Seismic Response of Mountain Tunnels by Comprehensive Analysis Methods and Feasible Aseismic Measures

Zhiyuan Cheng[1, †], Yunhua Su[2, †], Chenhan Xu[3, *, †]

[1]College of Civil Engineering, Tongji University, Shanghai 200092, China

[2]College of Harbour, Coastal and Offshore Engineering, Hohai University, Nanjing 210098, China

[3]College of Civil Engineering, Jilin University, Changchun 130000, China

*Corresponding author: xuch2418@mails.jlu.edu.cn

†These authors contributed equally.

Abstract. In mountainous area, earthquake is an inevitable factor during the construction of tunnel. Earthquake can cause great damage to faults and mountain slopes, and at the same time, the deformation and failure of mountain tunnels are closely related to faults and landslides. This study analyzes the impacts of faults and landslides on the mountain tunnel by numerical modelling, model test and field investigation, and discusses the corresponding engineering countermeasures. Mountain tunnel through fault tends to be damaged severely because it may be shorn by fault dislocation. However, the fractured tunnel may undergo even severer damage due to earthquake wave. Various factors, including earthquake wave, condition of surrounding rock, width of fault, relative position of fault and tunnel, fault friction velocity, fault activity and lining section type, affect the seismic performance of tunnel through fault. In addition, buffer layer, grouting, shock absorption gap, sectional tunnel lining with flexible joints, fiber reinforced concrete lining, and ultra-excavating are all available aseismic or anti-dislocation measures. The damage mode and degree of landslide to tunnel are related to the type of tunnel, and the different relative positions of the tunnel and the sliding surface controls damages. Landslide prevention and control engineering measures mainly include weight loss, drainage, construction of retaining works, improvement and reinforcement of soil and rock properties of sliding zone, etc.

Keywords: earthquake, mountain tunnel, fault, landslide, seismic response, aseismic measures.

1. Introduction

There are many tunnels in China. As far as railway tunnels are concerned, by the end of 2020, China's railway operating mileage has reached 145000 km, among which 16798 railway tunnels have been put into operation, with a total length of about 19630 km [1]. It shows that with the development of China’s economy, the scale of tunnel construction in China is largely increased. Recent decades, the western region such as Xizang and Yunnan provinces, is the new exploration zone in China, and thus the railway construction is the priority task. However, the western region is located in a high altitude and high intensity earthquake mountainous area, leading to the difficulty of building railway through the mountains. Therefore, many scholars have conducted in-depth research on the geological problems faced by the tunnel construction in earthquake-prone mountainous areas, especially faults and landslides.

In the past, it was widely believed that tunnels were better able to withstand earthquakes than other above-ground structures in mountain area. But the impact of earthquake on mountain tunnels is still not negligible. The Hanshin earthquake in 1995, the Chi-Chi earthquake in Taiwan in 1999, and the Wenchuan earthquake in 2008 prove that earthquake can cause many kinds of damage to tunnels in mountainous areas, like collapse and collapse of the slope at the entrance of the tunnel, crack of the tunnel opening, collapse of lining and surrounding rock, cracking and dislocation of lining, cracking and uplift of bottom slab, deformation and cracking of primary lining [2]. The above effects have triggered a large number of researches on the causes and mechanisms as well as countermeasures of earthquake damage to mountain tunnel. These studies show that earthquake have the greatest impact on tunnels located on fault fracture zone. As for the tunnels built in earthquake-prone mountainous area, landslide stability, especially the stability of large and giant landslides is specially paid attention to.

It is believed that faults and landslides are the most important causes of the earthquake damage on mountain tunnel. Therefore, this study focuses on the impacts of faults and landslides, and provides the corresponding engineering countermeasures.

2. The mechanism of earthquake on mountain tunnel

Earthquakes have a great effect on buildings above ground as well as underground, especially those above the ground, due to the direct influence of fault dislocation and landslide. Compared with most overground structures such as highways and bridges, tunnel engineering has relatively good seismic performance. In the mountainous area with complex environmental conditions, it is advisable to adopt more tunnel scheme, which can not only ameliorate the alignment and improve the traffic capacity of the road, but also help to improve the overall ability of the route to resist earthquake disaster [3].

Generally, earthquake have the greatest impact on tunnels located on fault fracture zone. When the tunnel is located in the fault fracture zone, affected by the fault, it causes the arching effect, which reduces or instantly loses the self-holding force of rock pressure, and make the linear structure of the tunnel be destroyed by shear deformation. This sudden displacement is usually confined to a narrow area, but the resulting tunnel damage can be disastrous. In addition, the fault fracture zone is often located in the region with frequent earthquakes. The strong crustal movement and the release and adjustment of crustal-strain energy expand the range of fault rupture. In the effect of surrounding rock pressure and seismic force, the tunnel lining is vulnerable to earthquakes [3-6]. Besides, as for different types of faults, generally active faults and inactive faults, there are various damage mechanisms. For active faults, Earthquake excitation and fault displacement are the prime reasons for serious damage to fault-crossing tunnels. For inactive faults, tunnel structure on both sides of fault may suffer from shear action of fault as a result of the inconsistent movement of surrounding rock on both sides of the fault.

When the tunnel is built in earthquake-prone mountainous area, special attention should be paid to the problem of landslide stability, especially the stability of large and giant landslides. When tunnel is built in landslide area, tunnel and landslide actually influence and interact with each other [7]. Among other types of landslides in mountainous areas, debris landslides are also of concern. In the affected Wenchuan earthquake area, Debris landslides are the most common landslide type. Especially in the rainfall season, some spring water flows out from the fissures among rubbles on the toe or back edge scarp of a slope. When loading on the slope surface or excavation unloading at the foot of the slope, the pipe-network drainage system, in which underground water flow in a gravel clay slope will be demolished or clogged. Eventually, this might result in large increase in groundwater level and pore water pressure in the slope and cause instability of the slope [8, 9].

Overall, the earthquake damage to the tunnel is still not negligible, in which the direct damage is reflected in the fault dislocation caused by earthquake resulting in the tunnel damage, indirect damage is reflected in the large-scale landslide caused by earthquake resulting in the tunnel damage.

3. The impact of earthquakes on tunnels through fault and the aseismic methods available

3.1. The seismic performance of tunnels through fault

Since numerous cases that tunnels through fault underwent severe damage were recorded and caused great loss in human society, it is essential to find out the effect mechanism of earthquake on tunnels through fault, which can be divided into 2 parts: earthquake wave and fault dislocation. The types of earthquake damage to tunnel through fault at fractured zone mainly consist of dislocation of tunnel lining (Fig.1), longitudinal or transverse cracking of lining (Fig.2), chipping or peeling of lining (Fig.3), bulging of floor (Fig.4), and entire collapse of lining and surrounding rocks (Fig.5) [10, 11]. Researchers have been studying in this field for many years. Based on the analysis measures they depend on, the research methods are divided into 3 sections-numerical simulation and model test, numerical simulation based on field investigation, and probability method.

Fig. 1 dislocation of tunnel lining

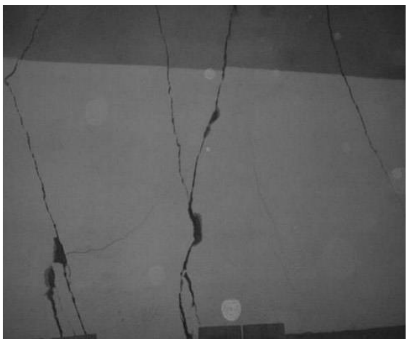


Fig. 2 cracking of lining

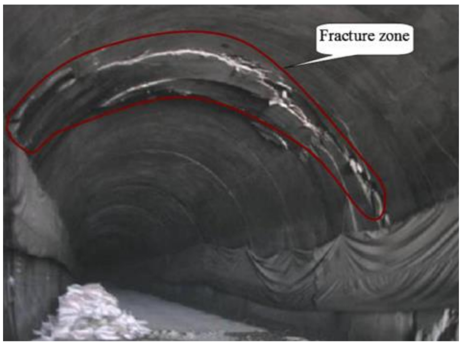


Fig. 3 spalling of lining

Fig. 4 bulging of floor

Fig. 5 collapse of lining

3.2. Controlling factors of the seismic performance of tunnels through fault

Now that the seismic response and failure mechanism of tunnels through fault in an earthquake has been discussed above, it is necessary to find out the factors that impact the seismic performance of the such tunnels, including characteristics of earthquakes, properties of the rock mass, and types of tunnel structure, which plays a primary role in the aseismic designs of tunnels.

Seven main factors that determine the seismic performance of tunnels through fault are given in this paper-earthquake wave, condition of surrounding rock, width of fault, relative position of fault and tunnel, fault friction velocity, fault activity and lining section type.

3.2.1. Earthquake wave

The properties of earthquake wave, such as the distance between the focus of an earthquake and the tunnel as well as the type of earthquake wave, have a great influence on tunnel structure, for they will amplify the seismic response of tunnel, especially near fault.

Zhao et al. proposed the oblique-incidence input method of P waves for the 3D fault site and applied the proposed method to investigate the influence of fault on the seismic response of a long-lined tunnel through fault subjected to P waves. The results showed that the seismic response of tunnel lining near the fault was amplified greatly [12]. Du et al. studied the long-lined tunnels through vertical fault zone subjected to SH waves based on the explicit finite element method. The results showed that the dynamic response of tunnels on meeting waves side was amplified, whereas that on back waves sides was reduced [13].

3.2.2. Condition of surrounding rock

Condition of surrounding rock plays a primary role in the seismic response of tunnel. Tunnels will undergo severer damage if surrounding rock condition is bad as well as surrounding rock mass stiffness at a high level.

Geng et al. studied the cross-sectional internal force distribution and longitudinal dynamic response characteristics of tunnel through fault fracture zone under seismic load with both dynamic numerical analysis and shaking table model test. The results showed that the condition of surrounding rock was the important factor affecting the internal force of tunnel liner caused by earthquake [6].

3.2.3. Width of fault

The change in width of fault affects the seismic response of tunnels. Generally, the damage increases with the width of fault increasing. However, a limitation exists when it comes to the influence of such increase.

Liu used the numerical method to analyze the acceleration and displacement response as well as their principles of the tunnel lining based on disparate width of fault. The results showed that the change in the width of fault affected the spectral characteristics of tunnel support structure and the distribution characteristics of internal force within fault range, especially the development law of the maximum principal stress [14]. By establishing a three-dimensional elastoplastic finite element model (FEM), An et al. proved that the damage to tunnel increased with the increase of width of fault zone, but when the width increased to 26m, the influence of width of fault zone on tunnel damage became stable [15].

3.2.4. Relative position of fault and tunnel

The relative position of fault and tunnel, including the dip angle of fault as well as the angle between fault strike and axial direction of the tunnel, impacts the severity of damage of tunnels through fault influenced by earthquakes. The increase of dip angle as well as the angle between fault strike and axial direction of the tunnel both leads to a much severer failure pattern.

Ghafari et al. fabricated a physical model, which was the largest single gravity (1g) model for simulation faults (normal and reverse) ever built, to evaluate the influence of various fault angles, affected by normal and reverse faults. The results showed that the increase of fault angle could increase the tunnel displacement as much as two times [16]. Meanwhile, Liu et al. carried out the shaking table comparison test and concluded that the smaller the angle between fault strike and axial direction of the tunnel was, the severer damage it would precipitate, and the more obviously the cracks would develop [17].

3.2.5. Fault friction velocity

If the fault dislocates at a high velocity, damage on tunnels through fault will deteriorate because the force exerted to the tunnel lining will increase, leading to the increase in the range as well as the magnitude of tensile stress, indicating a more conspicuous seismic response.

Qi et al. used the numerical model based on finite element method (FEM) to analyze the effect of vertical displacement rate on the first principal stress across the fault tunnel. The results showed that increasing the vertical displacement rate of the fault would increase the tensile stress at the bottom of the section at the fault of the tunnel and expand the tensile range of the tunnel lining [18].

3.2.6. Fault activity

Faults can be divided into two types-active fault and inactive fault. Active faults are those that are likely to precipitate disastrous earthquakes or sub-surface deformation in the future, while inactive faults, on the contrary, are those that will not cause such disasters in the future, in spite of the dislocation caused by earthquakes that occur elsewhere. The failure degree and failure mode of tunnel varies with different fault activity.

Zhang et al. made a detailed classification of active faults as well as inactive faults. The difference in the seismic responding characteristics of tunnels through various kinds of faults were studied. The results showed that tunnels through active faults would be shorn by fault dislocation and fault displacement determined the extent of damage, while tunnels through inactive faults would undergo uneven deformation and damage, due to the different nature of the stratum [7].

3.2.7. Lining section type

Tunnel with a rectangular cross section demonstrates a poor mechanic performance in the static situation, for it bears extremely high bending moment at its corners, thus not to mention its performance under the circumstances of earthquakes. On the contrary, since the tunnel with a circular cross section boasts a good mechanic performance with the static load, it shows better aseismic performance in earthquakes.

Liu et al. compared and studied the influence of lining section type on the stress and plastic strain of tunnels with chain-structures under active fault movement by the finite element method (FEM). The results showed that with the tunnel section constantly tending toward a perfect circle, the maximum and minimum principal stresses and shear stress of the secondary lining decreased while the equivalent plastic strain increased [19].

3.3. Aseismic methods available

It turns out to be very important to research on the aseismic issues on tunnels through fault because it guarantees the safety function of tunnels. Based on the seismic performance of tunnels through fault and its determining factors discussed above, all the aseismic measures taken is on purpose of reaching the following 3 aspect of efficacy:

(1) Alleviating the dynamic response of the tunnel structure, including reducing the acceleration amplification factor and replacement as well as designing the stiffness of the lining structure so that it can have co-deformation with the surrounding rock, decreasing the interaction between them;

(2) abating the effect of fault dislocation Implementing by anti-breaking countermeasures;

(3) reducing the total loss of the society by taking special constructing measures to make the repair work much easier as well as less costly.

Consequently, the current aseismic measures available can be divided into 3 categories-abating the dynamic response of the tunnels under the circumstances of earthquake waves, mitigating the effect of fault dislocation on tunnels, and methods making the tunnel repair work more approachable after an earthquake.

3.3.1. Measures of abating the earthquake dynamic response

3.3.1.1. Buffer layer

Buffer layer (Fig.6) is a special layer made by particular material. Typically, it is set out of the primary lining, between shotcrete and surrounding rock. It can also be set between the primary lining and the secondary lining. The stress exerted on the tunnel lining can be reduced by mediating the stiffness of buffer layer.

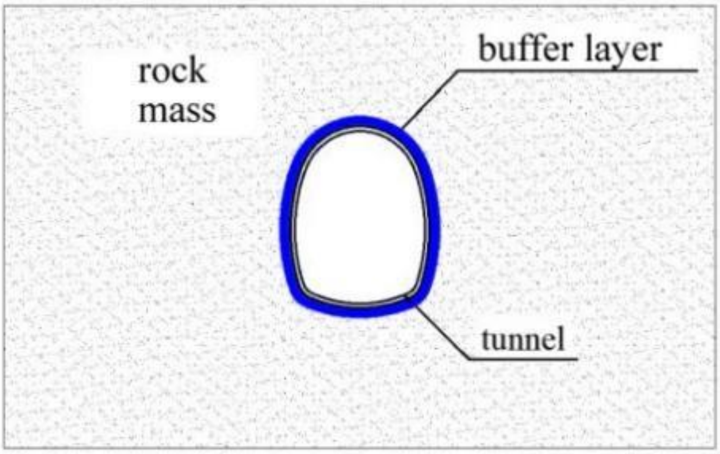


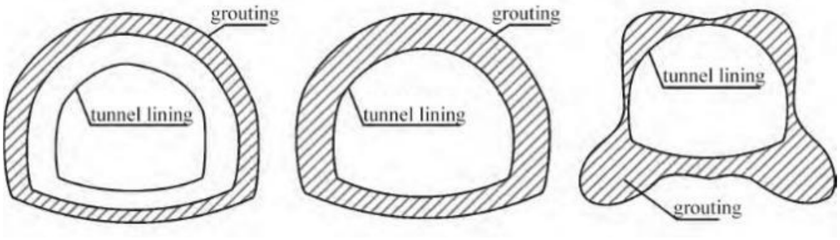
Fig. 6 buffer layer

The aseismic effect of buffer layer depends on its material, strength, stiffness, thickness, length, elastic modulus and spatial arrangement. Wang et al. conducted the large-scale shaking table model tests on the tunnel across the fault zone based on the wave function expansion method. The results showed that the buffer layer was very effective, and with the lower elastic modulus of the buffer layer, the dynamic stress concentration of the secondary lining decreased [20]. Cui et al. carried out model tests based on both fault dislocation and fierce earthquake wave input with different thickness of shock absorption layer. The results showed that the damping effects of 10 cm thick-shock absorption layer of the tunnel were obviously better than those of 5 cm thick and 15 cm thick shock absorption layers [21].

3.3.1.2. Grouting

The method of grouting reinforcement can be used to enhance the completeness of surrounding rock and ameliorate the aseismic ability of the tunnels through fault. The spacing of grouting and the thickness of grouting layer determines the efficacy of grouting.

Zhu et al. studied the aseismic mechanism and effect of tunnel structure with different seismic measures through the seismic dynamic simulation method. The calculation results showed that full-ring spacing grouting had the best aseismic performance among all the measures (Fig.7), and combining the aseismic methods of grouting, buffer layer and ultra-excavation together was recommended in design [22]. The numerical simulation using the finite difference method (FDM) conducted by Wang et al. also showed that the full-ring spacing grouting was better than the full-ring contact grouting in controlling the main stress of tunnel structure [23].



(a) full-ring spacing grouting (b) full-ring contact grouting (c) local grouting

Fig. 7 Different grouting measures

3.3.1.3. Shock absorption gap (without flexible joints)

Instead of constructing the tunnel as a whole structure, the tunnel lining can be divided into several sections (Fig.8) so that the longitudinal position where dislocation takes place can be defined for sure, fostering a slighter damage to the tunnel. Thus, shock absorption gap is applied to decrease the internal force of the tunnel structure, so that the earthquake effect can be mitigated, greatly heightening the safety of the tunnel structure and enhancing the safety factor. Additionally, other aseismic measures, such as enhancing secondary lining and deploying the doubled layer lining structure, can be taken concomitantly with the shock absorption gap, showing a better aseismic performance.

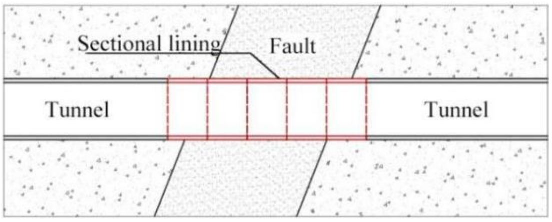


Fig. 8 sectional lining

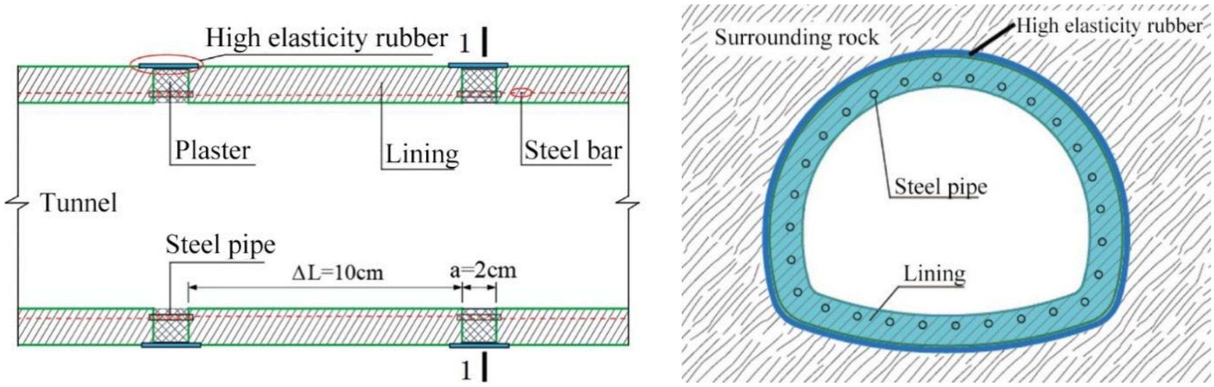
Cui et al. conducted static stick-slip dislocation tests and large 3-direction 6-DOF strong shock tests through the shaking table model tests. The results showed that effect of setting shock absorption gap was obvious for resisting stick-slip dislocation and strong earthquake shock, far much superior than taking tunnel structure-strengthening measures [24]. Sui et al. carried out shaking table contrast tests on unprotected linings, the aseismic joint and the doubled-lining structure and compared their dynamic responses as well as destructive patterns in earthquakes. The results showed that the shock absorption gap dramatically reduced sectional internal forces of the fault-crossing structure. Additionally, the doubled layer lining structure was also recommended [25].

3.3.2. Measures of mitigating the effect of fault dislocation on tunnels

3.3.2.1. Sectional tunnel lining with flexible joints

Given that the continuous lining tends to be severely damaged in an earthquake, due to the tremendous shear force caused by fault dislocation, a design idea or method has been devised that if the lining structure of a tunnel is segregated into several sections, namely the sectional tunnel lining with flexible joints deployed at the gaps between the contiguous two sections, rather than overall lining structure, the fault dislocation effect will be abated to a great extent, posing a much slighter damage to the lining system [26, 27].

As to the components of the flexible joints, Shen et al. designed a sectional tunnel with steel wire mesh, plaster and high elasticity rubber belt composing its flexible joint (Fig.9). The test results showed that the joints between sectional linings could make structure localize damage rather than global damage, and the flexible joint could adapt to the differential deformation of fault during the strong earthquake because the lining sections demonstrated a stair-stepped failure mode (Fig.10) [28]. Yan et al. designed a steel reinforced rubber joint and used both experimental and numerical methods to investigate its property. The results showed that the damage of the lining with the joints in the model test was mainly concentrated in the fault areas because of the joints' adjustment, and the joints efficiently decreased the maximum relative displacement between lining segments [29].



(a) longitudinal profile of tunnel lining and joint (b) cross-section 1-1 of tunnel joint

Fig. 9 designed flexible joint

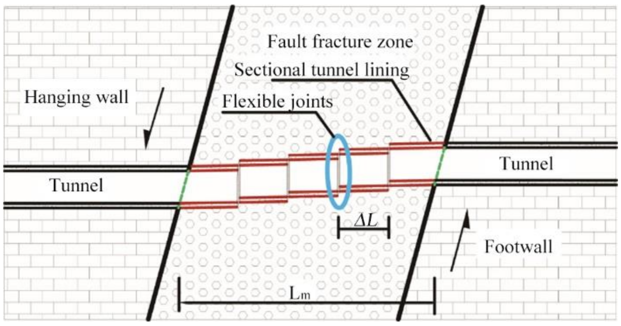


Fig. 10 the stair-stepped failure mode

3.3.2.2. Fiber reinforced concrete lining

Fiber reinforced concrete is a cementitious composite material with a dispersed reinforcement in a form of fibers. Polypropylene fibers can be divided into microfibers and macrofibers depending on their length and the function that they perform in the concrete [30]. The use of fiber reinforced concrete in the lining structure of tunnel through fault can ameliorate the anti-breaking property to a great extent, the efficacy of which varies among different types of fiber reinforced concrete.

An et al. studied the seismic performance of fiber-reinforced concrete tunnel lining by finite difference method (FDM). The results showed that the seismic performance of steel-basalt hybrid fiber-reinforced concrete secondary lining was better than that of steel fiber-reinforced concrete secondary lining [31]. Cui et al. (2020) carried out the anti-breaking model test of the fiber reinforced concrete lining in the active fault zone of high earthquake intensity. The results showed that the results obtained by the numerical simulation shared a good consistency with that of the model test. Moreover, the safety of steel polypropylene hybrid fiber reinforced concrete tunnel lining was the highest [32].

3.3.3. Measures making the tunnel repair work more approachable

3.3.3.1. Ultra-excavating

Based on the most likely volume of fault displacement caused by an earthquake, an ultra-excavation (Fig.11) of the tunnel cross-section can be designed. After an earthquake, the enlarged tunnel cross-section can ensure the clearance of the cross-section, including a variety of discontinuous deformation of the lining. Thus, it will be more possible that the tunnel lining can be repaired within a short period after an earthquake takes place as well as with a relatively lower reparatory cost.

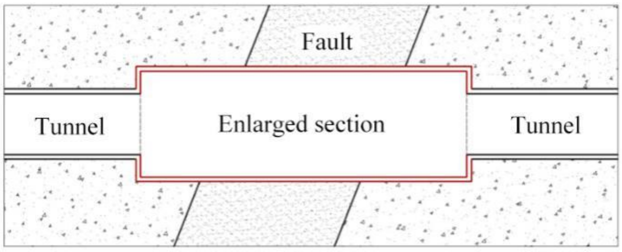


Fig. 11 ultra-excavation

Song et al. put forward that when the fault dislocation affects the normal traffic operation, the footwall tunnel can be expanded and backfilled according to the characteristics of the normal fault. Meanwhile, adjusting the slope of the tunnel axis could eliminate the dislocation amount of the fault [33]. Li et al. carried out the shaking table model test and derived the optimum range of the enlarged section on both sides of tunnel through fault [34].

3.3.3.2. Aseismic reinforcement technology for lining

As is mentioned above, the tunnel lining crossing the fault rupture zone is likely to collapse, which will not only pose threat to drivers' and passengers' lives, but put tunnel repair work in a trouble. Thus, special aseismic reinforcement technology for the tunnel lining crossing the fault rupture zone should be applied in the aseismic design of tunnel, reducing maintenance time and cost.

Cui et al. established the aseismic reinforcement criterion of second liner collapse control of tunnel structure of fault rupture zone and did some numerical simulation. The results showed that under the condition of fault dislocation, second liner needed to apply double-layer reinforcement between 2D (diameter of tunnel) section from hanging fault and 1.5D section from footwall. [35].

4. Influence of landslide caused by earthquake on tunnel and related measures

4.1. The effect of earthquakes on landslides

The formation of seismic landslide is mainly affected by the comprehensive factors such as ground motion, landform, stratum lithology, hydrology, land use and vegetation cover. In view of the difference of engineering geological conditions in different places, the contribution of various factors to the development of landslide is different. Strata which provides a material basis in the development of geological disasters, landform control space boundary conditions of the geological disasters, instructs the slope erosion and slope of river hydrology geological characteristics, increase the slope instability, control both topography and geomorphology, geological structure and can control the rock mass structure and the characteristics of the combination of comprehensive control effect on the development of geological disasters, the ground motion is the dynamic triggering condition of seismic landslide [36-37].

4.2. Influence of landslide on tunnel deformation and failure

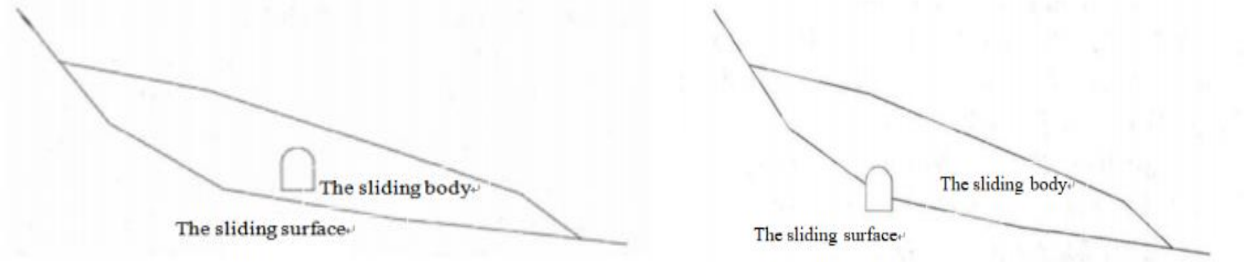
4.2.1. Failure mechanism analysis of tunnel caused by landslide

The whole process of landslide can be summarized into four stages: creep sliding, uniform sliding, accelerated sliding and temporary stability. Therefore, the study of creep sliding stage has a guiding effect on the control of landslide and tunnel diseases [38].

The tunnel deformation and cracking caused by landslide are shown as follows: (1) With the increase of bias pressure, the tunnel itself is difficult to bear as the landslide compresses the tunnel, leading to tunnel deformation and cracking;(2) in the process of sliding body movement and landslide thrust, the overall longitudinal bending deformation, overturning and displacement of the tunnel will occur.

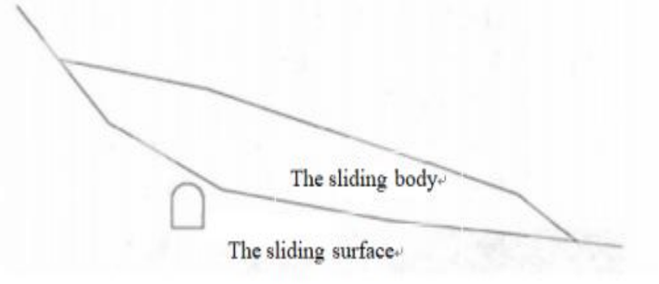
4.2.2. Analysis of stress characteristics of tunnel in landslide

In the sliding body of the unstable slope, according to the different relative positions of the tunnel and the sliding surface, the stress characteristics and deformation characteristics of the tunnel structure are also different, which can be analyzed in the following three cases: (1) the tunnel is located in the sliding body above the sliding surface (Fig.12(a)); (2) the tunnel intersects the sliding surface (Fig.12(b)). (3) the tunnel is located below the sliding body (Fig.12(c)) [39].



(a) A schematic image of the tunnel in the sliding body

(b) a schematic image of intersection position of tunnel and slip surface



(c) a schematic image of the tunnel below the slide body

Fig. 12 the stress and deformation characteristics of the tunnel structure in different cases

4.2.2.1. Stress and deformation characteristics of tunnel in sliding body

In this case, the upper side of the tunnel is mainly used as a beam structure to bear thrust F, while the lower side bears soil resistance and residual anti-slip force P, as shown in Fig.13. As the landslide thrust near the central axis of the landslide is greater than that on the two sides, the bending moment is larger in the middle and smaller on the two sides, and the stress characteristics of the tunnel are also larger in the middle and smaller on the two sides. The tunnel will undergo bending deformation, and transverse cracks will appear in the inner wall of the hillside, and the tunnel and the landslide will slide together. The middle part of the tunnel is longitudinal bending under the influence of landslide thrust and landslide slip, and the side wall of the mountain has transverse cracks. This type of geomechanical model can be named as integral sliding type according to its stress characteristics [40].

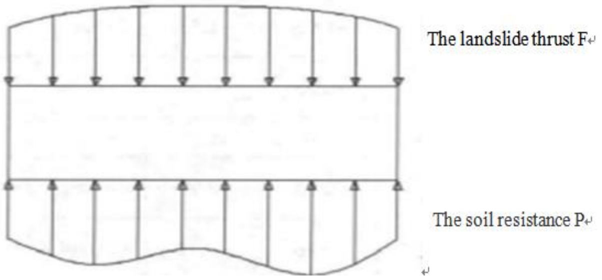


Fig. 13 A schematic image of tunnel force

4.2.2.2. Failure analysis of tunnel intersecting slip surface

Tunnel fellowship with sliding surface, the mechanical characteristics of the tunnel is similar to the anti-slide pile, landslide thrust force q, F and soil under the two kinds of force and pressure P after superposition, the stress state changes of the tunnel, under shear and apparent bias effect, internal asymmetric bending moment, thrust slip plane wall sections and vault above the action of bending moment, the first began to destroy. This geomechanical model may be called the middle shear type.

At this point, the sliding surface to the tunnel cross section is divided into two parts, in the upper part of tunnel in sliding bed due to the bedrock of rigid sliding bed fixation and relatively stable, while the upper sliding body in tunnel, due to the backer lateral landslide thrust, near the slope foot wall at the same time the sliding resistance F ', the force under the condition of the deformation of the tunnel is mainly for the lining cracking, Longitudinal bending and global displacement are secondary deformations.

4.2.2.3. Stress and deformation analysis of tunnel under sliding body

Due to the disturbance of the sliding body, the sliding of the sliding body will generate additional disturbance to the tunnel, resulting in extrusion position and influence on the bedrock below the sliding surface. Therefore, the stress state and deformation characteristics of the tunnel at this time are greatly related to the distance H from the vault to the sliding surface. When H is greater than a certain value, the disturbance of the sliding body on the bedrock of the sliding surface can be ignored, so the stress and deformation of the tunnel will weaken with the increase of H. This geomechanical model can be called the disturbance type at the upper part of the tunnel according to the stress characteristics.

The geomechanical models of the relationship between landslide and tunnel deformation were summarized and listed in Table 1. According to the geomechanical model analysis, the tunnel deformation characteristics in the landslide section are mainly related to the position of the tunnel in the landslide body, and the relative position of the sliding surface and the tunnel determines the tunnel deformation characteristics [41].

Table 1. A geomechanical model for the relationship between landslide and passage deformation

The model name	The position of the tunnel relative to the landslide	Main deformation characteristics of tunnel
The overall passage type of tunnel	The tunnel is inside the slide, above the slide surface	Mainly in longitudinal bending and overall displacement
Tunnel middle shear type	The tunnel intersects the slippery surface	The main lining is longitudinal crack, the whole tunnel is inverted downward, and the deformation of the side of the backer is serious
Tunnel upper disturbance type	The tunnel is in the slide bed, below the slide surface	The main damage to the vault and the side wall of the mountain, the width of the crack is large and the extension is long

4.3. Landslide prevention and control

4.3.1. Weight loss and back pressure

The method is to brush the "sliding part" above the landslide body to reduce the weight and reduce the sliding force. For the sliding body on the circular surface sliding machine, according to the principle of its mechanical balance, the weight of the upper brush side of the "sliding part" can be reduced, the value of the "sliding moment" can be reduced, and the stability coefficient can be increased. If the brush side is turned to the "sliding part", it will play the role of filling pressure, and can promote the stability of the landslide.

4.3.2. Eliminate or mitigate water hazards – drainage

(1) Exclude surface water

The cutting ditch is arranged above and on both sides of the slide body, and the branch drainage ditch is arranged on the slide body, so that the surface water cannot enter or penetrate into the slide body. Care must be taken that the gutter must not leak and must be repaired frequently, otherwise it will have the opposite effect. In order to reduce the infiltration of surface water and allow it to flow rapidly into drains, the compacted ground should be leveled and the cracks or impermeable layers should be filled with mortar clay, especially the deep cracks extending to the slip surface (zone).

(2) Drainage of groundwater

The selection should be made according to the structural characteristics of slope rock mass and hydrogeological conditions. Usually, blind gullies or supporting blind gullies are built around or inside the slope to cut off or remove the underground water flow. For the deep landslide, because the buried depth is more than 10~15 meters, it is difficult to drainage with other drainage works, drainage tunnel, vertical seepage well with horizontal pipeline, horizontal borehole group and seepage pipe dredging can be considered. Among them, horizontal drilling (flat hole) drainage for landslide prevention and control is very good. This method is cheap in cost and will not affect the stability of the slope, so it is likely to replace the horizontal drainage tunnel.

4.3.3. Construct retaining works

This kind of engineering measures are mainly in the lower part of the sliding body to build retaining buildings, such as anti-sliding retaining wall, anti-sliding stone stack, anti-sliding pile and other measures. The landslide near the river bank, in order to prevent the erosion of the river below the slide body, cut erosion, usually build the diversion dike (along the dam or groin dam), underwater breakwater, can also be in the foot of the slope stone protection or use precast concrete sink row, etc.

In recent years, anti-slide pile has become the main anti-slide measure. It has the advantages of convenient construction, unrestricted construction period, saving labor and materials, small disturbance to the landslide (sliding body) and so on. Anti-slide piles are usually made of reinforced concrete (rail) piles with square or circular sections or steel tube bored piles. On the plane, it can be arranged in the shape of plum blossom or square, with the spacing generally 3~5 meters, and it can go deep into the stable rock and soil body below the sliding surface (belt). In addition, there are large square piles, with a width of more than 2 meters and a depth of 20 meters.

4.3.4. Improve the soil and rock properties of the reinforced sliding zone

(1) For the larger landslide, the anchoring piles made of reinforced concrete are widely used at home and abroad. The rock slide of monoclinal structure can be anchored by anchor rod, prestressed anchor cable + ground beam reinforcement, arch frame slope protection, etc.

(2) For fractured rock mass, Portland cement can be used or cemented with bitumen to improve the strength of slope and structural plane and increase the sliding resistance. The grouting holes should be drilled to 3~5 meters below the sliding surface, and the underground water should be avoided in the landslide body. Electrochemical reinforcement method and freezing method can be used for soil slopes.

5. Conclusion

Generally, a tunnel has a better seismic performance than other structures above the ground. However, when the earthquakes happened, the damage caused by faults or landslides was still considered not negligible.

Because of the fault dislocation triggered by earthquake and the secondary effects stimulated by earthquake wave, tunnel through fault tends to meet severe damage, especially at the longitudinal location where it goes through the fault rupture zone. Through fault, numerical simulation, model tests and on-site investigation, it is found that the seismic response of tunnel share a high level of consistency, indicating that the tunnel in the hanging wall will undergo greater damage than that in the footwall. Various factors affect the seismic performance of tunnel through fault, with earthquake wave, condition of the surrounding rock, the width of fault, relative position of fault and tunnel, fault friction velocity, fault activity, and lining section type being the primary ones. Based on these factors, particular aseismic and anti-dislocation measures are put forth. Aseismic measures, including buffer layer, grouting, and shock absorption gap, can effectively alleviate the dynamic response of the tunnel structure, while anti-dislocation measures, including sectional tunnel lining with flexible joints and fiber reinforced concrete lining, can abate the effect of fault dislocation. Moreover, ultra-excavating the tunnel and aseismic reinforcement technology allow the repair work to be much simpler.

Earthquakes can trigger landslides, and Newmark models are now used internationally to assess the risk. Landslides have different effects on tunnels according to three different types of tunnels. When the tunnel is inside the slide, the deformations are mainly in longitudinal bending and overall displacement above the slide surface. When the tunnel intersects the slippery surface, the mainlining is a longitudinal crack, the whole tunnel is inverted downward, and the deformation of the side of the backer is serious. When the tunnel is below the slide surface, the main damage to the vault and the sidewall of the mountain, the width of the crack is large, and the extension is long.

Landslide prevention and control engineering measures mainly include weight loss, drainage, construction of retaining works, improvement and reinforcement of the soil and rock properties of the sliding zone. Landslides caused by earthquake damaged the tunnel. In order to further effectively mitigate the disaster risk, it is suggested to strengthen the earthquake landslide for earthquake events and disaster chain survey logging, shift the focus of work from earthquake relief to pre-earthquake prediction. In addition, it is necessary to make the national overall spatial planning, clarify the restrictions on high-risk areas, prohibit the control requirements of construction land use, and avoid disasters. Therefore, the formulation of targeted treatment measures to avoid heavy losses caused by landslide has certain engineering reference value for designing and constructing similar projects in the future.

In the future, more research should focus on the inducement of earthquakes and landslides, which turns out to be the foundational issue for this topic. For one thing, the inducement influences to which extent tunnels will be damaged as well as which aseismic method suits most in certain cases. For another, it determines whether the research approaches and the test methods are justifiable. To be more specific, it is essential to make clear whether the excitement input procedure of fault displacement then earthquake is rational, for it determines whether an experiment can simulate the natural conditions better. Therefore, future research is supposed to take the effects of different kinds of inducement into consideration as they are carrying out numerical simulation or model tests.

References

[1] Tian S, Wang W, Gong J. (2021) Development and prospect of railway tunnels in China (including statistics of railway tunnels in China by the end of 2020). Tunnel Construction, 41(2): 308

[2] Li T. (2008) Failure characteristics and influence factor analysis of mountain tunnels at epicenter zones of great Wenchuan earthquake. Engineering Geology. 16(6):742-750.

[3] Qian Q, He C, Yan Q. (2009) Dynamic response characteristics of tunnel in Wenchuan earthquake and its implications. Investigation and analysis of earthquake damage in wenchuan earthquake engineering. Chinese Society for Rock Mechanics & Engineering, 633-643

[4] Wang C, Qin R, Tang X. (2012) 3rd Ed. Chongqing University Press.4-7

[5] Wang W, Su Z, Lin J, Kan Jia R, Wang T, Huang C. Modern tunneling Technology. 38(2).52-60

[6] Geng P，Wu C，Tang J，Li L. (2012) Analysis of dynamic response properties for tunnel through fault fracture zone. 31(7):1406-1408

[7] Zhang Z, He C, Wang Y. (2009) Stability of Giant Landslides and Location Selection of Traffic Tunnel in Earthquake Area. Chinese Society of Rock Mechanics and Engineering. Seismic damage investigation and analysis of Wenchuan earthquake engineering. Chinese Society for Rock Mechanics & Engineering. 9.

[8] Su L, Xu X, Geng X, Liang S. (2017) An integrated geophysical approach for investigating hydro-geological characteristics of a debris landslide in the Wenchuan earthquake area. Engineering Geology. 219(9).52-63

[9] Shang Y, Zhou J, Tong W. (2002)The influence of pipe seepage system on the stability of a pebbly-clay slope. Journal of Geological Hazards and Environment Preservation. 13 (1)41-43

[10] Li L, Wang K, Yang D, Chang S, Zhang Q. (2016) Analysis on the Earthquake Damages Characteristics of Tunnel through Fault Zone. International Journal of Earth Sciences and Engineering, 9(3): 934-941

[11] Shen Y, Gao B, Yang X, Tao S. (2014) Seismic damage mechanism and dynamic deformation characteristic analysis of mountain tunnel after Wenchuan earthquake. Engineering Geology, 180: 85–98

[12] Zhao M, Ouyang W, Huang J, Du X, Zhao X. (2019) Analysis of axis dynamic response of rock tunnels through fault fracture zone under P waves of earthquake. Rock and Soil Mechanics, 40(9): 3645-3655

[13] Du X, Su C, Huang J, Wang Y, Zhao M, Ouyang W. (2019) Analysis of Dynamic Response of Rock Tunnels with Vertical Fault Fracture Zone under SH Waves. Technology for Earthquake Disaster Prevention, 14(2): 269-280

[14] Liu K. (2011) Study on the Failure Mechanism under Fault Movement and Seismic Dynamic Response of the Chenglan Across-fault Tunnel. Beijing, Being Jiaotong University. (Master’s thesis)

[15] An S, Tao L, Bian J, Han X, Wu X. (2020) Damage Analysis on Subway Tunnel Structure under Effect of Reverse Fault Dislocation. Journal of Hunan University (Natural Sciences), 47(7): 147-156

[16] Ghafari M, Nahazanan H, Zainuddin Md Yuso, Nik Norsyahariati Nik Daud. (2020) A Novel Experimental Study on the Effects of Soil and Faults’ Properties on Tunnels Induced by Normal and Reverse Faults. Application Science, 10: 3969

[17] Liu Y, Lai J, Xin J, Li X, Xing R. (2019) Comparison test of dynamic response characteristics of the tunnels through fault. Rock and Soil Mechanics, 40(12): 4693-4702

[18] Qi B, Wang F, Chen J. (2020) Numerical simulation on structural response of tunnel passing through fault under the action of stick slip fault dislocation. Building Structure, 50(S2): 753-758

[19] Liu X, Gu X, Dai Z, Li X. (2014) Influence of Section Type on a Tunnel Structure Under Active Fault Movement. Modern Tunnelling Technology, 358: 71-77

[20] Wang S, Gao B, Sui C, Wen Y. (2015) Mechanism of Shock Absorption Layer and Shaking Table Tests on Shaking Absorption Technology of Tunnel Across Fault. Chinese Journal of Geotechnical Engineering, 37(6): 1086-1092

[21] Cui G, Wu X, Wang M, Wang D, Zhu C. (2017) Model Tests on Damping of Shock Absorption Layer of Stick-Slip Fracture Tunnel in Highly Seismic Areas. Chinese Journal of Geotechnical Engineering, 39(11): 2125-2131

[22] Zhu Z, Yu J, Sui C, Wang D, Zhu Y, Sun M. (2014) Comprehensive Seismic Measures for Tunnel Structure in the Area of High Intensity Active Fault. China Railway Science, 35(6): 55-62

[23] Wang L, Cui G, Jing H. (2019) Study on Anti-seismic Effect of Surrounding Rock Grouting of Fault-crossing Tunnels in Highly Seismic Area. High Speed Railway Technology, 3(10): 25-29

[24] Cui G, Li P, Wang M, Zhu C. (2020) Model Tests for Safety of Stick-Slip Fault Tunnel in Strong Earthquake Area using Rigid-Flexible Combined Anti-Shock Absorption Technology. Journal of Vibration and Shock, 39(5): 194-207

[25] Sui C, Gao B, Shen Y, Wang J, Xin C. (2017) Shaking Table Tests and Analysis for Fault-crossing Tunnels with Multi Ant-seismic Structures. Journal of the China Railway Society, 39(11): 124-130

[26] Kiani M, Ghalandarzadeh A, Akhlaghi T, Ahmadi M. (2016) Experimental Evaluation of Vulnerability for Urban Segmental Tunnels Subjected to Normal Surface Faulting. Soil Dynamics and Earthquake Engineering, 89: 28-37

[27] Liu X, Liu J, Li X, Chen G. (2015) Experimental Research on Effect of Antidislocation of Highway Tunnel Lining with Hinge Joints in Thrust Fault. Chinese Journal of Rock Mechanics and Engineering, 34(10): 2083-2090

[28] Shen Y, Wang Z, Yu J, Zhang X, Gao B. (2020) Shaking Table Test on Flexible Joints of Mountain Tunnels Passing Through Normal Fault. Tunnelling and Underground Space Technology, 98: 103299

[29] Yan G, Shen Y, Gao B, Zheng Q, Fan K, Huang H. (2020) Damage Evolution of Tunnel Lining with Steel Reinforced Rubber Joints under Normal Faulting: an Experimental and Numerical Investigation. Tunnelling and Underground Space Technology, 97: 103223

[30] Blazy J, Blazy R. (2021) Polypropylene Fiber Reinforced Concrete and its Application in Creating Architectural Forms of Public Spaces. Case Studies in Construction Materials, 14: e00549

[31] An D, Chen Z, Meng L, Cui G. (2020) Application of Fiber-Reinforced Concrete Lining for Fault-Crossing Tunnels in Meizoseismal Area to Improving Seismic Performance. Advances in Mechanical Engineering, 12(7): 1-10

[32] Cui G, Wang X, Wang D. (2020) Study on the Model Test of the Antibreaking Effect of Fiber Reinforced Concrete Lining in Tunnel. Shock and Vibration, 2020: 5419650. https://doi.org/10.1155/2020/5419650

[33] Song C, Li W, Jiang F, An A. (2020) Seismic Analysis and Fault Dislocation Design of the Tunnel through Rift Valley of Nairobi-Malabar Railway. Journal of Engineering Geology, 28(4): 867-876. doi: 10.13544 /j.cnki.jeg.2020-041

[34] Li L. (2014) Research on Seismic Response and Seismatic Design of Tunnel Crossing Fault. Chengdu, Southwest Jiaotong University. (Doctoral thesis)

[35] Cui G, Zhao Q, Wang M, Lin G. (2015) Aseismic Reinforcement Technology of Second Liner Collapse Control of Tunnel Structure in Fault Rupture Zone. Journal of Chang'an University (Natural Science Edition), 35(2): 107-113

[36] Tan C, Lei W, Sun W, Wang J, Zhang C, Wu S. (2008) Risk assessment of geological hazards in typical clayey loess areas of China. The geological report, 27(11): 1771-1781.

[37] Zhang Y, Shi J, Sun P, Yao X. (2009) Coupling of internal and external dynamics and disaster cases of Wenchuan earthquake. Journal of Geomechanics,15(2): 131-141.

[38] Chen Y. (2012) Application of high pressure jet grouting method in foundation reinforcement of bridge and tunnel. Science and Wealth, 2012(3): 177.

[39] Pi Z, Deng J. (2014) Influence of landslide on tunnel deformation and failure. Transport Construction & Management, 2014(07): 62-66.

[40] Wu G. (2011) Discussion on advanced support and construction technology of tunnel. Scientific and technological information development and economy, 18(9): 195-196.

[41] He Y. (2011) Application of chemical grouting in construction of excavated pile of bridge. China Science and Technology Expo, 2011(34): 156.