Seismic Response of Tunnel across Inactive Fault: Numerical Analysis

Ruohan Li a, Yong Yuan b, Xu Zhao c

a Department of Geotechnical Engineering, Tongji University, 1239 Siping Road, Shanghai 200092, China.
b State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, 1239 Siping Road, Shanghai 200092, China.
c Key Laboratory of Urban Security and Disaster Engineering of Ministry of Education, Beijing University of Technology, Beijing 100124, China

lirh@tongji.edu.cn

Abstract. Earthquake damage investigations in recent years have revealed that fault zone is one of the most dangerous areas of tunnels in earthquakes, leading scholars to investigate the mechanisms of seismic response of fault-crossing tunnels and the aseismic measures. However, due to the complex fault-rock-tunnel interaction, the seismic response mechanism of tunnels crossing inactive faults is not yet complete and the suitability of different aseismic measure has not been evaluated. In this paper, a series of 3D numerical models of fault-crossing tunnels were established to study the seismic response of tunnels crossing inactive faults with different widths. On this basis, the suitability of grouting and flexible joints for fault-crossing tunnels were discussed. Due to the difference of physical property between the fault and the surrounding rock, the differential deformation will be produced at the interface, and resulting in a shear damage of the tunnel. The tunnel crossing wide fault is more vulnerable in earthquake than that crossing narrow fault. For the tunnel crossing inactive faults, especially those with wide widths, grouting reinforcement is a desirable aseismic measure. It can reduce the acceleration response of the tunnel within the fault and significantly reduce the tensile damage, while flexible joints have little effect on the acceleration response and the damage reduction of the tunnel within the fault. The present study can contribute to a better understanding of the seismic response of tunnels crossing inactive faults and provide some guidance to the seismic design.

1. Introduction

Driven by the growing demand for infrastructure in mountainous areas, the construction of tunnels in highway and railway networks have been accelerated. Challenges and complex geological conditions are met with in tunnel projects than in the past. Numerous cases of damages of mountain tunnels have been reported in earthquakes[1–4], which have led scholars and engineers into topics researching seismic response and seismic design of tunnels and other underground facilities.

Earthquake damage investigations on mountain tunnels reveal that fault or fracture zone is one of the most dangerous areas of tunnels in earthquake [5–7]. In order to study the seismic response and earthquake damage mechanism of fault-crossing tunnels, scholars have carried out numerous researches including scaled model tests[8–10] and numerical simulations[11–13]. Recent evidence suggests that the tunnel will be severely damaged by the violent shearing action when the fault dislocated[14,15]. Meanwhile, if the fault is not dislocated, the discontinuity of the strata will cause
the tunnel to deform unevenly in the longitudinal direction[16], and the fault interface will reflect and refract the incident seismic waves, causing increased tunnel deformation[17,18]. However, due to the complex fault-rock-tunnel interaction, the seismic response mechanism of tunnels crossing inactive faults is not yet complete, leading to a gap between research and engineering practice. A number of aseismic measures have been proposed to reduce seismic damage in fault-crossing tunnels, including flexible joint[19], buffer layer[20], and fibre reinforcement concrete[21], etc. However, few studies have been carried out to compare the aseismic effects of different aseismic measures, and the suitability of each measure has not been evaluated.

In this paper, a series of 3D numerical models were established to investigate the seismic response and damage pattern of tunnels crossing inactive faults with different widths. Two aseismic measures, grouting reinforcement and flexible joints were proposed, and the aseismic effects of two measures on tunnels crossing different widths of faults were analysed and their suitability was evaluated. This study may provide some reference for the seismic design of fault-crossing tunnels.

2. Numerical modelling
In order to investigate the influence of different fault widths on the seismic response of tunnels and evaluate the seismic performance of different aseismic measures, a series of 3D numerical models of a mountain tunnel crossing faults were established.

2.1. Engineering background
The Xianglushan Tunnel is part of the Central Yunnan Water Diversion Project, located in the central part of China's Yunnan Province. The objective of the project is to deliver water from the Shigu River to the central part of Yunnan Province. The tunnel is a key project along the entire route, with a total length of 63.4km. The geological conditions along the tunnel route are complicated, crossing three major active fault zones, including the Longpan-Qiaohou fault, the Lijiang-Jianchuan fault and the Heqing-Eryuan fault. Among them, the Heqing-Eryuan fault was chosen as the prototype for numerical calculations due to its strong seismic activity. Figure 1 shows the sketch of Heqing-Eryuan fault and the longitudinal profile of Xianglushan Tunnel. The width of the Heqing-Eryuan fault is 120m and the dip angle of the fault is 60°. The average burial depth of the tunnel is 1000m and the rock on both sides of the fault is mainly basalt and limestone, which can be classified as type IV according to the Chinese code. It should be noted that this paper focuses on the seismic response of the tunnel lining and the effect of the high geo-stress is ignored. The tunnel has a circular cross section with an inner radius of 4.2 m and outer radius of 4.75m. The lining has a thickness of 550 mm and is made of C30 concrete.

![Figure 1. Sketch of Heqing-Eryuan fault and longitudinal geologic profile of Xianglushan Tunnel.](image-url)
2.2. Finite element model
Nonlinear finite element models were established in the finite element program ABAQUS to simulate the seismic response of fault-crossing tunnel and the aseismic effect of different aseismic measures. Figure 2 shows the 3D models with a fault dip angle of 60° and with a fault width of 10 m and 100 m. The overall dimensions of the numerical model are 300 m (length) × 100 m (width) × 50 m (height). The diameter of the tunnel is 9.5 m and the burial depth is 20 m. For models setting flexible joint as aseismic measure, the lining within the fault is installed with flexible joints with 0.5m width at 6m intervals. For models setting grouting as aseismic measure, the strata within 0.5 times the tunnel diameter on the outside of the lining within the fault are set as the grouting zone. The details of the two aseismic measures are plotted in Figure 2.

![Figure 2. Numerical models.](image)

Eight-node reduced-integration brick elements (C3D8R) is used in the simulation. The tunnel lining is tied to the surrounding rock in the numerical simulation by assuming that there is no relative displacement between the lining and the rock. The interaction between the fault and the surrounding rock is simulated by applying “surface to surface contact” in ABAQUS to evaluate the potential slipping and the friction coefficient between them is set to 0.4[22]. The Mohr-Coulomb model of elasto-plasticity is adopted for the constitutive model of surrounding rock, fault, grouting, and flexible joint[23], as listed in Table 1. The concrete damaged plasticity model is used to simulate the tunnel lining. The tension and compression stress-strain relationships of the C30 concrete are shown in Figure 3. The Rayleigh damping is used in numerical simulation and the damping ratio is set as 0.05. In order to simulate the shear deformation of the ground under shear wave action, the vertical boundaries introduce kinematic contrains are conducted[24], forcing the nodes at the same height to move simultaneously preventing any rotation. A synthetic motion is applied in the numerical simulation, which is provided in the " Evaluation of Seismic Safety " section of the geotechnical investigation report for the Xianglushan Tunnel, as shown in Figure 4 and the peak ground acceleration is 0.12 g, for a 63% probability of exceedance in 50 years. The seismic wave energy is mainly concentrated in the frequency band from 0 Hz to 20 Hz, and the first dominant frequency is 6.3 Hz.

![Figure 3. Stress-strain, damage-strain and damage factor constitutive relationships for concrete.](image)
Table 1. Physical properties of materials in numerical simulation.

| Item           | Young’s modulus (MPa) | Density (kg/m$^3$) | Poisson’s ratio | Cohesion (kPa) | Friction angle (°) |
|----------------|-----------------------|--------------------|-----------------|----------------|-------------------|
| Surrounding rock | 6000                  | 2300               | 0.30            | 700            | 39                |
| Fault          | 300                   | 1700               | 0.35            | 100            | 20                |
| Tunnel lining  | 30000                 | 2500               | 0.2             | -              | -                 |
| Grouting       | 6000                  | 2200               | 0.30            | 900            | 35                |
| Flexible joint | 600                   | 2100               | 0.35            | 150            | 25                |

Figure 4. Synthetic motion used in numerical simulation.

2.3. Analysis procedures
In order to investigate the aseismic effect of flexible joint and grouting, six numerical models were established and numbered from 1 to 6, as shown in Table 2. The models with 10 m fault and 100 m fault are conducted to compare the effect of fault width on seismic response of fault-crossing tunnel. In addition, each model is set up with two aseismic measures, flexible joints and grouting within the faults. Furthermore, the seismic mitigation effect of different aseismic measures can be compared with different models.

Table 2. Analysis cases in numerical simulation.

| No. | Fault width (m) | Aseismic measure |
|-----|-----------------|-----------------|
| 1   | 10              | None            |
| 2   | 10              | Flexible joints |
| 3   | 10              | Grouting        |
| 4   | 100             | None            |
| 5   | 100             | Flexible joints |
| 6   | 100             | Grouting        |

3. Results and discussion

3.1. Effects of fault width
The distributions of the maximum acceleration of the tunnel vault along the longitudinal direction for the two models with 10 m fault and 100 m fault are plotted in Figure 5. It can be found that the acceleration of the lining within the fault is significantly greater than that on both sides of the fault. The maximum acceleration of the lining within 10 m fault is 2.4 m/s$^2$ and the maximum acceleration of the lining within 100 m fault is 2.2 m/s$^2$. Comparing the acceleration response of along the
longitudinal direction, it can be seen that the acceleration in the hanging wall is larger than that in the footwall, which is consistent with the so-called “hanging wall effect” observed in seismic investigation[1].

Three crests and troughs are observed along the longitudinal direction of the lining in the 100 m fault. This might be a result of the superposition of seismic waves reflected within the fault. A similar phenomenon has been found in other study investigating the relationship between the burial depth and the seismic response of tunnel[25]. However, this phenomenon is not evident in the model with 10m fault because the fault width is less than the wavelength of the main frequency component of the seismic wave, which also makes the acceleration within the fault exceed that within the 100 m fault.

Figure 6 presents the distribution of lining tensile damage of two models. It can be found that the lining damage is mainly concentrated near the interfaces between the fault and the surrounding rock. Due to the difference of physical property between the fault and the surrounding rock, the differential deformation will be produced at the interface, and resulting in a shear damage of the tunnel. The maximum tensile damage in the model with 100 m fault is 0.95, which is greater than that in the model with 10 m fault (0.23). It can be explained by the fact that, within a certain range, the wider the fault width, the greater the differential deformation and the more severe the tunnel damage. This is also in line with the earthquake damage investigation of the Wenchuan earthquake[26].

**Figure 5.** Maximum acceleration in longitudinal direction of the tunnel.

**Figure 6.** Tensile damage distribution of tunnel lining with different fault width: (a) 10 m fault; and (b) 100m fault.

### 3.2. Comparison between different aseismic measures

The distributions of the maximum acceleration of the tunnel vault along the longitudinal direction for the models with different aseismic measures are plotted in in Figure 7. As can be seen in Figure 7(a), the installation of aseismic measures has little effect on the acceleration of the tunnel. The grouting reinforcement slightly reduces the acceleration of the tunnel within the fault, while the flexible joints do not change the overall acceleration response of the tunnel. As shown in Figure 7(b), for the model with 100 m fault, the grouting reinforcement effectively reduces the acceleration of the tunnel within the fault, especially in the area close to the fault interface, while the flexible joints only slightly reduce the acceleration in a region close to the footwall.
Figure 8 and Figure 9 presents the distribution of lining tensile damage of the models with different fault width setting different aseismic measures. As can be seen from Figure 8, the grouting reinforcement efficiently reduces the tensile damage of the tunnel in the fault with 10 m width. Although the flexible joints concentrate the tunnel damage in the vicinity of the joints, they give no reduction in the tensile damage of the tunnel. As shown in Figure 9, the grouting reinforcement significantly reduces the tensile damage of the tunnel in the fault with 100 m width from 0.95 to 0.34, while the flexible joints only marginally reduce the tensile damage of the tunnel from 0.95 to 0.93.

![Figure 7. Maximum acceleration in longitudinal direction of the tunnel.](image)

![Figure 8. Tensile damage distribution of tunnel lining crossing 10 m fault with different aseismic measures: (a) grouting; and (b) flexible joint.](image)

![Figure 9. Tensile damage distribution of tunnel lining crossing 100 m fault with different aseismic measures: (a) grouting; and (b) flexible joint.](image)

4. Conclusions
In this paper, a series of numerical models for the tunnel crossing fault were conducted. The influence of different fault widths on the seismic response of tunnel and the suitability of different aseismic measures were investigated.

The following conclusions could be drawn:
(1) The acceleration response of the tunnel within the fault with 10 m width is greater than that of the tunnel within the fault with 100 m width;
(2) There is a “hanging wall effect” in fault-crossing tunnels in earthquake, i.e. the acceleration response in the hanging wall is greater than that in the footwall, while the “hanging wall effect” of the fault with 10 m width is more remarkable than the fault with 100 m width;

(3) Due to the difference of physical property between the fault and the surrounding rock, the differential deformation will be produced at the interface, and resulting in a shear damage of the tunnel. The tensile damage of the tunnel in the fault with 100 m width is much more severe than that in the fault with 10 m width, and the damage is mainly concentrated at the interface between the fault and the surrounding rock;

(4) Grouting reinforcement can reduce the acceleration response of the tunnel within the fault and effectively reduce the tensile damage of the tunnel;

(5) Flexible joints have little effect on the acceleration response of the tunnel within the fault. Although flexible joints concentrate the tensile damage of the tunnel in the vicinity of the joints, they have a slight effect on tensile damage reduction;

(6) For the tunnel crossing inactive faults, especially those with wide widths, grouting reinforcement is a desirable aseismic measure. It can reduce the acceleration response of the tunnel within the fault and significantly reduce the tensile damage.

Acknowledgments
This research was supported by the National Natural Science Foundation of China (51778487; 41672288; 41922059), the Shanghai Committee of Science and Technology (18DZ1205103), and the support from the Fundamental Research Funds for the Central Universities of China.

References
[1] Wang W L, Wang T T, Su J J, Lin C H, Seng C R and Huang T H 2001 Assessment of damage in mountain tunnels due to the Taiwan Chi-Chi earthquake Tunn. Undergr. Sp. Technol. 16 133–50
[2] Yashiro K 2007 Historical Earthquake Damage to Tunnels in Japan and Case Studies of Railway Tunnels in the 2004 Niigataken-Chuetsu Earthquake Q. Rep. RTRI 48 136–41
[3] Li T 2012 Damage to mountain tunnels related to the Wenchuan earthquake and some suggestions for aseismic tunnel construction Bull. Eng. Geol. Environ. 71 297–308
[4] Zhang X, Jiang Y and Sugimoto S 2018 Seismic damage assessment of mountain tunnel: A case study on the Tawarayama tunnel due to the 2016 Kumamoto Earthquake Tunn. Undergr. Sp. Technol. 71
[5] Wang Z, Gao B, Jiang Y and Yuan S 2009 Investigation and assessment on mountain tunnels and geotechnical damage after the Wenchuan earthquake Sci. China, Ser. E Technol. Sci. 52 546–58
[6] Wang Z Z and Zhang Z 2013 Seismic damage classification and risk assessment of mountain tunnels with a validation for the 2008 Wenchuan earthquake Soil Dyn. Earthq. Eng. 45 45–55
[7] Yu H, Chen J, Yuan Y and Zhao X 2016 Seismic Dammage of Mountain Tunnels durring the 5.12 Wenchuan Earthquake J. Mt. Sci. 13 1958–72
[8] Fan L, Chen J ling, Peng S quan, Qi B xi, Zhou Q wen and Wang F 2020 1.Seismic response of tunnel under normal fault slips by shaking table test technique J. Cent. South Univ. 27 1306–19
[9] Kiani M, Akhlaghi T and Ghalandarzadeh A 2016 Experimental modeling of segmental shallow tunnels in alluvial affected by normal faults Tunn. Undergr. Sp. Technol. 51 108–19
[10] Baziar M H, Nabizadeh A, Jung Lee C and Yi Hung W 2014 Centrifuge modeling of interaction between reverse faulting and tunnel Soil Dyn. Earthq. Eng. 65 151–64
[11] Zhou H, He C, Wang S, Peng F, Zhu S and Yuan D 2020 2.Dynamic Stress Concentration Factors and Damage Mode of Horseshoe Tunnels Crossing Fault Fracture Zone Geotech. Geol. Eng. 0123456789
[12] Wang X, Xiong Q, Zhou H, Chen J and Xiao M 2020 Three-dimensional (3D) dynamic finite element modeling of the effects of a geological fault on the seismic response of underground caverns Tunn. Undergr. Sp. Technol. 96 103210
[13] Sabagh M and Ghalandarzadeh A 2020 Numerical modelings of continuous shallow tunnels subject to reverse faulting and its verification through a centrifuge Comput. Geotech. 128 103813

[14] Liu X, Li X, Sang Y and Lin L 2015 Experimental study on normal fault rupture propagation in loose strata and its impact on mountain tunnels Tunn. Undergr. Sp. Technol. 49 417–25

[15] Zhong Z, Wang Z, Zhao M and Du X 2020 Structural damage assessment of mountain tunnels in fault fracture zone subjected to multiple strike-slip fault movement Tunn. Undergr. Sp. Technol. 104 103527

[16] Li L, Xian L, Yao C, Guo D and Liu C 2020 Numerical Modeling of Seismic Responses and Seismic Measures of Tunnel Crossing a Fault Zone: A Case Study Adv. Mater. Sci. Eng. 2020

[17] Huang J, Zhao M and Du X 2017 Non-linear seismic responses of tunnels within normal fault ground under obliquely incident P waves Tunn. Undergr. Sp. Technol. 61 26–39

[18] Yang Z, Lan H, Zhang Y, Gao X and Li L 2013 Nonlinear dynamic failure process of tunnel-fault system in response to strong seismic event J. Asian Earth Sci. 64 125–35

[19] Shahidi A R and Vafaeian M 2005 Analysis of longitudinal profile of the tunnels in the active faulted zone and designing the flexible lining ( for Koohrang-III tunnel ) Tunn. Undergr. Sp. Technol. 20 213–21

[20] Xin C, Gao B, Wang Y, Zhou J and Shen Y 2015 Shaking table tests on deformable aseismic and damping measures for fault-crossing tunnel structures Rock Soil Mech. 36 1041–9

[21] An D, Chen Z, Meng L and Cui G 2020 Application of fiber-reinforced concrete lining for fault-crossing tunnels in meizoseismal area to improving seismic performance Adv. Mech. Eng. 12 1–10

[22] Yan G, Shen Y, Gao B, Zheng Q, Fan K and Huang H 2020 1.Damage evolution of tunnel lining with steel reinforced rubber joints under normal faulting : An experimental and numerical investigation Tunn. Undergr. Sp. Technol. 97 103223

[23] Zhao K, Chen W, Yang D, Zhao W, Wang S and Song W 2019 Mechanical tests and engineering applicability of fibre plastic concrete used in tunnel design in active fault zones Tunn. Undergr. Sp. Technol. 88 200–8

[24] Tsinidis G, Pitilakis K and Trikalioti A D 2014 Numerical simulation of round robin numerical test on tunnels using a simplified kinematic hardening model Acta Geotech. 9 641–59

[25] Chen C H, Wang T T, Jeng F S and Huang T H 2012 Mechanisms causing seismic damage of tunnels at different depths Tunn. Undergr. Sp. Technol. 28 31–40

[26] Cui G, Wang M, Yu L and Lin G 2013 Study on the characteristics and mechanism of seismic damage for tunnel structures on fault rupture zone in Wenchuan seismic disastrous area China Civ. Eng. J. 46 122–7