Aseismic Study on Mountain Tunnels in High-Intensity Seismic Area

Gao Bo, Wang Shuai-shuai, Wang Ying-xue and
Shen Yu-sheng

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Abstract

The chapter discusses the antiseismic and shock absorption study on the mountain tunnels in high-seismic intensity areas using numerical analysis and shaking table test for recent years and proposes the seismic challenges of tunnel design in Sichuan-Tibet Railway. The aseismic design of the tunnel entrance and the inner part in the fracture zone are presented according to the previous research results.

Keywords: mountain tunnels, high-intensity area, aseismic design, antiseismic, shock absorption

1. Introduction

There have been many investigations on the underground structures damages during strong earthquakes in the world (Konagai, 2005; Sharma and Judd, 1992), and after the Wenchuan earthquake, our research team investigated the earthquake disaster of the mountain tunnels located in the Du (Dujiangyan)-Wen (Wenchuan) highway (Wang et al., 2009). It has been investigated that the mountain tunnel suffered serious damages at the tunnel portal due to widespread landslides and rockfalls, and the major damage of the inner part of the tunnels were concentrated in the poor geological sections due to forced displacement, when tunnel crossed the fracture zones and active fault. The serious mountain tunnel damage during Wenchuan earthquake inspired Chinese researchers and engineers to pay attention to the antiseismic and shock absorption research of the mountain tunnel.

In this chapter, the studies of our research group on the antiseismic and shock absorption of mountain tunnels in high-intensity seismic area in recent years are presented. The first part of this chapter introduces the studies of antiseismic and damping design of the mountain tunnels in high-intensity seismic zone located in the Ya (Yaan)-Xi (Xichang) highway. The second part introduces the challenges in the aseismic design of mountain tunnels located in Chuan (Chengdu)-Zang (Lhasa) high-speed railway.

2. Brief description of Yaxi Expressway

As shown in **Figure 1**, Yaxi Expressway begins in Yaan and ends in Lugu Town, designed as a four lane highway with speed of 80 km/h, and the line has a total length of 240 km, which passes through the mountains with a tunnel ratio as 55%. Climbing from the margin of the Sichuan basin to Hengduan mountainous highlands, the Yaxi Expressway crosses through the China Southwest Geological disaster prone deep canyon area, along the line the terrain conditions are extremely precipitous, with extremely complex geological structure, changeable climate, and fragile ecological environment. The engineering construction conditions are very hard, and it is very difficult to ensure operation safety, so the highway project is considered as one of the highest contents of science and technology expressway in mountainous area with the worst natural environment.

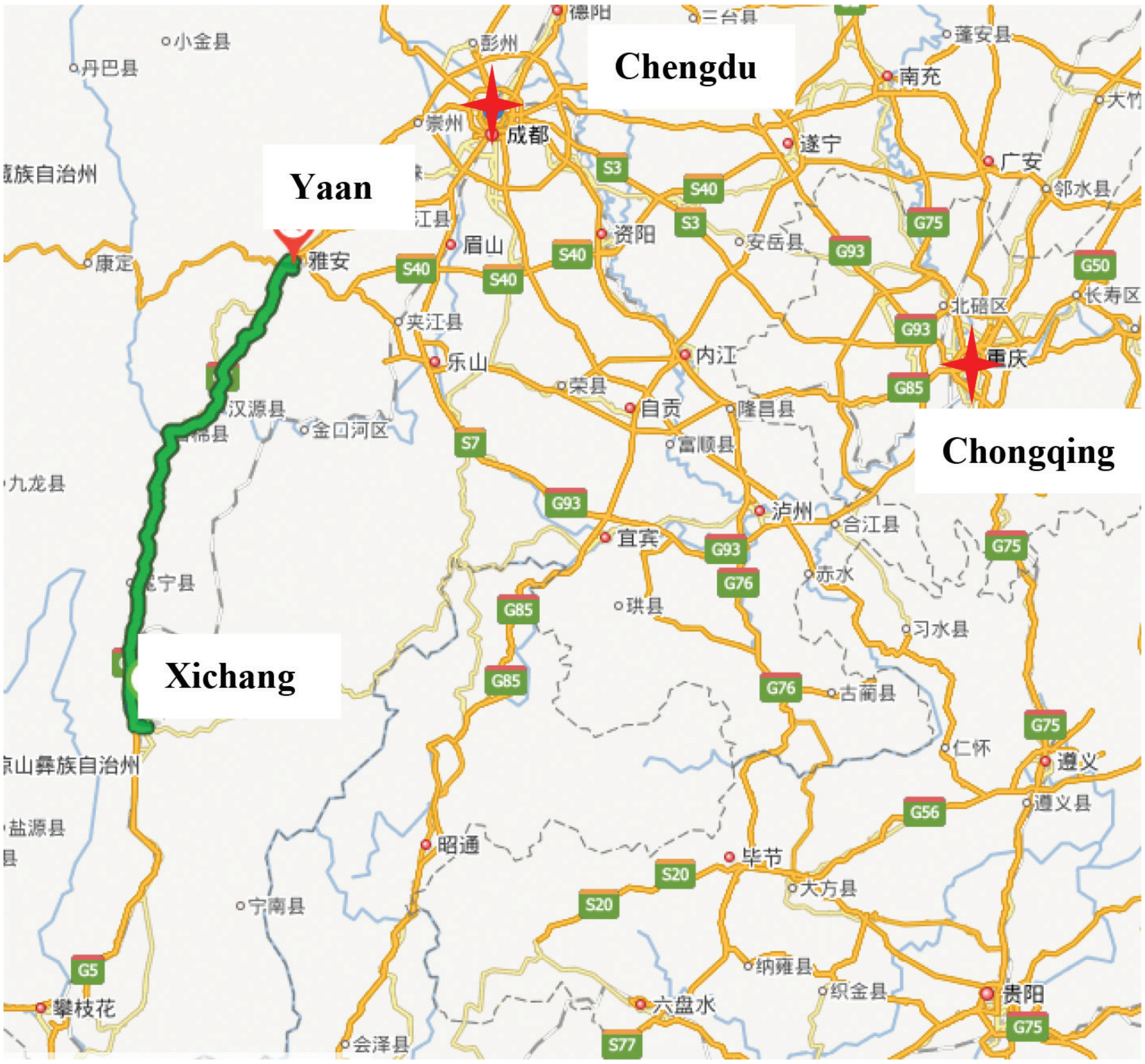


Figure 1. Yaxi Expressway.

Yaxi Expressway crosses 12 earthquake fault zone, and the PGA reaches from 0.15 to 0.4 g, which is the largest ground motion parameter in the highway design and construction in China at present. The tunnels of Yaxi Expressway are all located in high-intensity seismic zone, especially the Le Bukoragi tunnel, which passes through the Anning River active fault zone with an amplitude ground motion of 0.4 g. Investigations have shown that the mountain tunnel entrance and the inner part across the fault tend to sustain serious damage subjected to strong earthquake motions (Wang et al., 2009), so it is essential and important to investigate the deformation mechanism of the mountain tunnel.

In this chapter, the aseismic studies of our group on the dynamic response of the mountain tunnels are presented for recent years, and the antiseismic and shock absorption measures in the tunnel design are introduced.

3. Aseismic study on tunnel portal of Yaxi Expressway

In this section, the research results on the dynamic stress and deformation mechanism of tunnel entrance achieved by numerical simulation and shaking table test in recent years are introduced.

3.1. Numerical analysis on the dynamic response of the tunnel entrance

The numerical models of Cheyang tunnel and Xudianzi tunnel entrance in the dynamic time history analysis by FLAC3D are shown in **Figure 2** and **Figure 3**.

The bending moments of the Cheyang tunnel liners in the entrance at 8.7 second subjected to vertical shear waves are shown in **Figure 4**, when the maximum bending moment is in the left arch foot position. The distribution of the bending moment of the tunnel cross-section indicates that the dynamic stress concentration is in the arch foot position where the tunnel transverse shape mutates.

As shown in **Figure 5**, most elements of the slope in the tunnel entrance are in tension plastic state, especially these elements around the cavities are in tension plastic state during the strong ground motion.

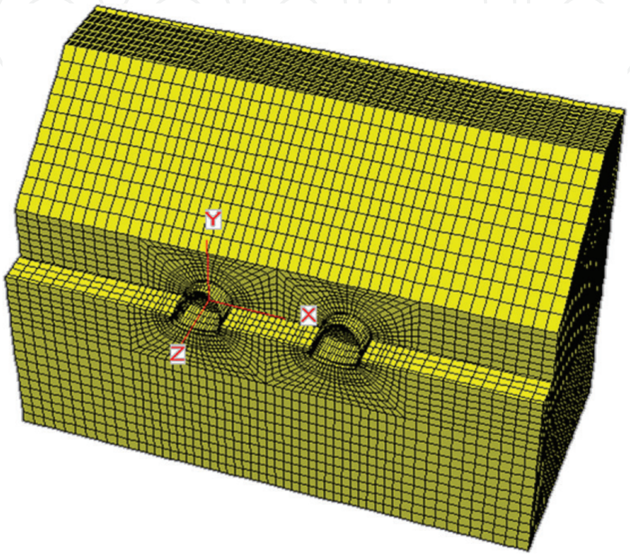


Figure 2. Analysis model of Cheyang tunnel.

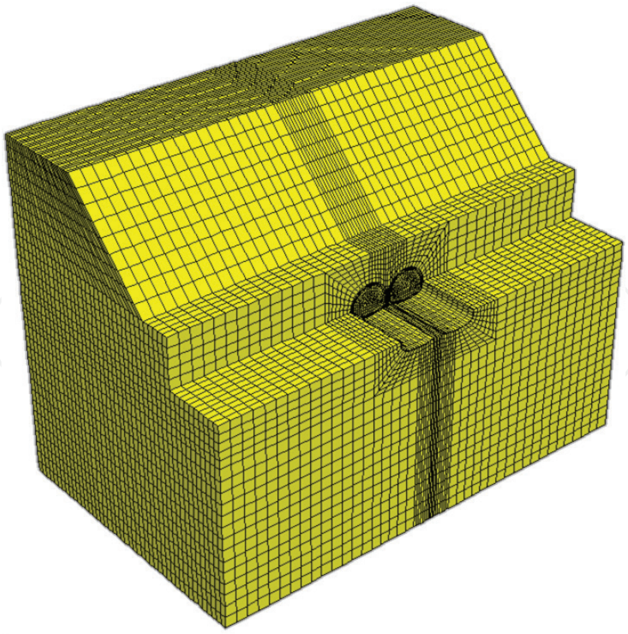
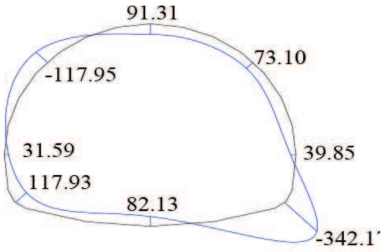
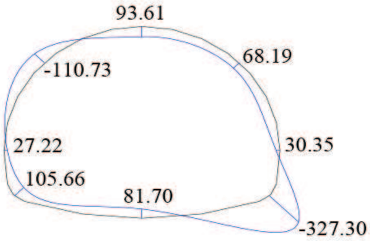


Figure 3. Analysis model of Xudianzi tunnel.



a) Left tunnel (kN.m)



b) Right tunnel (kN.m)

Figure 4. The bending moments of Cheyang tunnel in the entrance at 8.7 second.

The analysis results demonstrate that the bending moment of the liner in the entrance is much larger than that of the inner part, as the peak bending moments along the Xudianzi tunnel presented in **Figure 6**, it is shown that the maximum peak bending moment is in the position of tunnel entrance, and the associated value decreases as the distance to the tunnel entrance increases, and when the distance reaches four times the tunnel diameter, the tunnel entrance has little effect on the dynamic stress of the inner part.

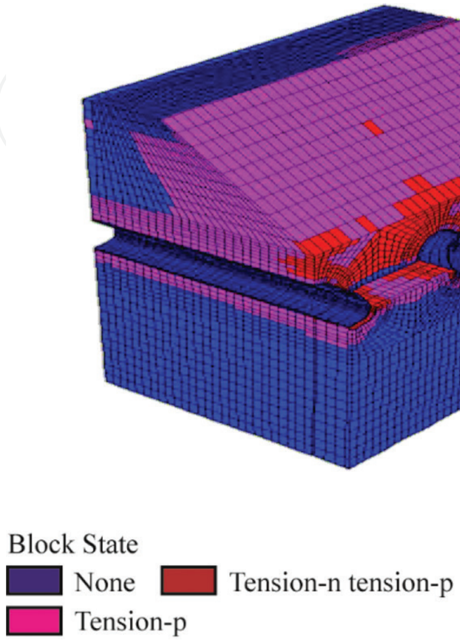


Figure 5. The tension plastic zone of Cheyang tunnel entrance.

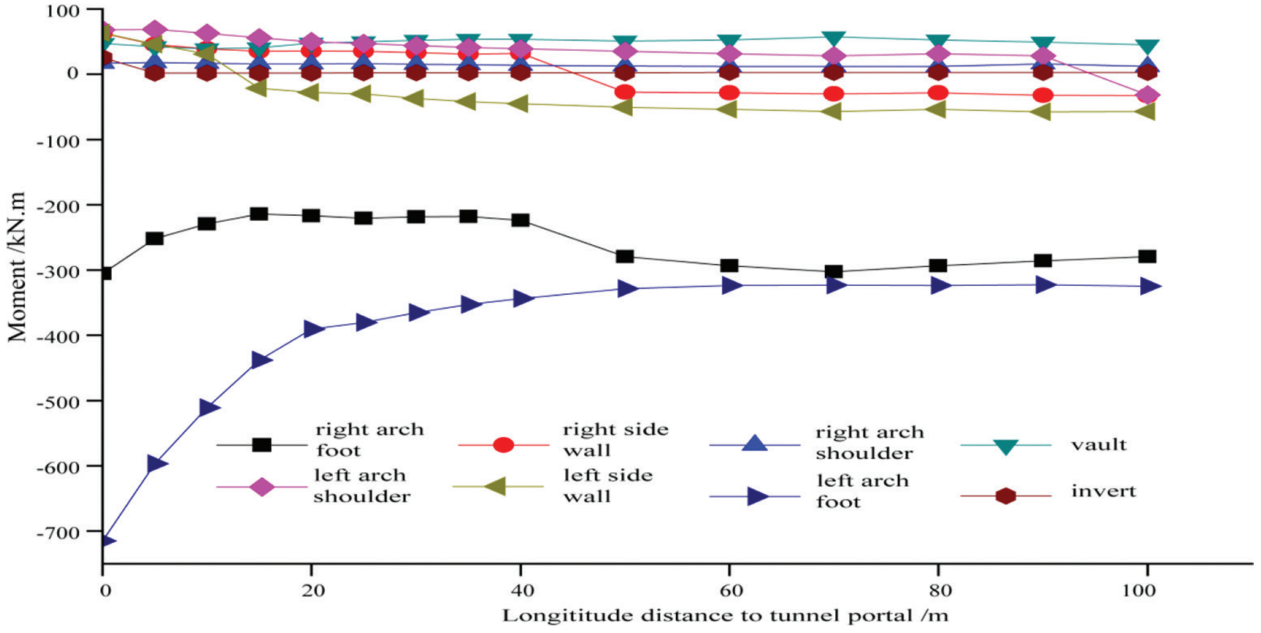


Figure 6. The peak bending moments of Xudianzi tunnel.

According the analysis in the previous sections, it is important to keep the stability of the tunnel entrance slope in the aseismic design.

3.2. Antiseismic and shock absorption study

Studies have shown that grouting the surrounding rock (Shen et al., 2014; Wang et al., 2014) and covering the tunnel with a soft layer (Kim and Konagai, 2001; Wang et al., 2015) are effective measures for mitigating seismic damage to tunnels, as shown in **Figure 7** and **Figure 8**.

The dynamic analysis of Xudianzi tunnel entrance for two kinds of structures with grouting and covering damping layer were achieved using FLAC3D, the analysis models are presented in **Figure 7** and **Figure 8**.

The bending moments distribution of the section in the entrance are presented in **Figure 9** and **Figure 10**, the bending moment values of the arch foot positions can be found larger than that of other positions. The maximum bending moment decreases with grouting as shown in **Figure 9**, and the associated value is effectively reduced by covering the tunnel with a soft isolation layer as seen in **Figure 10**.

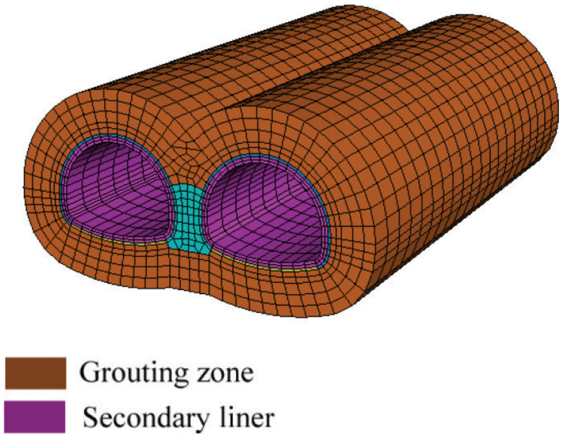


Figure 7. Grouting the surrounding rock.

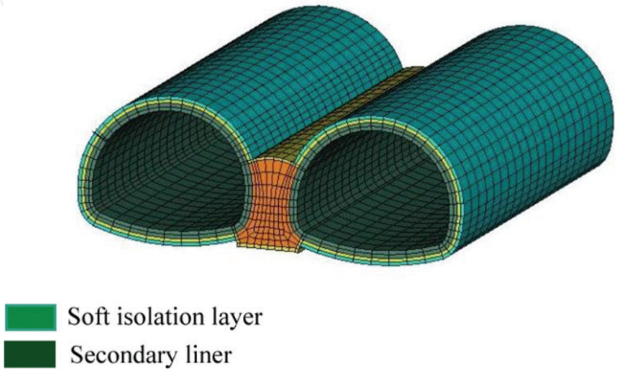


Figure 8. Covering the tunnel with a soft isolation layer.

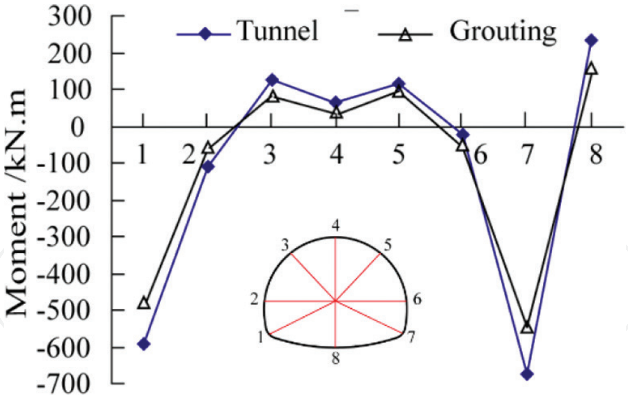


Figure 9. The bending moments with grouting.

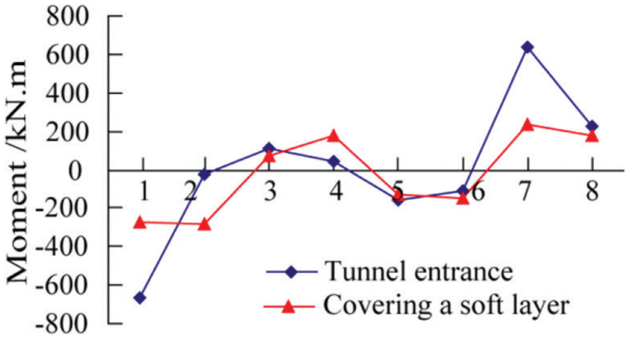


Figure 10. The bending moments with covering a soft isolation layer.

3.3. Shaking table model test on tunnel entrance

Two large scale shaking table model tests of the portals of two parallel tunnels were carried out, with the model geometry similarity ratio of 25, to investigate the dynamic response of tunnel liners and the interaction between surrounding rock and tunnel structure subjected to vertical shear waves in 2007. The model test items and methods of test are introduced in the research paper (Sun et al., 2011), and two cases are introduced here: case 1 for general tunnel entrance, and case 2 for covering the tunnels with soft isolation layer.

The distribution of ground cracks of tunnel entrance models subjected to vertical shear waves are presented in **Figure 11** and **Figure 12**.

The ground cracks are concentrated in the slope near the portal, as shown in **Figure 11**, and these shear cracks in the tunnel arch shoulders position are mostly caused by the interaction between the tunnel structure and surrounding rock under shear waves; however, the distribution of the ground cracks on the top surface of the entrance are in different directions of "X" shape.

Figure 11. The distribution of ground cracks.

Figure 12. The distribution of ground cracks with soft isolation layer.

The ground cracks are in tunnel arch shoulder position when the tunnels are covered with soft isolation layer, illustrated in **Figure 12**. The number of the model ground cracks for case 2 is significantly reduced by covering the tunnel with soft isolation layer.

The damage patterns of the liner models of the right tunnel are drawn in **Figure 13** and **Figure 14** after vibration, **Figure 13** shows that the side wall of general tunnel liner was badly damaged and fallen down after strong ground motion, and the damage of the tunnel liner with covering a soft damping layer is obviously reduced as illustrated in **Figure 14**.

3.4. Summary

The numerical analysis and model test results show that the dynamic response of the tunnel entrance is larger than the inner part subjected to shear waves, and the liner damage can be effectively eliminated by covering a soft isolation layer.

Figure 13. The fracture of the liner (right tunnel) in case 1.

Figure 14. The fracture of the liner with soft isolation layer (right tunnel) in case 2.

4. Aseismic study on tunnel in fault and fracture zone

The tunnel earthquake investigations (Konagai, 2005; Sharma and Judd, 1992; Wang et al., 2009) have shown that tunnels crossing fault and fracture zone suffered serious damage during earthquake.

In this section, the shaking table model test and numerical analysis results are introduced to investigate the dynamic response of the Le Bukoragi tunnel in fault and fracture zone.

4.1. Shaking table model test on tunnel across fault fracture zone

To investigate the dynamic stress and deformation mechanism of the tunnel in fault and fracture zone, two large scale model tests were carried out: case 1 for the general tunnel, and case 2 for the tunnel across fault fracture zone.

The longitudinal sections of the two models are shown in **Figure 15** and **Figure 16**. The similarity ratios and the material physical parameters of the surrounding rock and liner are presented in the research paper (Sun et al., 2011; Wang et al., 2015). The longitudinal width of the fault zone is 10 cm, by contrast with the prototype width reaching up to 3 m, and the physical parameters of the rock model in the fault fracture zone are listed in **Table 1**.

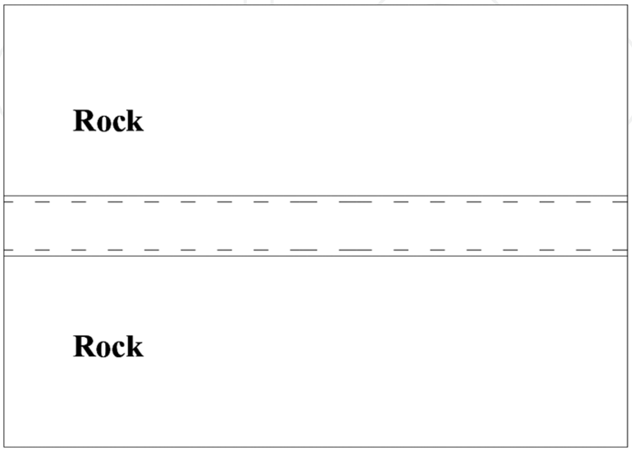


Figure 15. Longitudinal section of the general tunnel in case 1.

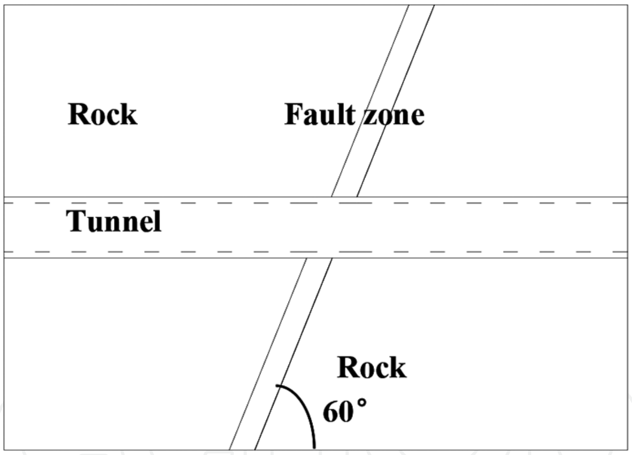


Figure 16. Longitudinal section of the tunnel across fault zone in case 2.

Parameter	Rock prototype	Rock prototype	Rock model	Units
Cohesive strength	85	45	2.4	kPa
Fraction angle	17	1	19.2	°
Young modulus	0.9×10^3	45	30.1	MPa
Density	1.9	1.5	1.3	g/cm^3

Table 1. Rock parameters of the fault zone.

As shown in **Figure 17**, the longitudinal cracks appear in the vault, arch foot, side wall, and invert positions of the liner after vertical shear wave excitation, caused by bending moment and compressive strain. As illustrated in **Figure 18**, one circumferential shear crack appears in the fault fracture zone caused by shear strain, which shows that the dynamic response of the liner will be greater when the tunnel passes through the fault fracture zone, due to the stiffness difference between the hard rock and fracture zone.

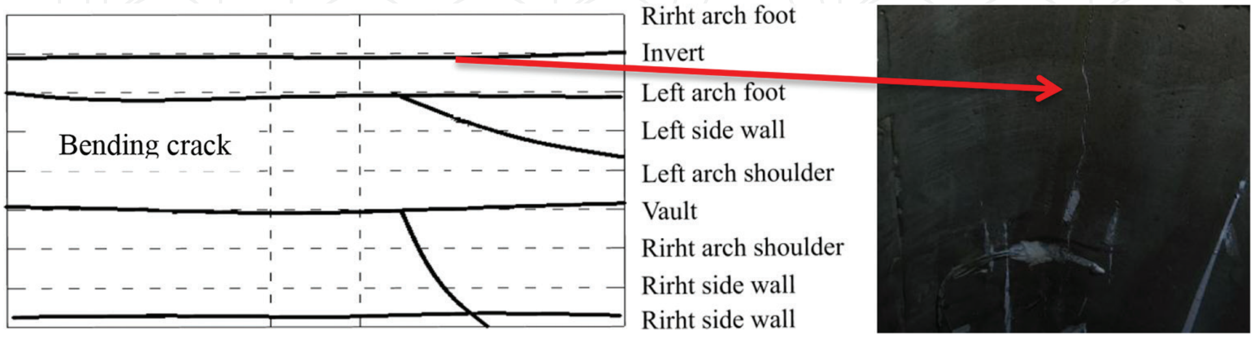


Figure 17. The cracks of the general tunnel in case 1.

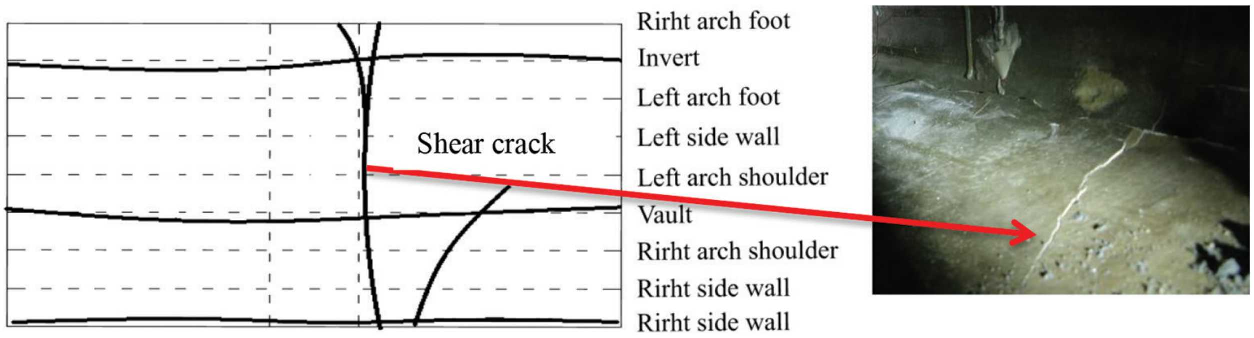


Figure 18. The cracks of the tunnel across fault zone in case 2.

4.2. Numerical analysis on jointed tunnel across fault fracture zone

It is possible to see that the stiffness difference between the soft rock in the fracture zone and the hard rock has an obvious effect on the tunnel response according to shaking table model test results. Here, the numerical analysis of the tunnel across the fault and fracture zone is introduced, and the analysis model using FLAC3D can be seen in **Figure 19**.

Researches (Shahidi and Vafaeian, 2005) have shown that the structure design using deformation joints to tolerate the longitudinal differential displacements can effectively reduce the damage of the tunnel, so two analysis cases were performed: case 1 for general tunnel without joints, and case 2 for the design structure with deformation joints along the longitudinal tunnel.

As shown in **Figure 20**, it is indicated that the displacement amplitudes of the vault in the fault zone are greater than other parts along the tunnel, which shows that the dynamic response of the tunnel in the fault fracture zone becomes larger for the differential stiffness between the soft and hard rock, as illustrated in **Figure 21**, the amplification effect of the bending moments of the linear vault are obvious in the fault fracture zone.

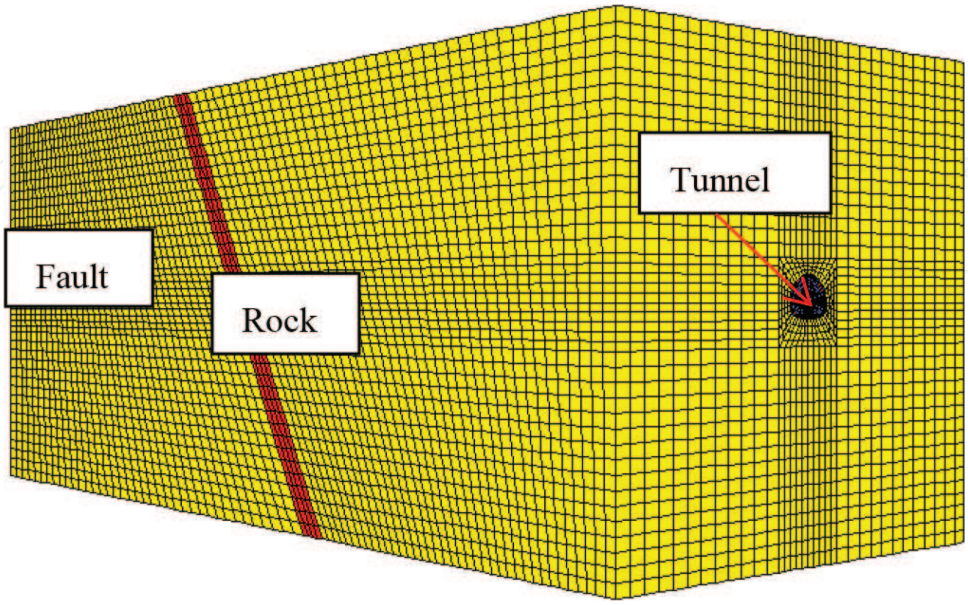


Figure 19. The numerical model of tunnel across fault zone.

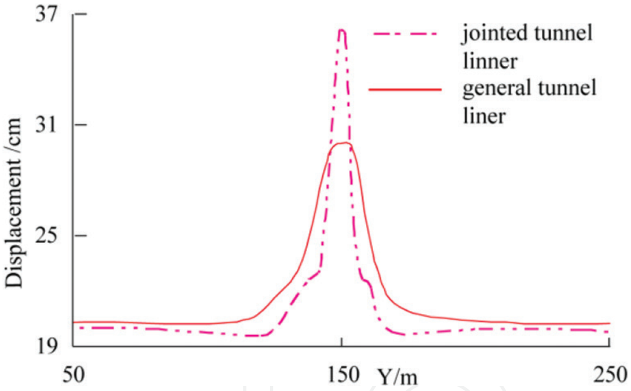


Figure 20. The displacement amplitude of vault of tunnel across fault zone.

As illustrated in **Figure 20**, it proves that the displacement amplitudes of the jointed tunnel in case 2 are greater than that of the general tunnel in case 1 in the fault fracture zone, while the associated values of the joined tunnel in other positions are smaller than that of the tunnel without joints. It can be seen from **Figure 21** that the moments amplitudes of the joined tunnel are smaller than the general tunnel, due to the better deformation capacity of the joined tunnel.

4.3. Summary

The research results by the shaking table tests and numerical analysis shows that the dynamic response of the tunnel becomes larger due to the differential stiffness between the fault fracture zone and hard rock, and the dynamic response of the tunnel decreases with joints along the tunnel.

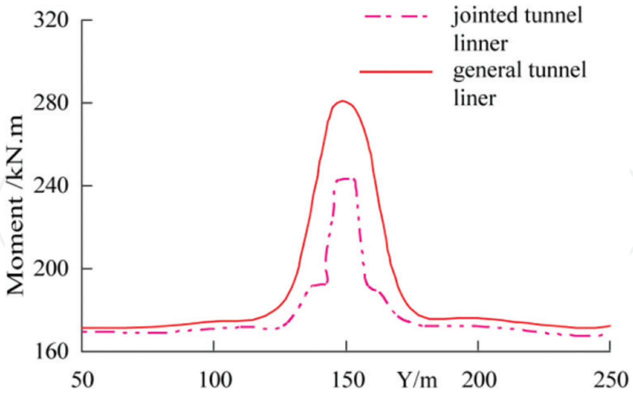


Figure 21. The bending moment amplitude of vault of tunnel across fault zone.

5. The challenges in the aseismic design of Sichuan-Tibet Railway tunnels

As shown in **Figure 22**, the Sichuan-Tibet Railway passes through several crust splicing tapes and active faults (Shang et al., 2005), especially for Chengdu to Kangding section with strong earthquake rupture in history. Studies have shown that the strong earthquake vibration, and the formation of secondary disasters such as landslides faulting, landslides, avalanches, and other damage are great challenges for the line selection and structure design (Konagai, 2005; Shang et al., 2005; Sharma and Judd, 1992).

As described, the tunnel portal and the inner part passing through the fault and fracture zone always suffered serious damage, and it is very important to reduce the risk and damage from strong earthquake and its secondary disasters.

The sections of the tunnel in which the antidamping design must be concentrated are presented, and according to the antiseismic and shock absorption research results, the following principles are shown in **Figure 23**:

(i) The primary dangers at tunnel entrances are landslides and rockfalls, and efforts should be concentrated to improve the stability of the slope, as illustrated in **Figure 23**, such as bolting and shotcreting, reducing the slope gradient by slope cutting, and improving the thickness of the tunnel backfill.

(ii) The settlement joints are proposed to set for improving the deformation capacity of the tunnel in the entrance, and it is also recommended when the tunnel passes through the fault and fracture zone.

(iii) The surrounding rock should be grouting, and it is suggested to cover the tunnel with soft isolation layer to reduce the dynamic stress of the liner in the tunnel portal.

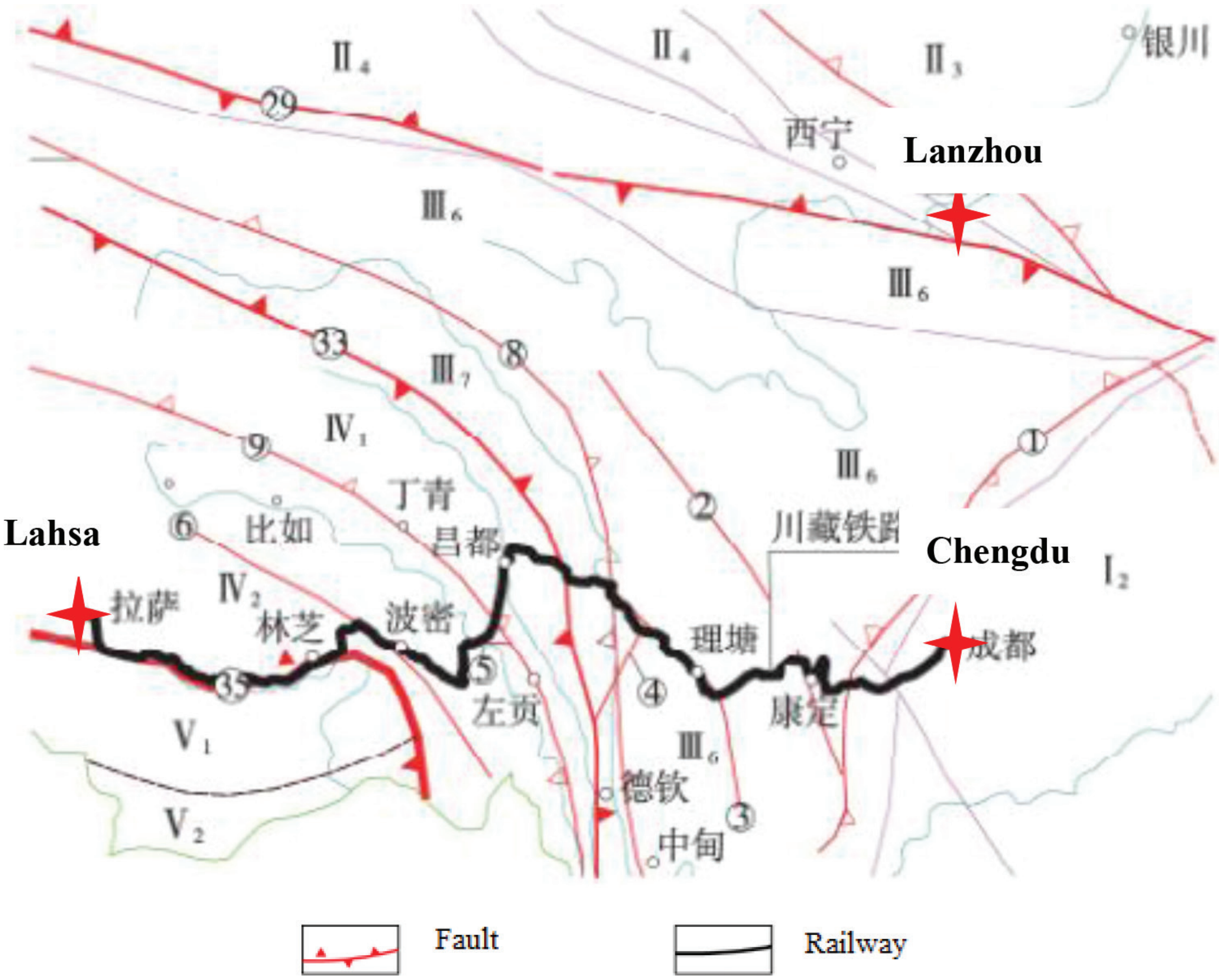


Figure 22. The distribution of faults along the Sichuan-Tibet Railway (Zhang et al., 2016).

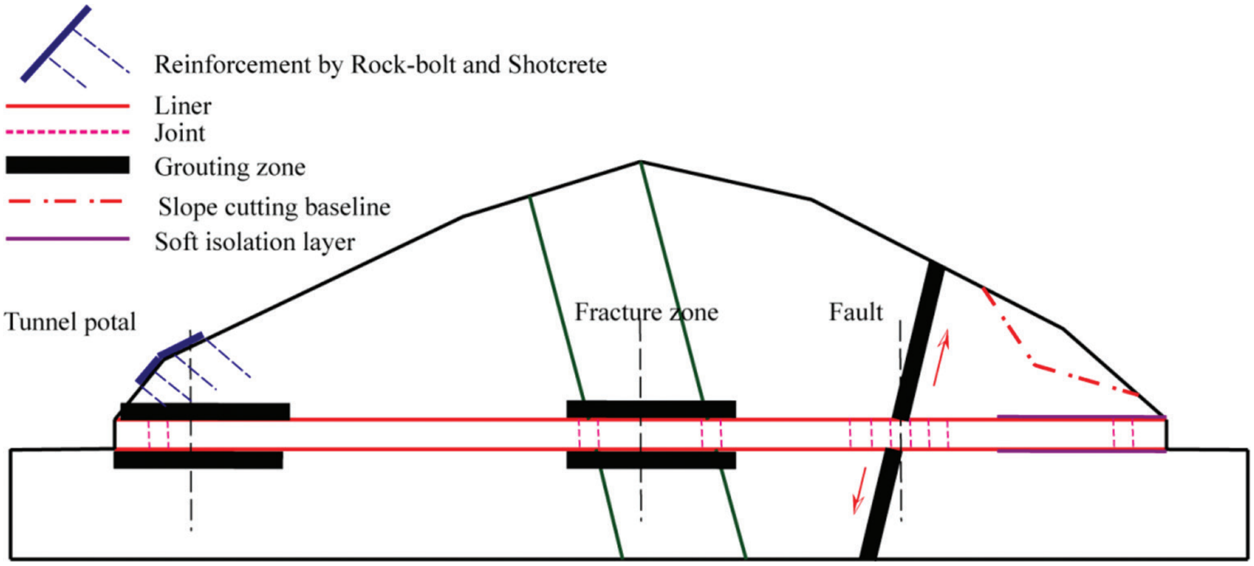


Figure 23. The aseismic design schematic diagram along the tunnels.

6. Summary

The chapter introduces the research results on the anti-seismic and shock absorption studies of our group of mountain tunnels in high seismic intensity areas in recent years, and discusses the challenges in the design of tunnels in Sichuan-Tibet Railway. It shows that the dynamic response of the tunnel in the portal and the fracture and fault zone becomes larger, and the dynamic response of the tunnel in the entrance can be effectively mitigated by grouting the surrounding rock and covering soft isolation layer, and the dynamic stress of the tunnel passing through the fracture and fault zone decreases with joined structure design.

Conflict of interest

The authors declare that there is no conflict of interest.

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Author details

Gao Bo*, Wang Shuai-shuai, Wang Ying-xue and Shen Yu-sheng

*Address all correspondence to: prgaobo@vip.sina.com

Civil Engineering School, Southwest Jiaotong University, Sichuan, China

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