A review of research on seismic damage characteristics and anti-seismic reduction measures for cross-fault

Fansen Ran*, Hongtao Zhang

North China University of Technology, Beijing China

*rfs2014ns@163.com

Abstract. Previous earthquake disasters have proven that tunnel structures spanning faults have a greater risk of damage during earthquakes. However, underground tunnel engineering is a lifeline project related to the national economy, and ensuring its safe and reliable operation during earthquakes is of great practical significance. This article first brings together relevant research results at home and abroad, introduces the seismic damage characteristics of cross-fault tunnel structures, and then conducts a review of the anti-seismic and reduction measures taken in cross-fault tunnel structures at home and abroad from the aspects of rigid design and flexible design. Discuss, compare and summarize the range of advantages of different anti-shock-absorbing measures. Finally, a brief outlook is given on key issues that still require in-depth study of cross-fault tunnel structures.

Keywords: underground tunnel engineering; tunnel structures spanning faults; seismic damage characteristics; anti-shock-absorbing measures.

1 Introduction

The "14th Five-Year Plan for the Development of Modern Comprehensive Transportation System" clearly requires that the construction of railway trunk lines and urban rail transit be accelerated, and China's tunnel construction has entered the fast lane [1]. By the end of 2022, China has put into use 17,873 railway and highway tunnels, with a total length of 21,978 km [2, 3]. China has become a real tunnel construction country and is accelerating to become a tunnel construction power.

Many earthquake surveys at home and abroad have pointed out that the tunnel passing through the fault was severely damaged by the earthquake. In 1906, the California earthquake in the United States had a magnitude of 8.3. Two tunnels on the Southern Pacific Railway were severely damaged, and both tunnels crossed the San Andreas Fault [4]. In 1978, after the Izuoshima earthquake in Japan, the secondary lining of the Inatori tunnel across the fault had obvious cracks, steel bars were broken, and the structure failed [5]. Wang [6] et al. investigated the damage status of tunnels after the Jiji earthquake. The results showed that 49 of 57 tunnels were damaged to varying degrees, and the fault zone was almost destroyed. The investigation and research on tunnel earth-

H. Bilgin et al. (eds.), *Proceedings of the 2023 5th International Conference on Civil Engineering, Environment Resources and Energy Materials (CCESEM 2023)*, Advances in Engineering Research 227,
https://doi.org/10.2991/978-94-6463-316-0_35

quake damage carried out by Cui Guangyao [7] and others along the Wenchuan earthquake zone also showed that the serious damage to the tunnel body was mainly caused by the tunnel passing through faults. Longxi Tunnel, Zipingpu Tunnel and other tunnels were damaged in the earthquake. The larger tunnels pass through seismic fault zones. It is obvious that the structural vulnerability of tunnels crossing faults is higher under earthquake action.

Generally, in order to avoid or alleviate the negative impact of cross-fault tunnels under the action of earthquakes, the tunnel alignment will be optimized at the beginning of the design to avoid geologically poor sections and fault fracture zones. However, our country has a vast territory and faults are widely distributed. Moreover, restricted by geology, cost and other objective conditions, it is often difficult to avoid crossing active faults. Major projects such as the Sichuan-Tibet Railway, Central Asia Line D along the "Belt and Road Initiative" and the Jakarta-Bandung High-Speed Railway all cross several active fault zones, and the construction of a large number of cross-fault tunnels has become a realistic development need [8-10].

In view of the actual impact of seismic activity on cross-fault tunnels, this study integrates relevant research results at home and abroad, introduces in detail the damage characteristics of cross-fault tunnel structures in earthquakes, and summarizes the anti-seismic reduction measures adopted at home and abroad for cross-fault tunnel structures. measures, further comparing their advantages and disadvantages, and also briefly prospecting the future research directions of cross-fault tunnel structures.

2 Seismic damage characteristics of cross-fault tunnel structures

Previous research generally believed that tunnels, as typical underground buildings, will move with the movement of soil layers under earthquakes, and are constrained by surrounding rocks to maintain a constant shape of the tunnel, so they should have good seismic resistance [11]. It was not until the two major earthquakes at the end of the 20th century (the 1995 Hanshin Earthquake [12] and the 1999 Taiwan Chi-Chi Earthquake [13]) that people gradually realized that tunnels would also suffer severe damage from earthquakes. Therefore, when constructing tunnels, it is necessary to have a comprehensive understanding of the earthquake damage characteristics of cross-fault tunnel structures, so as to formulate corresponding countermeasures to ensure the safety of the tunnel. Through research on the response of cross-fault tunnels under the action of earthquakes at home and abroad, it is found that the seismic damage of cross-fault tunnels is manifested in two parts: vibration damage of the tunnel under the action of earthquakes and shear damage of the tunnel under the action of fault dislocation.

2.1 Earthquake induced damage

The vibration damage of tunnels under earthquakes is the product of motion interaction and belongs to the category of dynamic effects. Tunnel lining cracking is a major damage feature induced by earthquakes in tunnel fault zones. In Figure 1, it appears as longitudinal ruptures, transverse ruptures, oblique ruptures, and circumferential ruptures penetrating through transverse or oblique ruptures. Rupture etc. Examples with obvious earthquake damage characteristics include the Longchi Tunnel and Longxi Tunnel in the Wenchuan Earthquake, the Longdongzi Tunnel and the Jijiaya Tunnel, and the Sanyi Tunnel in the Jiji Earthquake [14].

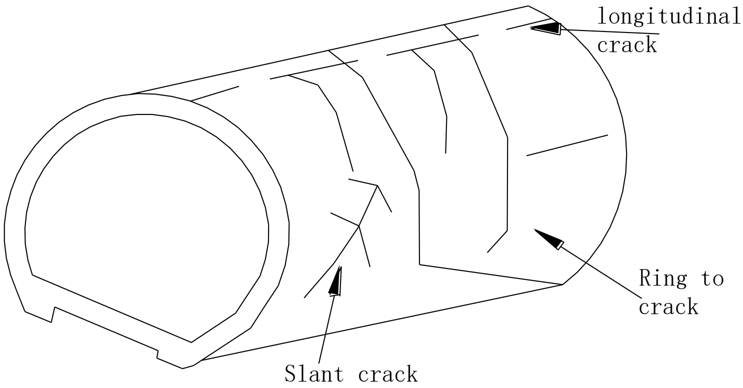

Fig. 1. Lining cracking of cross- fault tunnell.

Tunnel lining detachment or even surrounding rock collapse is another major damage characteristic of tunnels in fault zones induced by earthquakes. As shown in Figure 2, the high stress concentration caused by fault zone compression during earthquakes will cause the tunnel lining to fall off and the surrounding rock to collapse. Severe surrounding rock collapse will often lead to tunnel sealing and become the main cause of tunnel earthquake damage. The weak surrounding rock at the entrance of Longxi Tunnel collapsed, causing serious blockage of the tunnel. The secondary lining collapsed on the side wall of the Longdongzi left tunnel tunnel, causing serious damage to the tunnel[15].

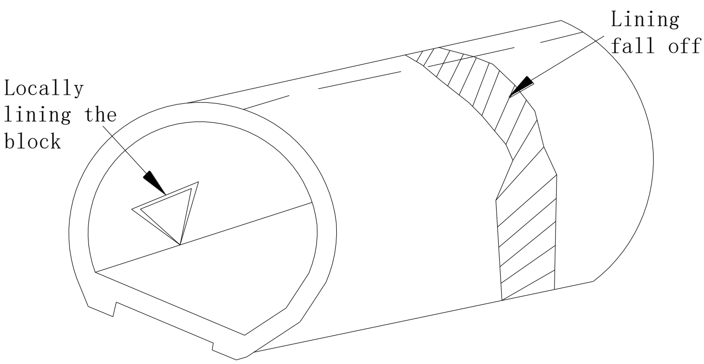

Fig. 2. The lining of a cross - fault tunnel falls off.

2.2 Fault shear failure

Fault shear failure also often occurs during earthquake damage to cross-fault tunnels. The tunnel seismic damage induced by fault dislocation is the relative displacement caused by the stiffness mismatch between the tunnel and the surrounding rock during vibration, which is a static effect. As shown in Figure 3, there is a significant relative displacement difference in the surrounding rock of the tunnel crossing the fault zone under the action of the earthquake. This is caused by the significant mutation in stiffness between the better surrounding rock and the tunnel surrounding rock in the fault zone. As a result, the tunnel structure shifted significantly at the location of the fault fracture zone, and the lining failed due to fault shear.

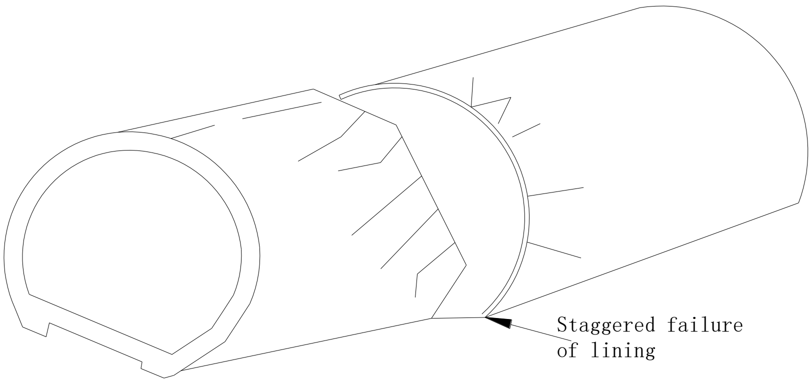

Fig. 3. Shear dislocation of tunnel lining across faults.

Among domestic and foreign earthquake events, the more common types of dislocation damage include [16]: the 1906 earthquake in San Francisco, USA, caused the Wright No. 1 Tunnel to suffer severe dislocation damage, with a horizontal dislocation degree of up to 1.37m; In the 1995 Hanshin Earthquake in Japan, the Rokko Tunnel on the Zhongshan Yang Shinkansen Line passed through the Rokko Fault System. Therefore, the tunnel structure suffered significant seismic shear dislocation damage after the earthquake; in the 1999 Jiji earthquake in Taiwan During the earthquake, the Shigangba water diversion tunnel passed through the Chelungpu fault, which caused the tunnel lining to suffer significant dislocation damage in the fault area. The deformation of the tunnel in the vertical direction reached 4.0m, and the deformation in the horizontal direction was as high as 3.0m, which caused damage to the entire tunnel system; in the F8 fault area near the Longxizi Tunnel of the Duwen Expressway [19], both construction joints and non-construction joints have significant misalignment damage, and the deepest misalignment depth can reach 0.6m. It can be clearly seen that under the influence of earthquakes, the risk of dislocation damage in tunnel fault zones is relatively high.

3 Anti-seismic and damping measures for cross-fault tunnel structures

Conducting seismic research on cross-fault tunnels is a guarantee for safe tunnel operation. However, in the seismic design of cross-fault tunnels, it is impossible to design a structure to resist earthquake damage. An effective method is to identify hazards during geological survey and take appropriate anti-seismic measures for the tunnel fault zone to localize the scope of earthquake damage. According to the vibration characteristics of underground structures, there are two main ideas for anti-seismic reduction measures for cross-fault tunnels. One is the rigid design method based on improving its own seismic performance, and the other is aimed at reducing the transmission of seismic energy from the ground to the structure. flexible design method. Currently, there are four mainstream methods in the industry for building tunnels across faults to reduce earthquake damage to tunnel structures, namely : ① Surrounding rock reinforcement; ② Setting up shock-absorbing layers; ③ Over-excavation design; ④ Articulated design.

3.1 Rigid design method

Rigid design mainly focuses on enhancing the structural stiffness to resist earthquake effects, which is called "hard resistance" . Its purpose is to enhance the stiffness of the tunnel lining structure itself or increase the overall stiffness of the surrounding rock within the fault fracture zone to reduce the harm caused by earthquakes. To a certain extent, it can reduce the displacement of the lining structure caused by the earthquake, but the structural stiffness The increase will inevitably strengthen the earthquake impact and increase the structural stress. Its desirability needs to be discussed.

3.1.1 Surrounding rock reinforcement. Surrounding rock reinforcement includes grouting reinforcement and the setting of anchor rods. Grouting reinforcement can change the quality of the surrounding rock, thereby promoting the integrity of the surrounding rock and improving the seismic resistance of the tunnel. For example, the Nanyangshan Tunnel uses micro-steel pipe pile grouting to reinforce the fault surrounding rock; the Majiazhai Tunnel uses advance small conduit grouting to reinforce the loose surrounding rock, and its seismic effect is significantly enhanced. Tang Yinfei [17] and others relied on detailed statistics and research on the historical earthquake damage of tunnel crossing fault sections, and carried out indoor experiments and numerical model analysis based on the Moganling Tunnel to analyze the impact of grouting reinforcement on the resistance of cross-fault tunnels. Based on the effect of the seismic reduction method, calculation models were constructed respectively, and the following conclusions were drawn: when the thickness of the grouting layer increases, the peak acceleration response and stress response of the tunnel lining are significantly reduced. As shown in Figure 4, Zheng Qing [18] and his team conducted a comparative study on three different grouting reinforcement methods—full-ring interval type, full-ring contact type, and local type—to evaluate the seismic resistance of these three methods on tunnel support structures. performance. The research results reveal the stress patterns of these three grouting methods in various strata, and suggest that the use of the full-ring interval grouting method can significantly improve the seismic performance of the tunnel support structure.

The setting of anchor rods is limited by its high anchoring cost, complicated technological process and relatively low seismic resistance cost-effectiveness. It is mainly considered for use in certain rock formation areas with poor geological conditions. With the development of our country's economy and the improvement of people's living standards, more and more attention has been paid to highway construction. Therefore, many areas have begun to use anchor technology to build highways or high-speed railways and other projects. This can not only reduce project costs but also effectively Ensure construction quality. For example, in the tunnel project of Lixiang Railway, anchor technology has been used to strengthen the soft rock structure.

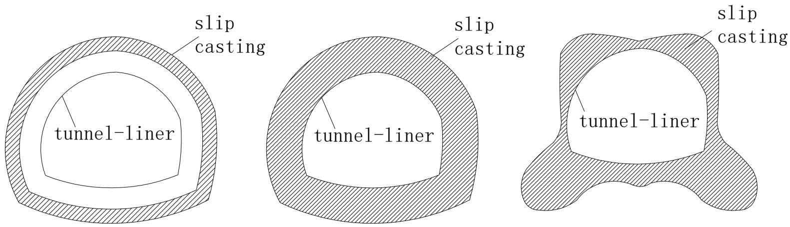

Fig. 4. Grouting reinforcement scheme for surrounding rock in a cross-fault tunnel.

3.1.2 Lining structure optimization. When an earthquake occurs, the higher the stiffness of the lining, the greater the internal force value. Using a lining structure with higher stiffness cannot achieve the expected seismic resistance effect, and "hard resistance" cannot effectively reduce the damage caused by earthquakes. The mechanical properties of the lining structure of a tunnel in a fault zone should match the characteristics of the surrounding rock and transitional surrounding rock in the fault zone. The tunnel structure cannot suffer more damage simply by increasing the stiffness or thickening of the supporting structure and other "hard resistance" measures. Serious damage.

The performance optimization of lining structures mainly includes the application of lightweight and high-strength materials, the application of appropriate stiffness linings, the most reasonable lining thickness design, and the enhancement of the load-bearing capacity of weak points. Taking the Suai Tunnel as an example, for the weak parts, that is, the node parts of the segments, the strength of the bolts is strengthened to enhance the seismic resistance of the tunnel.

3.2 Flexible design method

The core idea of flexible design is to reduce the inherent stiffness of the structure so that underground buildings can deform more effectively with changes in the stratum, thereby reducing the response speed of underground buildings under the influence of earthquakes. Underground buildings not only have the ability to withstand static loads, but can also effectively absorb seismic energy and forced displacements. In this industry, the main application methods include setting up shock-absorbing belts, using over-excavation designs, and articulated designs.

3.2.1 Set up shock absorbers. The placement of a shock-absorbing layer means placing specific materials between the tunnel's support structure and its adjacent surrounding rock, or isolating the rock at a specific distance outside the support structure. At the same time, the stiffness of the shock-absorbing layer is appropriately adjusted to achieve the purpose of reducing the strength of the tunnel support structure. The shock-absorbing layer can effectively reduce or avoid surface displacement caused by seismic wave propagation and the resulting lining damage and other problems. The location of the shock-absorbing layer can be between the surrounding rock and the supporting structure, or between the primary support and the secondary lining. By using a shock-absorbing layer to isolate the supporting structure and surrounding rock media, the input of seismic energy to the supporting structure can be effectively reduced or changed.

Commonly used shock-absorbing measures include shock-absorbing joints and shock absorbers, and have been used in actual projects. For example, there are four shock absorption points in the Suai Tunnel, and the shock absorption points are connected with SMA steel plates and Ω-shaped rubber waterstops. The lining of the cross-fault section of Galongla Tunnel is equipped with one shock-absorbing joint every 5m with a width of 0.5m.

Implementing seismic attenuation measures in tunnels can result in excellent seismic performance. Sui Chuanyi [19] and his team conducted in-depth research on the role of shock-absorbing equipment in the seismic performance of tunnels, and they found that shock-absorbing equipment can significantly reduce the internal stress of the structure, thereby enhancing its seismic resistance. Nakamura [20] and Shahroulls [21] conducted an in-depth study on the role of the damping layer in the seismic resistance of tunnels. They found that setting the damping layer in the transition area between soft and hard surrounding rocks can significantly improve the seismic performance of the tunnel. Zhu Zhengguo [22] and his team studied the strength of the shock-absorbing layer and concrete. Their research found that although the increase in concrete strength does not significantly help improve the seismic resistance of the structure, adding a shock-absorbing layer can bring significant seismic effects.

The actual performance of the tunnel's shock-absorbing layer is closely related to its structural strength, thickness, length, spatial layout and other factors. Wang Yonggang [23] and his team artificially created ground motions and used finite element numerical simulation to study the vibration response of tunnels under different numbers of earthquake-absorbing joint arrangements. Research results show that configuring three earthquake-absorbing joints can achieve the best earthquake-absorbing effect; Liu Yang [24] and his team suggested that the tunnel's earthquake-proof measures should maintain a safe distance of about 100m from the fault; Wang Linhui [25] aimed at cross-fault An in-depth comparative study of the shock-absorbing effects of tunnels in the broken zone under different shock-absorbing layer designs was conducted. Research shows that setting up a seismic-absorbing layer between the secondary lining and primary support is the most efficient method, and the longer the longitudinal length of the seismic-absorbing layer, the more significant the improvement in the seismic resistance of the tunnel.

3.2.2 Section over-excavation. The over-excavation design is a passive design, which assumes that the tunnel section will undergo permanent deformation along the fault displacement plane under the action of strong earthquakes. The core concept is to expand the tunnel section to adapt to the cumulative creep displacement of the fault zone over a certain period of time and possible earthquakes. A certain seismic displacement value is generated, and the tunnel expansion is used to ensure the clearance area requirements of the tunnel. At the same time, it is beneficial to the tunnel's use for a certain period of time and post-earthquake structural repair. The amount of over-excavation is mainly determined by the seismic intensity, surrounding rock conditions and tunnel cross-section. During the expansion process, the tunnel structure is usually a double-layer lining structure, with porous materials (such as foam concrete) or no porous materials filled between the inner and outer linings. Filled with porous materials, in the case of fault displacement, the gap between the inner and outer linings can ensure the clear area of the tunnel cross-section and minimize the damage to the tunnel structure caused by the displacement.

There have been many successful cases at home and abroad using expanded excavation to cross tunnel fault zones. The Malaysian Railway Tunnel Network 1 adopted measures to expand the fault-affected zone and excavated the inner contour of the tunnel to 45cm, and there have been no problems in operation so far; the Berkeley Hills Tunnel of the San Francisco Bay Area Rapid Transit System in the United States is in the process of crossing the Hayward fault zone The "expansion excavation" method was adopted, and through stratigraphic creep analysis and seismic displacement analysis, it was believed that the allowable fault displacement movement during the tunnel crossing the fault fracture zone was 1 foot. The operation practice of multiple tunnels has shown that it is feasible to expand and dig through fault zones. The bidding section for tunnel expansion should be clear. Li Yu et al. [26] selected Wushaoling Tunnel as the research target. After expanding and analyzing different parts of the tunnel and analyzing its mechanics, they found that for tunnels in fault zones, expansion can create fault offsets. It has the advantage of bringing redundant space and reducing the overall stress of the structure. However, for ordinary sections of tunnels, excavation will significantly increase the bending moment and shear force, and excavation will be more harmful to it.

3.2.3 Articulated design. Aihara [27] first suggested the use of flexible connection methods to cross fault fracture zones in the design of natural gas pipelines, and emphasized that this flexible connection method needs to be able to adapt to changes in all aspects of the tunnel structure. As an iconic structural means in flexible design, "articulated design" has demonstrated significant advantages.

The core idea of applying "articulation design" to the tunnel structure is: when the tunnel structure crosses the fault zone, the tunnel support structure is mainly connected segmentally, and each segment is connected with weakened materials or structural measures, so that each structural measure It not only maintains its independence as much as possible but also shortens the tunnel segments as much as possible, so that damage to the connecting support structure during the dislocation of the fault zone mainly occurs at the connecting part or part of the structure without causing overall damage to the structure. The more successful examples of hinged design are mainly the BOLU highway tunnel in Turkey passing through the Bakacak fault zone and the Zekidagi fault zone, and the Koohrang water conveyance tunnel in Iran passing through the 300-meter-wide Zarab fault zone [28].

3.3 Discussion and analysis

The two main damage forms of cross-fault tunnels under earthquake action are earthquake-induced damage and fault dislocation shear failure. Fault displacement damage is often accompanied by earthquake-induced damage, but it does not always exist when there is earthquake-induced damage. Fault dislocation damage. The external manifestations of earthquake-induced damage are cracking and detachment of the lining, and collapse in severe cases, while fault shear damage is manifested as longitudinal dislocation of the tunnel.

There are two design concepts for seismic reduction of cross-fault tunnel structures: rigid design and flexible design. Compared with the two, flexible design takes into account both safety and economy and should be the priority method of seismic reduction.

There are two methods of rigid design: surrounding rock reinforcement and lining optimization. Surrounding rock reinforcement is more common. There are three methods of flexible design: shock-absorbing layer, over-excavation design and hinged design. The shock-absorbing layer is often used.

Over-excavation design and hinge design are mainly proposed to deal with the influence of fault dislocation, which is beneficial to tunnel fault zones, but harmful to ordinary sections of tunnels.

4 Conclusion and Outlook

This article reviews relevant domestic and foreign literature on cross-fault tunnel structures, introduces in detail the two main damage characteristics of cross-fault tunnels under earthquake action, summarizes the main anti-seismic reduction strategies for cross-fault tunnel structures at home and abroad, and conducts comparative analysis. The advantages and scope of application of each measure are analyzed.

In order to accelerate the realization of global interconnection, more cross- fault tunnels will be constructed, which will put forward higher demands on the seismic resistance of cross-fault tunnel structures. The seismic research on cross-fault tunnel structures still needs to be improved. The author believes that further research can be conducted in the following aspects:

Deeply study existing tunnel earthquake damage cases, build a database of earthquake levels, tunnel earthquake damage characteristics, quantity and specific information, and explore the commonality and individuality of earthquake damage in tunnels that cross faults, providing a reference for analyzing the earthquake mechanism of cross-fault tunnels and making decisions on earthquake reduction measures.

Strengthen the systematic research on the practicality and adaptability of seismic resistance measures for cross-fault tunnel structures, with special emphasis on the research and application of major projects. At present, tunnel anti-seismic reduction measures are still in the research stage and are not very practical. We should vigorously promote anti-seismic reduction measures, enhance the seismic resistance of cross-fault tunnel structures, and carry out verification and verification of tunnel anti-seismic reduction measures.

References

1. State Council of the People's Republic of China. Notice of the State Council on Issuing the Development Plan for the Modern Comprehensive Transportation System during the "14th Five-Year Plan" (Guofa [2021] No. 27) [J]. Gazette of the State Council of the People's Republic of China, 2022, 15(4): 8-28.
2. Gong Jiangfeng, Wang Wei, Li Xu, et al . Statistics of China's railway tunnels as of the end of 2022 and overview of key tunnels for newly opened projects in 2022 [J]. Tunnel Construction (Chinese and English), 2023, 43(4): 721- 38.
3. Journal of China Highway and Transportation Engineering, Editorial Department. Review of academic research on traffic tunnel engineering in China·2022 [J]. Journal of China Highway and Transportation Engineering, 2022, 35(4): 40-43.
4. Song Wuran. Be wary of secondary earthquake disasters and strengthen disaster chain risk prevention - commemorating the 65th anniversary of the 8.6-magnitude earthquake in Alaska, USA [J]. Disaster Prevention Expo, 2022, 15(2): 15-16 .
5. Toruwa. Site of the Izu Peninsula Okinawa earthquake victim settlement area: Utilized geology[J]. 2017, 12(6): 89-94.
6. WANG H J. Analysis of strong ground motion data from the Jiji earthquake[J]. 2009.
7. Cui Guangyao, Wu Xiugang, Wang Mingming, et al . Analysis of earthquake damage formation mechanism of highway tunnels across fault zones in Wenchuan earthquake area [J]. Chinese Journal of Geological Hazards and Prevention, 2018, 29(2): 7-10.
8. Fu Yingmei, Gu Yunlong. Decision analysis of China's high-speed rail "going global"—taking Jakarta-Bandung high-speed rail as an example [J]. 2021, 24(2016-31): 15-16.
9. Zhong Wei, Li Xiuzhen, Cui Yun, et al . The impact of landslide disasters on the route selection of the Kangding-Chamdo section of the Sichuan-Tibet Railway [J]. Railway Standard Design, 2018, 62(1): 5-8.
10. ZUBAIR A M. Potential impact of the Belt and Road Initiative on Pakistan's civil engineering construction model[D]; Southwest University of Science and Technology, 2019.
11. Yu Haitao, Ren Huihui, Chen Juntao, et al . Shaking table test study on construction methods for variable stiffness tunnels under strong earthquakes [J]. Journal of Rock Mechanics and Engineering, 2023.

12. ITO A, OKUTSU M. IMPROVEMENT OF DISASTER PREDICTION SCREENING METHOD OF TELECOMMUNICATION CONDUIT FOCUSING ON MANHOLES [J]. Journal of Japan Society of Civil Engineers, Ser A1 (Structural Engineering & Earthquake Engineering (SE/EE)), 2019.
13. Chen Yang, Wang Qiuliang, Qin Weibing, et al . Analysis of engineering characteristics and time-frequency characteristics of near-fault ground motions in the Chiji earthquake in Taiwan [J]. 2021.
14. Cui Guangyao, Liu Weidong, Ni Songzhi, et al . Seismic damage analysis and seismic damage mechanism research on the ordinary section of the highway tunnel in Wenchuan earthquake [J]. Rock and Soil Mechanics, 2015, (S2): 8.
15. Briaud jl, Smith td, Tucker l m. a Pressuremeter Method For Laterally Loaded Piles. Proceedings Of The Eleventh International Conference On Soil Mechanics And Foundation Engineering, San Francisco, 12-16 August 1985 [J]. Language In India , 1985.
16. Liu Yang. Seismic response analysis of interval tunnels passing through liquefiable soil layers [J]. Zhejiang University, 2008.
17. Tang Yinfei, Xu Jinsong, Sun Runfang, et al . Research on mechanical characteristics and seismic dynamic response of high-fill corrugated steel culverts [J]. Subgrade Engineering, 2018, (6): 6.
18. Zheng Qing. Seismic damage analysis of mountain tunnel and study on seismic dynamic response of tunnel entrance section [D]; Southwest Jiaotong University, 2010.
19. Sui Chuanyi, Gao Bo, Shen Yusheng, et al . Shaking table test analysis of seismic performance of tunnels with high and steep slopes [J]. Vibration and Impact, 2017, (19): 194-202.
20. Nakamura s, Yoshida n, Iwatate t. Damage to Daikai subway station during the 1995 Hyogoken-Nambu earthquake and its investigation [J]. Japan Society of Civil Engineers, Committee of Earthquake Engineering, 1996, 6: 287-95.
21. SHAHROUR I, KHOSHNOUDIAN F, SADEK M, et al. Elastoplastic analysis of the seismic response of tunnels in soft soils [J]. Tunnelling and underground space technology, 2010, 25(4): 478-82.
22. Zhu Zhengguo, Cui Zhenwei, Ma Chaoyi, et al . Performance optimization of steel fiber foam concrete material for initial support of earthquake absorption [J]. China Railway Science, 2022, (003): 043.
23. Wang Yonggang, Zhu Zhaolin. Forward modeling of P-SV converted waves in fractured anisotropic media [J]. Petroleum Geophysical Exploration, 2005, 44(1): 5.
24. Liu Yang, Zhao Renda, Xiang Xingyun, et al . Research on seismic reduction and isolation design of long-span continuous beams in high-intensity areas [J]. Journal of Railway Science and Engineering, 2018, 15(5): 9.
25. Wang Linhui. Research on seismic response and shock-absorbing layer measures of tunnel structures that cross faults[D]; Southwest Jiaotong University, 2014.
26. Li Yu, Zhang Yu. Analysis of the impact of adjacent tunnel expansion construction [J]. Modern Tunnel Technology, 2007, 44(3): 6.
27. Caulfield rj, Kieffer ds, Tsztoo df, et al. Seismic Design Measures for the Retrofit of the Claremont Tunnel [J]. 2005.
28. Xin Chunlei, Gao Bo, Zhou Jiamei, et al . Shaking table test study on conventional anti-seismic reduction measures for cross-fault tunnels [J]. Journal of Rock Mechanics and Engineering, 2014, 33(10): 9.