Influence of tectonic stress on the structural safety of
mountain tunnel under the strike-slip faulting

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Abstract: The distribution of tectonic stress around the fault is very complicated, which may affect tunnel behavior under the dislocation of fault. Therefore, this paper aims to investigate the influence of tectonic stress on the structural safety of mountain tunnel under the strike-slip faulting. Variable lateral stress coefficients from 0.3 to 3.0 are considered via a series of three-dimensional finite element models. Safety assessment indices based on the overall lining damage in compression/tension and the ovalization of the tunnel cross-section are used to evaluate the damage of tunnel structure subjected to fault movement quantitatively. The results show that the cross-sectional damage and ovalization of tunnel lining mainly distribute around the fault plane, and the tectonic stress plays a crucial role in the tunnel’s response to strike-slip faulting. With the increasing lateral pressure coefficient, both the value and distribution scope of the cross-sectional compressive damage in the longitudinal direction increase; while the value and distribution of cross-sectional tensile damage decrease when the coefficient is larger than 1.0, and its damage is slighter than compressive damage. The cross-sectional ovalization of the tunnel is also significantly affected by the lateral pressure coefficient, especially when the coefficient is larger than 1.0.

Keywords: tectonic stress, strike-slip faulting, numerical simulation, structural damage, deformation

1. Introduction

Tunnels built in southwestern China would cross several faults, and most faults are the strike-slip fault [1]. Once the fault movement occurs, the tunnel will suffer severe structural damage [2]. Several factors affecting the tunnel behavior under the faulting have been studied, such as fault dislocation and dip angle [3]. However, the complicated tectonic stresses around the fault are always ignored, which may affect the tunnel performance under the faulting, especially in southwestern China, where distributes extremely complex regional tectonic stress, and the geostress is dominated by horizontal principal stress [4]. Therefore, understanding the influence of tectonic stress on the structural safety of
mountain tunnels under the dislocation of strike-slip fault plays a crucial role in the design and construction of tunnels crossing the strike-slip fault.

Some safety assessment criteria have been proposed to evaluate the structural safety of tunnel lining when crossing the fault, which can be divided into three categories: (I) bearing capacity [5,6], (II) structural damage [3,7,8], and (III) structural deformation [3,9]. Gregor et al. [5] and Lin et al. [6] adopted the axial force-moment diagrams of tunnel lining to assess the lining capacity and identify the parameters that truly relate to the safety of the tunnel lining, respectively. Based on the concrete damaged plasticity (CDP) model, Yan et al. [7] performed numerical simulations to compare the tunnel lining damage with the joints or not under the normal faulting, and they found that the joints can efficiently decrease the damage extent in the zone with tensile stresses; Zhong et al. [8] introduced the overall lining damage index in compression (OLDC) and the overall lining damage index in tension (OLDT), which were proposed by Chen et al. [10], to evaluate tunnel’s cross-sectional damage subjected to multiple strike-slip faulting, and they also employed the index OLDT to preliminarily assess the damage of the tunnel linings under the normal faulting considering the fault dislocation and dip angle [3]. To estimate the structural deformation, cross-sectional deformation of tunnel lining is often used. Cai et al. [9] chosen the cross-section that the maximum tensile strain distributed to see tunnel deformation under the normal faulting, and they confirmed that the tunnel was compressed vertically and elongated horizontally. Wang et al. [3] used the diameter deformation rate to evaluate the damage of a circular tunnel under normal fault movement, and they found that the tunnel cross-section gradually changed from a circular shape to a horizontal ellipse and the cross-sectional deformation is mainly concentrated in the fault fracture zone. These safety assessment methods can be used as references in this work to evaluate the structural damage and deformation of tunnel lining.

In the following sections, the three-dimensional (3D) numerical model considering the CDP was first established, and then verified based on field observation. After that, the influence of tectonic stress on the structural damage and deformation of mountain tunnel under the strike-slip faulting were investigated by considering four lateral pressure coefficients (k) ranging from 0.3 to 3.0.

2. Numerical modeling

2.1. 3D finite element modeling

A 3D finite element model is established using ABAQUS to simulate the tunnel’s behavior and damage evolution under the strike-slip faulting. As illustrated in Figure 1, the geometry of the model is 300 m×100 m×200 m. The outer diameter (D) of the tunnel is 10 m with a lining thickness of 0.5 m, and the buried depth of the tunnel is 100 m. The strike-slip fault dips at 90°, and a 20 m width weak layer is set in the vicinity of the fault plane to simulate the fracture zone. Both the rock and tunnel are modeled by eight-node reduced-integration brick elements (C3D8R). Finer meshes are applied to the parts of the model close to the fault plane, while coarse meshes are divided far from the fault plane (Figure 1) to improve computational efficiency but retaining the computational accuracy. The mesh size of the tunnel around the fault and the fault fracture zone is 1.0 m and 2.0m, respectively, in the longitudinal direction. The whole model contains 149296 elements.

An elastic perfectly plastic constitutive model with Mohr-Coulomb failure criterion is adopted to simulate the behavior of the rock, including the competent rock mass and fault fracture zone. The competent rock mass is assumed to be IV rock according to the Specifications for Design of Highway Tunnels (JTG 3370.1-2018) [11], while Young’s modulus of the fault fractured zone is assumed to be one-tenth of the competent rock mass. This is because the fractured rock is usually simulated by weakening the parameters of the rock, such as Young’s modulus and cohesion [8]. Table 1 summarizes all rock parameters, and it should be noted that the dilation angle ψ of the rock is assumed to be φ/8, where φ is the friction angle [12]. The tunnel lining is made of C35 and its behavior is modeled as the CDP model, which was proposed by Lubliner et al. [13] and improved by Lee and Fenves [14]. The CDP model describes the stress-strain relationship of concrete under tension and compression, respectively, and considers the
damage evolution of concrete materials based on damage variables $d_k$. The stress-strain curve for concrete in this work is adopted based on the Chinese Code for the design of concrete structures (GB 50010-2010) [15]. The damage variables $d_k$, including the tensile damage variable $d_{kt}$ and compressive damage variable $d_{kc}$, are calculated based on the energy equivalence principle [16]. The $d_k$ varies from 0 to 1, where zero indicates that concrete is intact and 1.0 indicates complete damage of the concrete, and 0.95 is set as the limit value of damage in this work. The physical parameters of the tunnel lining are listed in Table 1.

The interaction between the tunnel and rock is simulated by contact surfaces, which are defined in terms of tangential and normal behavior. The tangential contact follows Columb’s friction rule, and the penalty method with a frictional coefficient of 0.4 is applied. The normal contact is assumed to be the hard contact, which means the surfaces only allow the transmission of normal contact stress when there is no gap between the tunnel and rock, while when the two contact surfaces are separated, the contact constraint between the two surfaces disappears. Such a contact algorithm can reasonably simulate the friction and compression between the tunnel and rock. The same contact surfaces are set to simulate the sliding of the fault plane.

2.2. Analysis procedure
The simulation is performed in the following three steps. First, the initial in-situ stress balance is carried out for the intact surrounding rock. To simulate the influence of tectonic stress, the lateral pressure coefficient is considered, and the lateral pressure coefficients in two directions are assumed to be the same [17]. At this stage, all sides except the top surface are constrained in the normal directions. Then, the excavation of tunnel and the construction of lining are simulated by killing and activating the corresponding elements. At last, the strike-slip faulting is simulated by applying a horizontal displacement to the moving block, just the entire left fault block (Figure 1), along the direction perpendicular to the tunnel axis, which is due to the fault plane was preset between the moving block and fixed block. To reduce the dynamic effects on the tunnel’s response, the fault movement is applied at a slow rate of 0.05m in every analysis step, and the total displacement 0.5 m is achieved along the fault plane. During this process, the nodes on the bottom of the model, lateral boundaries of the fixed block and left boundary of the moving block are constrained in the normal direction, and the end

| Material                | Density (kg∙m$^{-3}$) | Elastic modulus (GPa) | Poisson’s ratio | Internal friction angle (°) | Dilation angle (°) | Cohesion (MPa) |
|-------------------------|-----------------------|-----------------------|----------------|-----------------------------|-------------------|----------------|
| Competent rock mass     | 2000                  | 6.0                   | 0.35           | 39                          | 5                 | 0.7            |
| Fault fracture zone     | 2000                  | 0.6                   | 0.35           | 39                          | 5                 | 0.7            |
| Tunnel Lining           | 2500                  | 31.0                  | 0.20           | -                           | -                 | -              |

Figure 1. Geometry and mesh of 3D finite element model.

Table 1. Mechanical and physical properties of rock and tunnel lining used in the simulation.
boundaries of the tunnel are also constrained in the normal direction to eliminate the boundary effect owing to the limited length of the tunnel in the numerical model [9].

2.3. model validation

Figures 2(a) and (b) show the distribution of initial horizontal and vertical stress when the lateral pressure coefficient equals 3.0, respectively. The initial horizontal stress is about three times of the initial vertical stress (Figure 2(c)), indicating the reasonable distribution of initial in-situ stress.

Figure 2. Initial in-situ stress distribution ($k=3.0$): (a) horizontal stress, (b) vertical stress, and (c) stress along the vertical direction.

Due to the lack of research on tunnel’s response to strike-slip faulting, the validity of the numerical model is verified by field observation of the typical damaged Tawarayama tunnel during the Kumamoto earthquake [18]. Figure 3 compares the damaged Tawarayama tunnel and the damage distribution of the numerical tunnel model ($k=3.0$). The tensile damage distributes along the circumferential direction of the tunnel, leading to the failure of the tunnel ring (Figure 3(a)). Significant compressive damage is mainly located at the tunnel vault and inverted arch under the strike-slip faulting in the numerical simulation, and the similar structural damage that the vault collapse was found in Tawarayama tunnel at the fault fracture zone (Figure 3(b)). Therefore, the numerical model can be used to study the effect of tectonic stress on the tunnel’s response to strike-slip faulting.

Figure 3. Comparison between field observation of Tawarayama tunnel and damage distribution of numerical tunnel model ($k=3.0$): (a) ring damage of Tawarayama tunnel and tensile damage of lining in the simulation; (b) vault collapse of the Tawarayama tunnel and compressive damage of lining in the simulation.
3. Results and discussion

3.1. Safety assessment indices
To evaluate the structural damage and deformation of tunnel subjected to the strike-slip faulting, the overall damage indices, including OLDC and OLDT [10], are adopted to quantitatively estimate the damaged state of tunnel’s cross-section; and the ovalization of tunnel’s cross-section \( O \) is proposed to measure the structural deformation (equation (1)). OLDC and OLDT are calculated based on the damage variables \( d_k \) and energy dissipation of each element of the tunnel’s cross-section, and the energy dissipation of elements is used to calculated weights, which are defined as in equations (2) and (3), respectively.

\[
O = \left| \frac{D_{\text{hor}}}{D_{\text{ver}}} \right|
\]

(1)

Where \( D_{\text{hor}} \) and \( D_{\text{ver}} \) are the horizontal diameter and vertical diameter after the deformation, respectively. A bigger value of \( O \) refers to a larger ovalization.

\[
\text{OLDC} = \sum_{i=1}^{n} [d_{k,c}^i \cdot \bar{E}_i^c \left( \sum_{i=1}^{n} E_i^c \right)^{-1}] 
\]

(2)

\[
\text{OLDT} = \sum_{i=1}^{n} [d_{k,t}^i \cdot \bar{E}_i^t \left( \sum_{i=1}^{n} E_i^t \right)^{-1}] 
\]

(3)

Where \( E_i^c \) is the dissipated energy of the \( i \)-th element, \( d_{k,c}^i \) and \( d_{k,t}^i \) are the damage variables of the \( i \)-th element in compression and tension, respectively.

3.2. Effect of tectonic stress
Based on the safety assessment indices, four lateral pressure coefficients \((k=0.3, 1.0, 2.0, 3.0)\) are considered to analyze the influence of tectonic stress on tunnel behavior under the strike-slip faulting.

3.2.1. Structural damage
The damage of the tunnel lining mainly distributes around the fault plane (Figures 4 and 5). Figures 4(a) and (b) present the simulated compressive and tensile damage variable distribution along the longitudinal direction under the lateral pressure coefficient of 3.0 with a variation of fault dislocation \( \Delta \) in the range of 0.05~0.50 m, respectively. With the increase of fault dislocation, both the compressive damage and tensile damage become more severe. The compressive damage mainly distributes on the vault and inverted arch of the tunnel lining, while the tensile damage is mainly located at the arch waist of the lining. The concentrated degree of the tensile damage is obviously less than compressive damage, indicating that the tunnel is mainly subjected to compressive damage under the strike-slip faulting. The damaged scope of the lining is little affected by the fault dislocation. However, as the lateral pressure coefficient increases, the damage scope of the lining is significantly increased (Figure 5), and the compressive damages located at the vault and inverted arch become more serious, while the tensile damage located at the arch waist is weakened.

The overall damage of the tunnel lining cross-section with the increasing lateral pressure coefficient under the condition of \( \Delta=0.5 \) m is quantified and illustrated in Figure 6. It is evident that the value of OLDC is larger than OLDT (Figures 6(a) and (b)), indicating that the compression damage of the lining cross-section is more severe than the tensile damage, which is consistent with the distribution of damage variables (Figures 4 and 5). Owing to the large fault dislocation, the tunnel lining is seriously damaged at the fault plane, so the compression damages of the lining cross-section reach the same peak value, namely the limit value of damage, at the fault plane under different lateral pressure coefficient. However, as the lateral pressure coefficient increases, both the value and the distribution scope of the OLDC in the longitudinal direction increase obviously. Particularly, when the lateral pressure coefficient reaches 3.0, the OLDC is distributed along the entire length of the tunnel,
while the area with more severe overall cross-sectional compression damage is mainly distributed in the -1.5D~1.5D range around the fault plane (Figure 6(a)).

A different trend is observed in the distribution of OLDT in the longitudinal direction (Figure 6(b)). The value of the OLDT at the fault plane decreases with the increasing lateral pressure coefficient. When the lateral pressure coefficient reaches 3.0, all value of OLDT in the longitudinal direction is less than 0.2, indicating that the tensile damage of the lining cross-section is very slight. The distribution scope of the OLDT is the largest under the condition of $k=1.0$, which is about -2D~2D to the fault plane, and when the lateral pressure coefficient larger than 1.0, the value and distribution scope of the OLDT decreases as the lateral pressure coefficient increases.

3.2.2. Structural deformation

Figure 4. Distribution of damage variables of tunnel lining in the longitudinal direction with the increasing fault dislocation $\Delta$, ($k=3.0$): (a) compressive damage variable; (b) tensile damage variable.

Figure 5. Distribution of damage variables of tunnel lining in the longitudinal direction with the increasing lateral pressure coefficient $k$, ($\Delta=0.50m$): (a) compressive damage variable; (b) tensile damage variable.

Figure 6. Distribution of overall damage indices in the longitudinal direction with the increasing lateral pressure coefficient $k$, ($\Delta=0.50m$): (a) OLDC; (b) OLDT.
The ovalization of tunnel cross-section can evaluate the service performance of the tunnel. With the increase of fault dislocation, the tunnel cross-sectional ovalization in the longitudinal direction increases under the condition of $k=3.0$, especially when the fault dislocation is larger than 0.30 m, an excessive ovalization would happen around the fault plane (Figure 7), which can also be found in Figure 8(b). The distribution scope of the tunnel cross-section ovalization is little influenced by the fault dislocation, which is about $-1.5D~1.5D$ to the fault plane. Such distribution scope is consistent with the area where distributes severe overall cross-sectional compression damage (Figure 6(a)). However, both the ovalization degree and distribution scope change with the increasing lateral pressure coefficient (Figures 8(a) and (b)). When the fault dislocation is very small ($\Delta = 0.05$ m), there still exists obviously ovalization of the tunnel cross-section around the fault plane except for $k=1.0$ (Figure 8(a)). This indicates that the lateral pressure coefficient plays a crucial role in the tunnel structural deformation under the strike-slip faulting. Especially under the condition of $k \geq 1.0$, the ovalization of the tunnel cross-section becomes more significant and the influence scope expands with the increasing lateral pressure coefficient (Figures 8(a) and (b)).

**Figure 7.** Longitudinal distribution of tunnel cross-sectional ovalization with the increasing fault dislocation under the condition of $k=3.0$.

**Figure 8.** Longitudinal distribution of tunnel cross-sectional ovalization with the increasing lateral pressure coefficient under the condition of: (a) $\Delta = 0.05$ m; (b) $\Delta = 0.5$ m.

4. **Conclusion**

In this paper, the influence of tectonic stress on the structural safety of mountain tunnel under the strike-slip faulting is investigated by considering four lateral pressure coefficients from 0.3 to 3.0 based on a series of 3D numerical simulations. According to the safety assessment indices, the structural damage and deformation of the tunnel lining are evaluated quantitatively. Though the ideal dip angle of strike-slip fault was adopted to simplify the analysis, the results can provide some references for tunnels cross strike-slip faults. The following conclusions can be drawn:

(i) The structural damage and cross-sectional ovalization of the tunnel lining mainly distribute around the fault plane. Under the strike-slip faulting, the tunnel is mainly subjected to compressive
damage, which mainly distributes on the vault and inverted arch of the tunnel lining, while the tensile damage is mainly located at the arch waist of the lining.

(ii) With the increasing lateral pressure coefficient, both the value and distribution scope of the cross-sectional compressive damage in the longitudinal direction increase obviously. The area with severe overall cross-sectional compression damage is mainly distributed in the -1.5D~1.5D range around the fault plane under the condition of $k=3.0$. The cross-sectional tensile damage is sligher than compressive damage, and its distribution scope is the largest under the condition of $k=1.0$, which is about -2D~2D to the fault plane. When the lateral pressure coefficient larger than 1.0, both the value and distribution scope of the cross-sectional tensile damage decrease as the lateral pressure coefficient increases.

(iii) The lateral pressure coefficient plays a crucial role in the tunnel cross-sectional deformation under the strike-slip faulting. Especially under the condition of $k\geq 1.0$, both the ovalization degree and distribution scope increase with the increase of lateral pressure coefficient.

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