Fortified length of the tunnel under the S-type fault displacement pattern

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Abstract: Many tunnels have been built in central and western China; these tunnels are facing serious damages of active faults. At present, the fortified length of tunnels remains to be solved under fault dislocation. To overcome this issue, a numerical calculation model is established on the basis of previous research on the numerical calculation and model test of tunnels across active faults, with Xiang Lushan tunnel project as the research background of the paper. The S-type fault displacement pattern is proposed, which is based on the deflection curve of the support of the fixed beam at both ends under the uneven settlement. The influence of S-type and linear fault displacement patterns on tunnel lining is investigated using the finite difference method. Meanwhile, through the orthogonal test of fault factors at different levels, the influence rule of the multi-factor combination of faults on the fortified length of the tunnel under the S-type fault displacement pattern is obtained. Results reveal that the S-type fault displacement pattern, compared with the linear displacement pattern, can eliminate the stress singularity at the boundary of the fault zone. Therefore, the S-type fault displacement pattern is more reasonable and can be used as the selection of fault displacement pattern. In addition, the fortified length of the tunnel ranges from 1.1 L to 2.0 L (L is the fault width), which is the result of the orthogonal test. The most influential factor for the fortified length of the tunnel is the angle between the fault strike and the tunnel axis, whereas the least influential factor is the fault dip angle. This research provides a reference for the fortified range of the tunnel crossing fault with certain practical significance.

1. Introduction
As a key component of major national infrastructure projects, tunnels play a huge role in ensuring the safety of national resources and promoting social and economic development, which are an important infrastructure for national strategies and lifeline projects. However, newly-built tunnels, especially long tunnels, often inevitably traverse complex and unfavorable geological sections in the western region and approach or cross seismically active fault zones, which are threatened by serious active fault displacement. For example, when the San Francisco 8.3 earthquake struck, the Wright railway tunnel crossing the San Andres fault was severely damaged, and the maximum fault volume of the
tunnel was 1.5 meters \cite{1}. A large earthquake of magnitude 7.6 occurred in Taiwan in 1999, and Wang et al. investigated 57 tunnels in the area, 49 of which were damaged to varying degrees; the relatively weak sections of the tunnels crossing the active fault were all devastated \cite{2}. Several road tunnels near the epicenter of the magnitude 8.0 Wenchuan earthquake were damaged in 2008. Shen et al. investigated the earthquake damage of 52 tunnels after the Wenchuan earthquake and classified them, among which six tunnels through or between faults were the most seriously damaged \cite{3}. The investigation of tunnel earthquake damage shows that the damage of the tunnel structure passing through the fault fracture zone is significantly higher than that of other sections. At present, most of the tunnel design codes mainly deal with active faults by avoiding them; clear suggestions on the engineering design and countermeasures of the tunnel crossing active faults, which are not conducive to the long-term operation safety of the water conveyance tunnel, are also lacking.

Scholars at home and abroad have conducted considerable research on the mechanical response and corresponding measures of tunnels under the action of fault dislocation. In the study of Russo et al., the anti-fault design of highway tunnels crossing active faults in Turkey adopted the concept of “articulated design,” and the flexible connection between lining segments was used, so that when the fault is staggered, the mechanical behavior mainly occurs in the connection parts \cite{4}. Shahidi et al. adopted the method of reducing the connection stiffness of the lining sections when the Koohrang-III water tunnel crosses the Zarab active fault. The flexible connection uses plastic concrete and reduces the reinforcement ratio. Their simulation verification achieved a good anti-missing effect \cite{5}. Caulfield et al. developed a joint anti-fault measure on the basis of the actual working conditions of the water conveyance tunnel crossing the Hayward active fault, combined with an on-site investigation and a numerical simulation, and adopted a design combining the enlargement of the tunnel cross-sectional size and the “hinge design” idea \cite{6}. Lin et al. studied the impact of thrust fault on a tunnel through model tests and numerical simulations. The impact of thrust fault on the tunnel is closely related to the dip angle of the fault and the stiffness of the stratum (soil). It is located above the thrust fault. The tunnel part is easier to deform and break than the lower plate part \cite{7}. Geng et al. investigated the dynamic response characteristics of the tunnel through the fault fracture zone along the longitudinal direction through the combination of dynamic analysis and shaking table model test. They determined that the reasonable seismic fortification length of the tunnel crossing the fault fracture zone is 3.5 times the tunnel span \cite{8}. Majid Kiani et al. studied a series of centrifuge model tests on segmental tunnels subjected to normal faulting. The results indicated the absence of sudden failure of segmental tunnels under normal faulting and the improvement of function in response to an increase in the overburden of the tunnel. The angle of the fault affected the tunnel behavior \cite{9}. Liu Xue Zeng et al. simulated the stress, deformation, and failure process of the tunnel structure orthogonal to the normal fault at 45°, 60°, and 75° through indoor model tests, respectively. They also studied the normal fault viscosity characteristics of force, deformation, and damage of the tunnel structure crossing fault under slip dislocation \cite{10-12}. Cai et al. studied the deformation and failure mechanism of tunnels in sand and soil under normal faults by conducting centrifuge model test and numerical analysis. The results showed that the surface subsidence caused by normal faults above the existing tunnels is significantly reduced when tunnels exist in the sand layer \cite{13}. The above studies have investigated the influence of active faults on tunnel mechanics and anti-missing measures, but they have not fully considered the influence of fault displacement pattern to determine the reasonable fortification length of tunnels under fault action.

Xianglushan tunnel is located in the Xianshuihe-East Yunnan earthquake zone in the Qinghai-Tibet earthquake zone. The total length of the tunnel is 63.426 km. The geological conditions along the route are complex, with multiple large faults (fractures). Among them, the Longpan-Qiaohou (F10), Lijiang-Jianchuan (F11), and Heqing-Eryuan (F12) faults are Holocene regional active faults. Most of the faults of the group intersect with the line at medium and large angles. The section of Xianglushan diversion tunnel in the Longpan-Qiaohou (F10) fault zone is circular with a diameter of 10 m. The initial support uses C20 shotcrete with a thickness of 20 cm, and the secondary lining uses C30 concrete with a thickness of 50 cm. The width of the fault zone is 200 m, and the maximum horizontal
vector value of the 100a displacement of the Holocene active fault can reach 1.9 m, which makes the Xianglushan tunnel face a serious threat of fault. This paper is based on previous research on the numerical calculation and model test of tunnels across active faults, and a numerical calculation model is established with Xiang Lushan tunnel project as the research background of the paper. The S-type fault displacement pattern is proposed, which is based on the deflection curve of the support of the fixed beam at both ends under the uneven settlement, and the influence of S-type and linear fault displacement patterns on tunnel lining is investigated using the finite difference method. Meanwhile, through the orthogonal test of fault factors at different levels, the influence rule of the multi-factor combination of faults on the fortified length of the tunnel under the S-type fault displacement pattern is obtained. This research provides a reference for the fortified range of the tunnel crossing fault with certain practical significance.

2. Numerical model

2.1. Calculation model and boundary
The FLAC3D software is used to establish a 3D calculation model to simulate the response of the lining under different faults. For the calculation prototype, the tunnel of Longpan-Qiaohou (F10) fault zone is selected. In the calculation model, the fault dip angle is 90°, and the width is 200 m. The calculation range is 600 m in the longitudinal direction; the horizontal and vertical lengths are 100 m. The model tunnel is a circular cross-section whose radius is 5.65 m. The primary shotcrete and the second lining of the tunnel are considered 1.05 m concrete lining. The calculation model is shown in Figure 1. The physical and mechanical parameters of the model are presented in Table 1. When simulating strike-slip fault displacement, the boundary of the footwall is fixed, and the normal displacement of the hanging wall and the upper and lower sides of the fault zone are restricted. Meanwhile, applying cement along the dislocation plane on the left boundary of the hanging wall and the fault zone is necessary to simulate the relative dislocation process between the hanging wall and footwall.

![Figure 1. Schematic of the calculation model](image)

| Type    | Grade | Density (kg·m⁻³) | Young’s modulus (GPa) | Poisson’s ratio | Cohesion (MPa) | Friction angle (°) |
|---------|-------|------------------|-----------------------|----------------|----------------|-------------------|
| Rock mass | IV    | 2700             | 3                     | 0.3            | 0.55           | 33                |
| Fault   | V     | 2000             | 0.8                   | 0.4            | 0.4            | 27                |
2.2. Fault displacement pattern
The fault displacement pattern indicates the displacement and deformation of fault zone when the fault is dislocated. Research on the influence of fault displacement pattern on tunnel lining structure shows that considering the fault displacement pattern in the numerical calculation of the tunnel crossing fault is necessary [14]. The diagram of the application of the fault displacement pattern is shown in Figure 2.

![Figure 2. Diagram of the fault displacement pattern](image)

3. S-type fault displacement pattern
The current research on the influence of fault displacement pattern on tunnel lining structure reveals that considering the fault displacement pattern in the numerical calculation of the tunnel crossing fault is necessary. However, research on the application of the fault displacement pattern is insufficient, and no specific formula exists for the displacement expression of the fault displacement pattern. On the basis of previous research results, this paper proposes the S-type displacement pattern and draws the expression formula of its displacement pattern. In addition, the influence law of the S-type and linear displacement patterns on the deformation and internal force of the articulated tunnel is analyzed.

3.1. S-type fault displacement pattern
Jalali et al. believed that one of the most probable patterns of tunnel structure deformation in the fault zone can be selected as the fault displacement pattern, which chooses the deflection curve of the beam as the most probable pattern of tunnel structure deformation when the fixed beam supports vertical displacement [15]. Therefore, the fault displacement pattern is considered the deflection curve of the structural beam because the structure deformation is similar to deformation S, which is called S-type displacement pattern. Fault movement in the S-type fault displacement pattern is illustrated in Figure 3.

![Figure 3. Fault movement in the S-type fault displacement pattern](image)

![Figure 4. Deformation drawing of fixed beam structure](image)

The deformation illustration of fixed beam structure is shown in Figure 4. The deflection curve equation of the beam when the support of the fixed beam is uneven settlement is as follows:
where \( a \) is the vertical displacement, \( l \) is the length of the beam, and \( x \) is the position of a point on the beam in the coordinate system.

Equation (1) takes the left end of the beam as the coordinate origin. However, the origin of the coordinate system is at the center of the fault zone in the calculation of the tunnel crossing fault. Therefore, through the transformation of coordinate system, the formula of the S-type fault displacement pattern is as follows:

\[
\omega = -\frac{2ax^3}{l^3} + \frac{3ax}{l^2} + \frac{a}{2},
\]

Equation (2)

In this paper, the curves of S-type and linear fault displacement patterns are presented in Figure 5.

**Figure 5.** Curves of two different fault displacement patterns

### 3.2. Influence of S-type and linear fault displacement patterns on tunnel structure

The difference in calculation result between the S-type fault displacement pattern proposed in this paper and the conventional displacement pattern is explained. The deformation and stress curves of the tunnel under the S-type and linear fault displacement models are shown in Figure 6. In the model, the fault width is 200 m, and the fault displacement is 10 cm.

The results indicate that the linear displacement pattern has a singularly linear stress at the soft and hard joints of the fault zone and the non-fault zone surrounding the rock. In addition, the proposed S-type displacement pattern transitions smoothly at the same location. Therefore, the results obtained by the proposed S-type fault displacement pattern may have reasonable results.
Orthogonal test

The following uses the S-type fault displacement mode as the input condition, when the displacement of fault is 0.2 m, through the orthogonal test of the fault zone factors (the angle between the fault strike and the tunnel axis, the fault dip angle, the fault width, and the fault rock elastic modulus). The influence law of the multi-factor combination of faults on the required length of the tunnel fortification is also obtained.

4.1. Factors and levels of orthogonal test

In the orthogonal test, the angles between the fault strike and the tunnel axis are 60°, 75°, and 90°. The dip angles of fault zones are 60°, 75°, and 90°. The widths of the fault zones are 160, 200, and 240 m. The elastic moduli of rock mass in the fault zones are 0.8, 1.5, and 2.2 GPa. The orthogonal test uses a four-factor three-level L9 (3^4) orthogonal table. Each factor and level are shown in Table 2, and a total of nine tests are performed.

| Level | Factor | Direction of dip (°) | Fault dip (°) | Fault width (m) | Young’s modulus (GPa) |
|-------|--------|---------------------|--------------|----------------|----------------------|
| 1     |        | 90                  | 60           | 160            | 0.8                  |
| 2     |        | 75                  | 75           | 200            | 1.5                  |
| 3     |        | 60                  | 90           | 240            | 2.2                  |

4.2. Method of calculating the fortified length of the tunnel

To obtain the formula for calculating the fortified length of the tunnel, first, the strength-checking formula of concrete rectangular section is simplified. Second, the joint action of the bending moment and axial force of lining element is considered. Last, on the basis of the combined deformation formula of mechanics of materials and considering the compressive and tensile strengths of lining concrete, the safety factor of tensile and compressive failures of lining concrete is calculated by Equation (3).

\[ F_i = \frac{\sigma_i}{\sigma_{\text{max}}} = \frac{\sigma}{\sigma_{\text{min}}} \]

where \( \sigma_i \) is the compressive strength of lining concrete, \( \sigma_{\text{max}} = 14.3 \) MPa, \( \sigma_i \) is the tensile strength of lining concrete, and \( \sigma_{\text{min}} = 1.43 \) MPa. \( \sigma_{\text{max}} \) is the maximum principal stress, and \( \sigma_{\text{min}} \) is the minimum principal stress of the lining concrete.

The engineering grade of Xianglushan tunnel is first grade. When the supporting structure of the tunnel reaches the ultimate strength under the basic combined load, the safety factor of the reinforced
Concrete under the normal service limit state is 1.35. This paper reflects the safety of the structure by calculating the longitudinal safety factor of the lining side wall. The range where the safety factor of the lining is less than 1.35 is determined as the fortified length of the tunnel. In addition, the article defines the control index of the fortification length as several times the width of the fault. For example, the fortified length of the tunnel is 1.5 L (L is the fault width), which means that the fortified length of the tunnel is 1.5 times the width of the fault zone.

4.3. Analysis of orthogonal experiment results

Table 4 presents the orthogonal test results of the tunnel. Different combinations of the main parameters have different effects on the fortified length of the tunnel, and its range of fortification length is 1.1 L–2.0 L in the orthogonal test. Figure 7 illustrates the safety coefficient curve of the tunnel side wall under different fault factors.

Table 4. Orthogonal test results

| Number | Parameters and their corresponding levels | Results |
|--------|------------------------------------------|---------|
|        | Direction of dip (°) | Fault dip (°) | Fault width (m) | Young’s modulus (GPa) | Fortified length of the tunnel (m) | Increase of the fortified length (%) |
| 1      | 90 | 60 | 160 | 0.8 | 204 (1.28 L) | 37.84 |
| 2      | 90 | 75 | 200 | 1.5 | 244 (1.22 L) | 64.86 |
| 3      | 90 | 90 | 240 | 2.2 | 268 (1.12 L) | 81.08 |
| 4      | 75 | 60 | 200 | 2.2 | 312 (1.56 L) | 110.81 |
| 5      | 75 | 75 | 240 | 0.8 | 292 (1.22 L) | 97.30 |
| 6      | 75 | 90 | 160 | 1.5 | 276 (1.73 L) | 86.49 |
| 7      | 60 | 60 | 240 | 1.5 | 364 (1.52 L) | 145.95 |
| 8      | 60 | 75 | 160 | 2.2 | 320 (2.00 L) | 116.22 |
| 9      | 60 | 90 | 200 | 0.8 | 304 (1.52 L) | 105.41 |

Figure 7. Safety coefficient curve of the tunnel side wall under different fault factors
In this paper, \( \kappa_j (j = 1, 2, 3) \) denotes the test index of each parameter at each level; here, the test index refers to the reduction of the shear stress and axial stress that is expressed in a percentage. \( \bar{k}_j \) is the average value of \( \kappa_j \) and can judge the optimal combination of the design parameters and the corresponding levels. \( R_j \) stands for the difference between each level of the same parameter, which is calculated by Equation (4).

\[
R_j = \max(\bar{k}_{j1}, \bar{k}_{j2}, \ldots, \bar{k}_{jm}) - \min(\bar{k}_{j1}, \bar{k}_{j2}, \ldots, \bar{k}_{jm}).
\]  

| \( K_{j1} \) | \( K_{j2} \) | \( K_{j3} \) | \( \bar{k}_{j1} \) | \( \bar{k}_{j2} \) | \( \bar{k}_{j3} \) | \( R_j \) |
|---|---|---|---|---|---|---|
| 183.78 | 294.59 | 240.54 | 240.54 | 294.59 | 278.38 | 281.08 | 297.30 |
| 294.59 | 278.38 | 324.32 | 308.11 | 367.57 | 272.97 | 240.54 |
| 367.57 | 272.97 | 324.32 | 308.11 | 61.26 | 98.20 | 80.18 | 80.18 |
| 61.26 | 98.20 | 93.69 | 99.10 | 98.20 | 92.79 | 90.99 | 93.69 |
| 122.52 | 90.99 | 108.11 | 102.70 | 122.52 | 90.99 | 108.11 |
| 61.26 | 7.21 | 27.93 | 22.52 |

The tendency chart, which reflects the influence level of each parameter, is presented in Figure 8 on the basis of Table 5. With this chart, the impact parameter for the fortified length of the tunnel is obtained. The most impact parameter concerning the fortified length of the tunnel is the angle between the fault strike and the tunnel axis, whereas the least impact parameter is the dip angles of fault zones.

![Tendency chart of the design parameters](image)

**Figure 8.** Tendency chart of the design parameters

### 5. Conclusion

This paper proposes the S-type fault displacement pattern, which is based on the deflection curve of the support of the fixed beam at both ends under the uneven settlement. Meanwhile, through the orthogonal test of fault factors at different levels, the influence rule of the multi-factor combination of faults on the fortified length of the tunnel under the S-type fault displacement pattern is obtained. On the basis of these analyses, the following relevant conclusions are drawn:

The S-type displacement pattern transitions smoothly at the soft and hard joints of the fault zone and the non-fault zone surrounding the rock. The results obtained by the proposed S-type fault displacement pattern may have reasonable results.
Through the orthogonal test, different combinations of the main parameters have different effects on the fortified length of the tunnel, and the range of its fortification length is 1.1 L–2.0 L (L is the fault width).

The most impact parameter concerning the fortified length of the tunnel is the angle between the fault strike and the tunnel axis, whereas the least impact parameter is the dip angles of fault zones. This research provides a reference for the fortified range of the tunnel crossing fault with certain practical significance.

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