Study on anti-dislocation measures for railway tunnels crossing active faults in complex and dangerous mountainous areas

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ABSTRACT: The geological environment of the Tibetan plateau region is complex, with extensive development of active faults. Tunnels built in this area would be greatly affected by active faults. To study the anti-fault measures for the tunnel, active faults were counted along the railway. We then analyze measures to reduce dislocations and review existing fundamental conclusions on fault prevention. Preliminary results on the staggered classification of active faults have been obtained through a literature analysis. Anti-fracture measures that might be applied to the railway were identified. It includes the use of segmental composite lining structure (such as steel-mixed composite structure), improving the stiffness of flexible articulated joints (such as corrugated steel), increasing the width of articulated joints, fault fracture zone core expansion design and other measures. The results can be used as a basis for a quantitative study of anti-fracture measures.

Keywords: Mountain railway tunnel; active faults; anti-dislocation measures.

0 INTRODUTION

The geological environment of Tibet Plateau in China is complex, with high altitude, high ground temperature, high intensity, high earthquake intensity, high ground stress, high water pressure, active fault zone and other geological characteristics (Fig. 1). The construction of railway in this area is a very complicated project, and the active fault will have a great impact on the safety of railway in this area. The railway starts from the Sichuan Basin through the Tibetan Plateau to Tibet, and the tunnel is buried at a depth of more than 2,000 meters. The terrain along the railway is very undulating. The railway crosses seven rivers (i.e., Yalong River, Jinsha River, Lancang River, Nu jiang, Palong Zangbo and Yalung Zangbo River) and eight mountains (i.e. Mangkang, Taniantaweng, Boshullaling and Sejila Mountains). Under the control of tectonic movement, regional structure and lithology, rock mass shows compressive ductile structural deformation, brittle fracture, cataclysmic mylonitization, plastic deformation and stress change under strong shearing stress. Multiple active faults developed along the Ya 'an to Nyingchi Railway (Pen et al., 2020; Xu et al., 2016). Tunnels acrossing active fault zones are faced with the risk of fault collapse under fault dislocation, and active faults have a great impact on tunnel construction and later operation. Therefore, special design is required for tunnels that cross many active fault zones.

Based on the engineering background of Ya 'an-Nyingzhi tunnel, this paper introduces the large active faults along the tunnel. The classification of fracture is carried out to lay a foundation for the subsequent design of anti-fracture measures. Then the basic principle of fault prevention in mountain tunnel is introduced. Finally, based on the existing research, the possible fault prevention measures for tunnels are analyzed.

1 ACTIVE FAULTS ALONG THE TUNNEL

There are 54 active faults along the Ya 'an-Nyingchi Railway, including 17 regional active faults. As shown in Fig. 1, there are more than 10 large active fault zones along the railway, including Longmen Mountain, Xianshuihe, Yulongxi, Litang, Garzi-Litang, Batang, Jinsha River, Lancang River, Bangong Hu-Nujiang, Basu, Jiali-Yigong, Yarlung Zangbo River, and Waka. These active faults are composed of small faults of different scales, of which more than 100 have an impact on engineering safety (Pen et al., 2020; Xu et al., 2016).

The Longmenshan active fault zone dislocated several tunnels during the 8.0-magnitude Wenchuan earthquake, causing great damage to tunnels in this area (Yu et al., 2016). As shown in Fig. 2, the Longmenshan fault belt stretches from Tianquan in the south to Mianxian in the north, with a length of about 500km and a width of 25-70km, extending 45° east-north. It is formed by the combination of three reverse wash slip fault zones with an inclination of 65°~80°. The stratigraphic lithology is distributed from Quaternary to Sinian period, mainly composed of clastic rock, SLATE, phyllite, granitic magmatic rock and volcanic rock. The rock is broken and cracks develop.

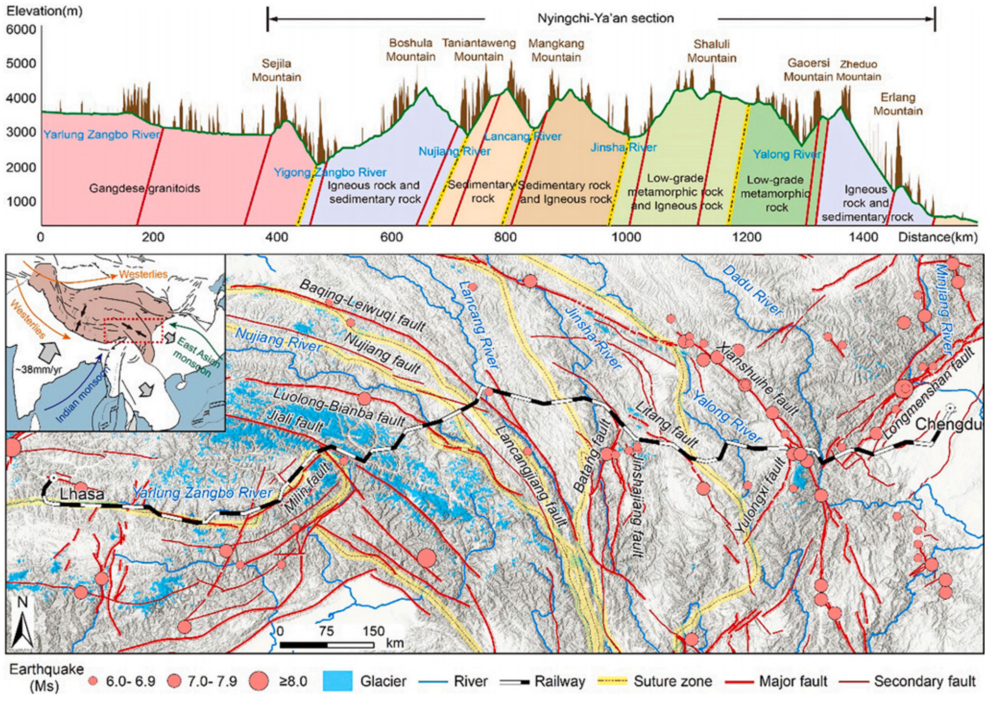

Figure 1. Geological and geomorphological setting of the Ya 'an to Nyingchi Railway. (Cui et al., 2022).

The three main faults of Longmen Mountain from north to south are the Back mountain fault zone of Longmen Mountain, the central fault zone of Longmen Mountain, and the front mountain fault zone of Longmen Mountain respectively (Fig. 2). The Back Mountain fault zone of Longmen Mountain mainly includes Wenchuan - Maowen fault and Pingwu-Qingchuan fault. Among them, the Wenchuan - Maowen fault is dominated by thrust, and the Pingwu-Qingchuan fault is dominated by strike-slip with a certain dip slip. The main fault zone of Longmen Mountain is Yingxiu-Beichuan fault, which has great right-lateral strike-slip and thrust effects. The Qianshan fault zone of Longmen Mountain is mainly Guanyan-Anxian fault, which is a brittle thrust with steeper dip Angle. The main active faults in the adjacent areas of Longquanshan tectonic belt include Longquanshan fault, Minjiang fault, Hukou fault and Xueshan fault. Among them, Longquanshan fault is dominated by thrust, Minjiang fault, Hukou fault and Xueshan fault are dominated by slip and have some thrust.

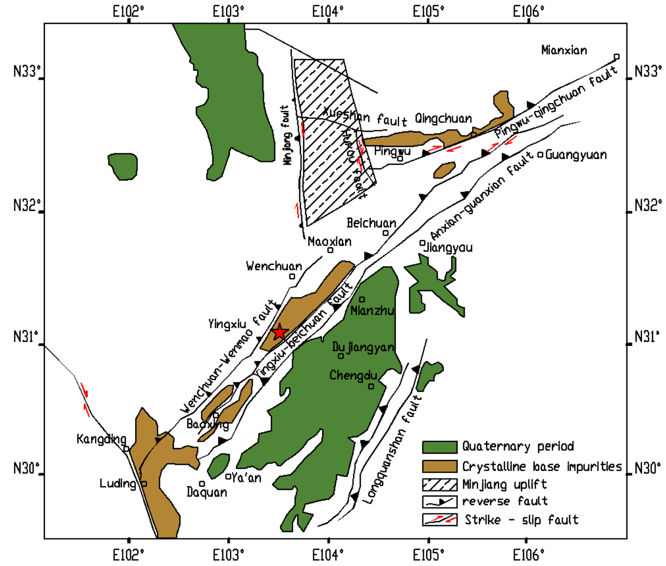

Figure 2. Regional tectonic background map of Longmenshan fault zone(Xu, 2014).

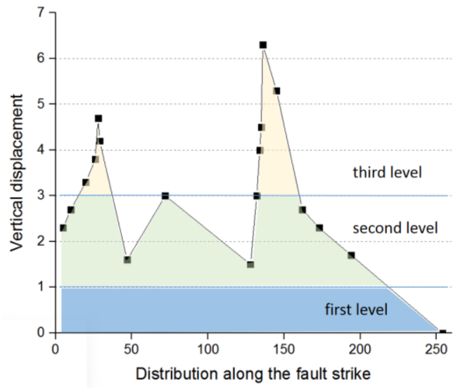

Figure 3. Longmenshan fault dislocation grading diagram.

The Ya 'an to Nyingchi Railway involves many active faults, and most current studies are still focused on the anti-fault measures of active faults, and there are few literatures on the detailed classification of fault motion to study the impact of faults on tunnels. Therefore, this section classifies the fault according to the fault value, and then studies the measures to reduce the tunnel fault according to the fault level. After fault slip value classification, the damage of tunnel under different fault levels is calculated, and the fault levels are corrected according to the damage conditions. Finally, the dislocation standard and dislocation grade of tunnels crossing active faults are determined according to the dislocation grade.

The classification method of active faults adopted in this paper is as follows: the fault momentum penetration value of the entire active fault zone section is the first grade, that is, the first level in Fig. 3. Most of the active fault zones reach the second level of fault momentum, that is, the second level in Fig. 3. Only a small part of the area that reaches the maximum slip momentum of the active fault zone is the third grade, that is, the third level in Fig. 3. In the following study, the application of this standard will be determined by case model calculation. The methods adopted in case model calculation include the lining hinge design in section 3.1, the surrounding rock expansion design in Section 3.2, and the methods and principles in Section 4. The slip momentum of active faults in Longmen Mountain is shown in Table 1 (Xu, 2014). Taking the Longmenshan regional active fault zone of Wenchuan earthquake in 2008 as an example, this section classifies the slip value of the fault, and the classification results are shown in Fig. 3.

Table 1. The dislocation of the Longmenshan active fault.

	Fault zone block	Main crack	Surface fracture	Dislocation quantity	Average ground fault distance	Occurrence
Longmenshan fault zone	Main boundary of mountain front Fault zone	Guanxian-Anxian fault	About 100 kilometers.	The shortening rate is less than 3 mm/a and the recoil rate is less than 1 mm/a vertical dislocation 0.39~2.70m,	1.6m vertically and 0.6m horizontally; Ratio of vertical and horizontal	Towards NE40~ 70 ° dip NW dip 30~50 °

				horizontal dislocation 0.20~0.70m	dislocation amount 2:1	
	Main central fault zone	Yingxiu - Beichuan fault	About 220 km	Vertical dislocation 1.60~6.00m, horizontal dislocation 0.20~6.50m, maximum 6m, total oblique displacement 7.6m	3.0m vertically and 3.1m horizontally; Thrust component: right-lateral strike-slip component is 1:1	Strike NE30 °~50 ° and dip NW 70 °~80 °
	Houlongmenshan fault	-	-	About 2 m maximum	The ratio of horizontal and vertical dislocations is 1 : 1~1 : 3	-

Kangding 1 tunnel, runs through the Selaha-Kangding fault, which is about 80 kilometers long. It is the main fault in the southern section of the Xianshuihe fault zone, and the fault activity is mainly left-lateral strike-slip. The fault is inclined to the west with an inclination of 70°-80 °, an activity rate of 5.5±0.6-10.7 mm/a, and its centennial slip is 1.07 m. According to the classification level in Fig. 3, it belongs to the second grade of fracture, and the anti-dislocation measures can be determined according to the subsequent fortification objectives.

2 ANTI-FRACTURE DESIGN PRINCIPLE

At present, the common anti-fault measures of tunnel include the hinged design of lining, the over-excavation design of surrounding rock, the vibration isolation and energy dissipation, the design of strengthening stiffness, and the application of new materials. Among them, many anti-fault methods are adopted, such as the hinge design of lining and the overbreak design.

2.1 Articulation design of tunnel lining

Flexible joint, deformation joint, shear joint, seismic joint and hinged joint are often used to describe the measures in the study of anti-fault hinged joint system of cross-fault tunnel structure. It has the following advantages: (1) it has a good anti-seismic and anti-fault effect (Jalali M, 2018); (2) The smaller the distance between the hinged joints, the better the overall flexibility of the tunnel structure and the better the control ability of deformation. The structure will not have too much adverse internal force response, which is conducive to the improvement of the anti-fault section and seismic ability of the tunnel. The value of segment length, that is, the quantitative calculation of joint spacing, has not reached a unified conclusion in the design of tunnel lining articulation.

2.2 Overbreak design

"Surrounding rock overbreak design" refers to the design of an appropriate enlarged cross-section size based on the predicted amount of active fault dislocation when the tunnel passes through the fault fracture zone. This design method can ensure the effective clearance area of the tunnel when the fault is moving, and can maintain the normal operation function of the tunnel. After the tunnel surrounding rock is overdug, due to the reservation of deformation space, the harmful displacement of the lining structure caused by fault dislocation, such as wrong platform, collapse and other lining diseases, will not damage the local intrusion limit. The cross-sectional overcut is generally calculated according to the centennial fault momentum estimate in the geological survey report. The Claremont tunnel in San Francisco, USA, Wushaoling Tunnel of Lanxin Railway in China, Chengdu-Sichuan section of Chengdu-Lanshan Railway in China are the application cases of tunnel surrounding rock excavation (Liang et al., 2004; Xian, et al., 2018).

2.3 Seismic isolation and energy dissipation structure

The design of seismic isolation and energy dissipation is a design method based on the design of tunnel overdigging. The main purpose of the design of energy dissipation device is to completely absorb the adverse displacement caused by fault dislocation by using the flexible damping layer and the initial supporting structure, so as to reduce the influence on the second lining of the tunnel. This method is mainly based on the design concept of "soft outside and rigid inside", filling the gap between the outer side of the secondary lining structure and the supercut profile with special energy-absorbing materials. The common measures for isolation and energy dissipation include foam concrete cushion, yield unit with small stiffness ratio, perforated concrete layer, etc. Therefore, when the isolation and energy dissipation device is used, the seismic response, damping and fault slip reduction effects of tunnel structures under different stiffness, damping and seismic wave frequency variables can be analyzed.

2.4 Reinforced stiffness design

Stiffness reinforcement design generally refers to the design concept of reinforcement of tunnel surrounding rock by pre-support measures such as grouting reinforcement. The purpose of this measure is to improve the overall stiffness ratio of support system and surrounding rock to resist the influence of surrounding rock stress on tunnel structure. In the design measures to strengthen stiffness, the initial support measures include the use of steel fiber concrete and the addition of steel arch. The methods adopted in secondary lining structure include improving the strength of lining concrete, increasing the ratio of structural reinforcement of secondary lining and increasing the thickness of secondary lining.

2.5 Application of new materials in lining structure

In the study of fault dislocated tunnel, the research and development of new materials to replace the traditional reinforced concrete materials, improve the mechanical properties of tunnel lining, is also one of the effective measures to deal with the threat of active fracture. Basalt fiber, new plastic concrete and fiber reinforced cement composites are the new materials for lining structure. One of the more mature alternatives is fiber concrete(Zhang, et al., 2018).

3 ANTI-FRACTURE MEASURES OF YA 'AN TO NYINGCHI RAILWAY

Previous studies have shown that the damage length of segmental tunnel is about 1/5~1/4 of the damage length of continuous tunnel. The articulated design avoids the large-scale collapse of the tunnel and ensures the integrity of the tunnel structure. However, due to the low tensile strength of concrete, tunnel lining will still have obvious cracking failure under fault action even if flexible joint design is adopted. At the same time, after adopting the segmented articulation design, the lining segment crossing the fault sliding surface will still have obvious shear failure under the fault movement, so it is recommended to increase the structural strength of the lining in the engineering design.

The joint strength has been studied by relevant scholars. The results show that the "in-seam arrangement" between the flexible joint and the fault sliding surface, the reduction of the flexible joint stiffness and the increase of the flexible joint width can effectively reduce the axial damage degree of the tunnel lining and improve the anti-fault performance of the structure. Therefore, in the tunnel of the fault-resistant flexible system, the structural design of the joint (such as corrugated steel) can reduce the joint stiffness and increase the joint width, which can further improve the anti-fault performance of the tunnel.

To sum up, all kinds of anti-fault design by changing tunnel lining materials, structural system and surrounding rock materials aims to reduce the damage degree of tunnel lining structures under active fault movement. Previous studies have shown that a single type of anti-fault design can effectively reduce the damage degree of tunnel lining, but there may still be obvious damage under large fault dislocations. Therefore, it is the research direction to develop new anti-fault structural system or combine different anti-fault design measures.

The geological environment along the Ya 'an to Nyingchi Railway is complex, with extremely high ground stress, tectonic stress, numerous active faults and great fault momentum. Therefore, in the design and research of the railway anti-fault, the design principle of relative flexibility is adopted in the axial direction of the tunnel, and the design principle of improving the stiffness of the tunnel lining is adopted in the lateral direction. The articulation design method of tunnel is studied comprehensively. The measures recommended in this study are: the use of segmental composite lining structures (such as steel-hybrid combination structures), increasing the stiffness of the flexible articulation (such as corrugated steel, compared to rubber articulation joints stiffness increase), increasing the width of the articulation joints, and the design of the core expansion of the fracture zone. By improving the strength of lining segments, the axial tensile strength of intersegment and the shear strength of hinged joint cross section, the above measures can be taken to improve the adaptability of tunnel lining to fault.

4 CONCLUSIONSTUDY

The following conclusions are drawn from this paper.

(1) In this paper, we have presented regional active faults along the railway under construction in the Tibetan plateau. Based on the momentum of the Longmen Mountain active fault in the Wenchuan earthquake, the fault dislocation grade is divided into three levels. This sets the stage for the development of anti-dislocation measures based on the grade of the fracture. Based on the existing common measures and the basic principles of fracture prevention, it was determined that the direction of tunnel protection measures in this area is the hinged design and the extended excavation design.

(2) Based on the existing research on the damage laws of tunnel-crossing faults, anti-dislocation measures for tunnel-crossing faults in complex and difficult mountainous areas should be a comprehensive approach that incorporates practical conditions. The research on the defensive measures of Ya 'an to Nyingzhi railway tunnel may adopt the integrated design methods such as sectional composite lining structure (such as steel-concrete composite structure), increasing the stiffness of flexible articular joints (such as corrugated steel, increased stiffness compared to rubber hinge joints.), increasing the width of articular joints, and expanding the core of fault fracture zone.

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