \) is the overlap of the neighboring two particles in the direction \( i \). The update of the unbalanced force of the zones in the FLAC3D framework also follows the above procedure, with the assumption that the applied force, mass, damping, and stiffness of a FLAC3D zone are concentrated on its gridpoints.

The essence of PFC3D and FLAC3D consists of the interchange of the velocity and nodal force between the FLAC3D zones and the PFC3D particles. In the coupling methods used in the present paper, this interaction was performed with a PFC wall element that was slaved to a FLAC3D zone face. For a PFC3D particle, the triangle ABC is the slave wall element whose vertices coincide with the gridpoints of the zone, and point P is the contact point of the particle. The triangle wall element interpolates the unbalanced force \( (F_n, F_s) \) by the PFC3D particle to the gridpoints A, B, and C.

Fig. 6 gives the comparison between these methods.

4. Response and mechanism of the tunnel subjected to fault rupture

To numerically investigate the model test results. A coupling model was constructed based on the model test package. The dimensions of the numerical model are consistent with the test model; i.e., the rock mass model is 72 cm \( \times \) 50 cm \( \times \) 40 cm in dimensions, and the diameter and liner thickness are 10 cm and 1 cm, respectively.

The tunnel liner is simulated with FLAC3D zones. The rock mass model is represented with PFC3D balls. Considering the calculation cost, approximately 1,000,000 discrete particles were generated. The micro-parameters of the PFC particle assembly were calibrated with trial runs based on the test results. The boundaries of the model rock mass were modeled with the wall element in PFC3D. The micro parameters were consistent with those of the balls, except that the friction was set to 0.1 to simulate the smooth inner face of the steel shear box. The offset of the shear box was modeled with a constant velocity of the wall elements.

Fig. 7 gives the cut-out view of the coupling model. As can be noted, the setup of the coupling model is consistent with the test model, and the components, dimensions, and material parameters of the coupling model are modeled according to the real test model.
To verify the feasibility of the numerical coupling model. The test was modeled with the DEM-FDM coupling method. And this case would serve as the benchmark case in the following parameter study. To compare with the surface deformation pattern observed in the experiment, the surface deformation information in the coupling model was extracted. Fig. 8 gives the deformed grid of the model surface at various faulting distance. The dimensions of the grid in the model test are consistent with that of the numerical model. A good match for the deformed grids in the model test and numerical modeling demonstrated the credibility of the coupling modeling.

Figure 7. Cut-out view of the coupling model showing the model tunnel, the surrounding model rock, and the shear box container

In Fig. 9, longitudinal deformation profiles of the tunnel at 50 mm faulting and evolution of the longitudinal deformation profile of the tunnel top arch with faulting are shown. Interesting findings can be found in Fig. 9 that the horizontal deformation of the left sidewall of the tunnel is less than that of the right sidewall, and the horizontal deformation of the tunnel top arch is less than that of the tunnel floor, indicating that the tunnel was ovaling under the effect of the strike-slip fault rupture. In simple words, the tunnel was laterally compressed by the strike-slip fault.

Figure 8. Deformation pattern of the model top surface in the numerical model

Figure 9. (a) Longitudinal deformation profile of tunnel at 50mm faulting. (b) Evolution of the longitudinal deformation profile of the tunnel toparch with faulting
To further explore the deformation mechanism of the tunnel, the evolution of the transversal deformation profile of various monitoring sections with faulting was shown in Fig. 10. The finding of the oval deformation pattern can be confirmed. And the relatively intact status of Sec. #6 demonstrated that the deformation was limited in the vicinity of the faulting plane, which is in agreement with the findings gained in the model test.

| Sec. #3 | Sec. #4 | Sec. #6 |
|---------|---------|---------|
| 20mm    |         |         |
| 30mm    |         |         |
| 40mm    |         |         |
| 50mm    |         |         |

**Figure 10.** Evolution of the transversal deformation profile of various monitoring sections with faulting (Green: undeformed, Red: deformed)

Knowledge regarding the cracking of the tunnel liner can be found in the tensile strain contours shown in Fig. 11. The main failure mechanism of the liner is due to the circular cracks concentrated in the vicinity of the shear zone, and the crack first occurs when the offset magnitude is 20–30 mm. These findings were confirmed with the observation in the model test, which again demonstrated the credibility of the coupling modeling.

5. Conclusions
In this study, a model test and a DEM-FDM coupling numerical analysis were conducted to investigate the response and mechanism of a tunnel subjected to strike-slip fault rupture. Based on the obtained results, the main conclusions of this work are summarized as follows:

In the model test, shear zone cracks on the model surface appear when a certain distance of the fault rupture was reached. Then, these cracks gradually propagate to the middle of the shear box from both ends until a penetrated shear band forms. For the model tunnel liner, cracks induced by faulting are mainly circular cracks concentrated in the vicinity of the shear zone, while the liner cracks at the footwall portion are basically longitudinal cracks. Compared to the footwall portion, tunnel liner damage at the
hanging wall portion was relatively minor, and the cracks were localized beyond the shear plane of the fault. The DEM-FDM coupling modeling technique was successfully introduced into the numerical simulation for the current problem of a tunnel subjected to a strike-slip fault rupture. The tunnel liner was simulated with continuous solid zones so that the deformation profile, stresses, and strains in the tunnel liner can be revealed. The surrounding rock mass model was simulated with discrete spherical particle assembly so that the discontinuous deformation and shear crack band of the rock mass during the fault rupture can be captured. After a sophisticated calibration process, the benchmark coupling model is capable of revealing various phenomena observed in model tests.

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