A Review on Seismic Response and Aseismic Measures of Fault-crossing Tunnels

Zhang L F¹, Li R H², Liu H¹, Fang Z B¹, Wang H B¹, Yuan Y², Yu H T²

¹ Powerchina Roadbridge Group Co., Ltd., Beijing 100048, China
² Department of Geotechnical Engineering, Tongji University, 1239 Siping Road, Shanghai 200092, China.

Abstract: Several earthquakes have challenged the traditional view that the seismic performance of tunnels is excellent. The seismic damage of these tunnels has led scholars and engineers to study the seismic response of tunnels and underground facilities. Many earthquake damage investigations of mountain tunnels reveal that fault or fracture zone is one of the most critical factors leading to tunnel damage. In this paper, the mechanisms of seismic damages and the main factors that influencing the seismic response of fault-crossing tunnels have been explained. Based on two different aseismic philosophies, different aseismic measures of fault-crossing tunnels including buffer layer, fiber concrete, flexible joint, grouting and enlarging tunnel across have been review, and the advantages and disadvantages of different aseismic measures as well as their application scope have been assessed. The ideal aseismic design of fault-crossing tunnels is as follows: verify the fault activity, accurately estimate the possible displacement and the earthquake intensity of the fault area, and then combine the advantages of different aseismic measures, set up composite aseismic measures at the place where the tunnel crosses the fault zone. It is believed that the present study will help in a better understanding of the seismic response of fault-crossing tunnels and have some guidance of aseismic design of fault-crossing tunnels in engineering practice.

1. Introduction

Driven by the growing demand for infrastructure in mountainous areas, the constructions of tunnels in highway and railway network is accelerated. More challenges and complex geological conditions are met with in tunnel projects, especially with large scale, than in the past. Numerous cases of damages of mountain tunnels have been reported in earthquakes, such as 1999 Chi-Chi, 2004 Mid-Niigata Prefecture, 2008 Wenchuan and 2016 Kumamoto earthquakes etc.¹⁻⁶. Seismic damages of these cases have led scholars and engineers into topics researching seismic response of tunnels and underground facilities. Many earthquake damage investigations on mountain tunnels reveal that fault or fracture zone crossing is one of the most critical factors leading to tunnel damages. Based on works of many scholars on earthquake damages of tunnels and underground facilities¹⁻⁵, damages to tunnels by faults in the past earthquakes are listed in Table 1.

| Year | Location          | Magnitude | Description of the damage                                      |
|------|-------------------|-----------|----------------------------------------------------------------|
| 1906 | San Francisco (USA) | 8.3       | Severe damages to 2 tunnels crossing San Andreas Fault         |
| 1923 | Kanto (Japan)     | 7.9       | Severe damages to over 100 tunnels. Damages caused due to fault intersection, slope instabilities and debris flow |
| 1930 | Kita-Izu (Japan)  | 7.3       | Severe damages arising from fault intersection and             |
1948  Fukui (Japan)  7.1  movement reported for one railway tunnel
1971  Los Angeles (USA)  6.6  Severe damages to 2 railway tunnels within 8 km from the earthquake fault
1978  Izu-Oshima-Kinkai (Japan)  7.0  Severe damages to about 9 railway and 4 road tunnels. Damages attributed to poor geological conditions, fault crossing and rock falls
1984  Naganoken-seibu (Japan)  6.8  Cracking observed in one head race tunnel majorly caused due to fault crossing
1995  Kobe (Japan)  7.2  The Rokko Tunnel of Sanyo Shinkansen crosses an active fault, and lots of cracks appeared in the lining after earthquake
1999  Chi-Chi (China)  7.3  The extent of damage to tunnel linings was influenced by the position of the tunnels in relation to fault zones, ground conditions, and closeness to the epicenter and surface slopes
2004  Mid-Niigata (Japan)  6.8  The Uonum tunnel was damaged due to the existence of Inokurayama fault
2008  Wenchuan (China)  8.0  The seismic damage in these tunnels was serious, especially close to the secondary faults
2016  Kumamoto (Japan)  7.3  A large fault was found to exist over the spans of S166 and S167 through in-situ investigation, in consistent with the secondary concrete lining collapse

All these records indicate that the tunnel section crossing fault is the most vulnerable part when subjected to an earthquake. But in use standards and codes guiding tunnel construction have mostly qualitative description upon this problem, which shows that existing research has not providing enough guidance for engineering practice. So it is urgent to conduct more in-depth and detailed research on the seismic performance of the tunnel crossing fault, to grasp general laws of the failure modes, and then put forward target aseismic measures.

A review of investigations carried out by previous researchers directing at the seismic performance and aseismic measures of tunnel cross fault is presented. Some damage cases of tunnels in recent earthquake damage investigation are presented, with special emphasis on failure modes of tunnels crossing fault. And the factors believed to have significant influences on the damages are explained. Finally, some feasible aseismic measures of tunnel cross fault are discussed.

2. Mechanisms of Seismic Damages

Based on seismic damage investigations of many tunnels, it can be found that the tunnel section crossing the fault is among the most venerate parts along the whole tunnel in an earthquake, which may cause collapse and other serious damages to tunnels. But it would not be the truth vice versa, a tunnel crosses a fault may be relatively intact or with less severe damages after earthquakes. For example, the new Sanyi No.1 tunnel crosses over two fault zones, Sanyi fault, and Shihliufen fault, but only the sections near Sanyi fault had been damaged in the earthquake, while no distinct damage had been found near Shihliufen fault. Therefore, it is necessary to find out what kind of fault-crossing tunnel will be damaged in an earthquake. Such experiences would serve as guidance in route planning and tunnel structure design.

In order to separate different types of faults, and then find out various damage mechanisms, faults are divided into two types in this paper: active faults and inactive faults. The active fault is generally defined as a fault that is expected to cause sub-surface deformation or destructive earthquakes in the future\(^{[10]}\).
And the inactive fault is defined as a fault that will not cause dislocation or earthquakes in the future.

2.1. Tunnel cross Active Fault

The active fault is expected to cause sub-surface deformation or destructive earthquakes in the future. Earthquake excitation and fault displacement are the prime reasons for serious damage to fault-crossing tunnels. Considering the different damage patterns observed in fault-crossing tunnels, and in order to clarify the mechanism causing seismic damage, the active faults that tunnel cross through are further divided into two types: causative fault and displaced secondary fault.

2.1.1. Causative fault.

From the earthquake damage investigations, it can be found that almost all the tunnels crossing the causative fault were sheared up by the fault dislocation. The damages to the tunnel are mainly cause by intense shear action of the displaced fault: the relative displacement leads to the reduction of the so-called arch effect, and results in shear deformation of the lining and then leads to total tunnel collapse.

Many studies have been carried out on the influence of fault dislocation on tunnels. Burridge[11] conducted a series of centrifuge model tests to assess the effect of fault movement on tunnels. The test results proved that even a 0.61m fault displacement would certainly fail the proposed tunnel, and the moments generated by the model earthquake were substantially smaller than those developed by the actual faulting. Cividini[12] analyzed the influence of the faulting process on tunnel and indicated that faulting might lead to the collapse of the tunnel. Ma[13] used a 3D discrete-continuum coupling approach to investigate the rupture process of a cross-active-fault tunnel from the micro perspective. The results revealed that shear failure is the primary failure pattern of the surrounding rock mass. Liu[14] conducted a series of model tests and analyzed the failure mechanism of fault-crossing tunnel subjected to reverse fault dislocation. The test results proved that under the action of fault dislocation, the stress mode of tunnel section is with tension on both sides, compression on the top and the bottom. With the fault dislocation, the oblique cracks at the two sides of the arch waist develop continuously, which eventually leads to the cracks and spalling caused by shear and compression of the lining, and accompanied by the collapse of the arch crown lining.

Combined with the earthquake damage investigation and related research, it can be found that, for the tunnel crossing causative fault, although it is affected by both fault dislocation and earthquake excitation, fault dislocation plays a decisive role in the failure mode of the tunnel. Under the severe shear action of fault, the tunnel suffers serious shear failure. The shear movement of the tunnel is determined by the fault displacement.

2.1.2. Displaced secondary fault.

For causative fault, the displacement of fault is proportional to the magnitude. But for the other displaced secondary fault, there is no direct relationship between the displacement of fault and the magnitude, so the damage patterns of the tunnel crosses displaced secondary fault might not be the same as that of the tunnel crosses causative fault, hence the damage mechanism remains to be further studied. Some scholars have carried out quantitative comparative analysis on fault dislocation and earthquake vibration. Cui[15] compared the influence of fault dislocation and earthquake vibration on tunnel and concluded that dislocation was the main factor leading to tunnel damage, and vibration was the secondary factor. When studying the failure mechanism under the joint action of fault dislocation and earthquake excitation, the difficulty is how to consider the combined effect in a same model.

One is a feasible method to apply fault dislocation and earthquake excitation successively in one model, which assumes that the dislocation of secondary fault is a chain reaction of the displacement of causative fault. And this standpoint is supported by some geologists[16]. Anastasopoulos[17] investigated the response of an immersed tunnel to the consecutive action of a major normal fault rupturing and a subsequent strong excitation by a numerical approach. Shen[18] used shaking table tests to analyzed the damaged Longxi tunnel in the Wenchuan earthquake, and the results showed that the fault movement suffered more serious damage for the tunnel structure than seismic motion.

Another practicable method is to artificially initiate the displacement of fault by inputting ground motion.
This method assumes that the dislocation of secondary fault is caused by the seismic wave. Yang\cite{19} used a 3-Dimensional discrete element model to investigate the dynamic response of tunnel-fault system, and divided the failure process of tunnel-fault system into five stages: (1) strain localization, (2) rupture initiation, (3) rupture acceleration, (4) spontaneous rupture growth and (5) stabilization. For the tunnel crossing displaced secondary fault, the primary cause of tunnel damage is also fault dislocation. However, the relationship between the magnitude of an earthquake and the displacement of secondary fault is not clear. The influence of earthquake waves on the response of tunnel cannot be ignored in the process of research and design.

2.2. Tunnel cross Inactive Fault
Inactive fault does not cause dislocation in an earthquake, so the influence of fault on the tunnel is similar to fracture zone in an earthquake. Due to the existence of such a fault, 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. Fang\cite{20} accomplished a series of shaking table tests to study the seismic responses of tunnel cross inactive fault, and the results indicated that the tunnel lining at fault is seriously damaged because of the relative displacement of hanging wall and footwall. He\cite{21} designed a series of shaking table tests to investigate the response of tunnel crosses inactive fault and verified the results by numerical simulation. It can be concluded that the failure mechanism of the tunnel in inactive fault zone is the discrepant seismic response caused by different rock properties between fault and the surrounding better rock quality, while the seismic response is mainly related with specific rock parameters. Ardeshiri-Lajimi\cite{22} analyzed the influence of a fault to the underground cavern stability. The numerical analysis indicated that the fault influence on seismic stability is similar to static conditions. Huang\cite{23} used a numerical method to investigate the non-linear responses of the tunnels within normal fault under obliquely incident P waves. The results showed that tunnel across the fault would suffer shearing failure, due to the shear dislocation of the fault, and tunnels located in different areas of the fault suffer different failure patterns. Liu\cite{24} conducted a shaking table test to investigate the influence of inactive fault on tunnels. The results showed that the main deformation of tunnel cross inactive fault is the circumferential strain of the arch waist. And the ultimate tunnel failure is caused be a joint effect of tensile crack and joint dislocation.

Due to the difference of material properties between fault and surrounding rock, the response of them is different under earthquake excitation. This kind of differential movement will cause the tunnel to suffer from the back and forth shear action on the interface. The shear action might cause shear failure or tension cracks parallel to the interface on tunnel lining. With the plastic zone of fault caused by earthquake combine with the development, extension, and transfixion of cracks, weak areas of the tunnel might then collapse.

3. Factors Affecting Tunnel Damages

3.1. Earthquake parameters

3.1.1. Fault activity.
The activity of fault is the key factor to determine the seismic damage of tunnel crossing fault because the failure degree and failure mode of tunnel various with different fault activity. For tunnels crossing active faults, they are sheared by fault dislocation, and the degree of failure mainly depends on fault displacement. And for tunnels crossing inactive faults, the seismic response of the stratum is inconsistent due to the different nature of the stratum, which leads to the uneven deformation of the tunnel and the failure. Therefore, in a design of fault-crossing tunnels, it is very important to find out the activity of fault. And for active fault, it is also very important to estimate the possible dislocation of fault.

3.1.2. Seismic waves.
The impact of propagating paths of earthquake waves on engineering structures has been proved
significant in many studies\textsuperscript{25,26}. However, few pieces of research investigate the incident angle of earthquake waves on tunnels within fault ground. Based on the finite element method with viscous-spring artificial boundary, Huang\textsuperscript{23} analyzed the effect of the different inclinations of incident P waves on the seismic response of fault-crossing tunnel. The results showed that, for the tunnel located in hanging wall, the larger the angularity of the incident angle of P waves, the more serious the damage that the tunnel suffers. And the opposite relationship for the tunnel was found in footwall. Zhao\textsuperscript{27} built a numerical model with an oblique fault and analyzed the tunnel response under P waves of earthquakes. With the increase of incident angle, the axial force and bending moment of tunnel increase first and then decrease.

The seismic response of the tunnel crossing an inactive fault is determined by the response of the stratum. And for fault site, the incident angle of seismic wave is an important factor that influences its seismic response\textsuperscript{28}. However, the research on the influence of the incident angle of seismic wave on fault-crossing tunnels is very lacking, and the influence mechanism remains to be studied.

3.2. Structure status

3.2.1. Tunnel depth.

It is a traditional view that with the increase of burial depth, the earthquake damage level of tunnel decreased. Sharma and Judd\textsuperscript{27} investigated 132 cases of underground structures that damaged in earthquakes, and concluded that there is considerably less damage at depths greater than 50m, and no heavy damage below 300m. This phenomenon also occurs in the homogeneous hard rock section of Duwen highway tunnels after the Wenchuan earthquake\textsuperscript{29}. But the relationship is not clear in weak rocks with faults or high situ stress\textsuperscript{31}.

Baziar\textsuperscript{30,31} analyzed the effect of burial depth on fault-tunnel interaction between reverse faulting and tunnel. The centrifuge test and numerical simulation results indicated that the fault-tunnel failure mechanism changes with the increase of burial depth, and the soil pressure induced by reverse faulting increases with the increase of burial depth. Cai\textsuperscript{32} used centrifuge model tests and numerical simulation studied tunnel response under normal faulting. The results show that the magnitude of the induced longitudinal strain at the tunnel crown increased with the tunnel depth, and the extent of tunnel deformation at the cross-section was also increased with burial depth. Kiani\textsuperscript{33} conducted a series of centrifuge model tests on segmental tunnels subjected to normal faulting, and found that the length of the zone affected by faulting in the tunnel decreased as the overburden increased, but the severity of damage increased in response to localization of fault displacement.

For tunnels located in homogeneous rock mass, it is considered that the greater the buried depth, the greater the earthquake damage. However, the seismic response of fault-crossing tunnel is determined by the shear action of fault. With the increase of buried depth, the pressure of surrounding rock becomes larger and the constraint capacity of the tunnel becomes stronger, which makes the tunnel more vulnerable to fault shear.

3.2.2. Condition of lining.

By some research, the relative rigidity between tunnel and surrounding rock is one of the crucial factors to determine the seismic response of the tunnel. And setting an appropriate relative stiffness is an important way to reduce the seismic damage of tunnels\textsuperscript{34}. Considering the rigidity of surrounding rock, it is impossible for a fault-crossing tunnel to resist the deformation of surrounding rock by improving its rigidity. Soto determine a reasonable stiffness of the tunnel has become a pivotal problem. Some researches have proved that segmental tunnel lining with a less stiffness has the ability to tolerate severer deformation to dissipate the effects of faulting than the continuous ones\textsuperscript{35}. Baziar\textsuperscript{30,31} analyzed the effect of tunnel rigidity on fault-tunnel interaction between reverse faulting and the tunnel and concluded that, for deep tunnels, an increase in the rigidity of tunnel section can enhance their performance in the faulting zone.

For the fault-crossing tunnels, the larger the longitudinal stiffness is, the greater the seismic response will be, and the increase of the transverse stiffness will improve the seismic performance of the tunnel. Therefore, the longitudinal stiffness of the tunnel should be reduced and the transverse stiffness of the
tunnel should be increased in the anti-seismic design of fault-crossing tunnels.

3.3. Geological condition

3.3.1. Dip angle of fault. For both active fault and inactive fault, the dip angle of fault is one of the critical factors affecting tunnel response during an earthquake[22]. Liu[36] designed a series of experiments to simulate normal fault displacement with different dip angles on tunnels. The experiments revealed that the failure modes and crack positions of tunnel appear to change with fault dip angles: when the dip angle is 75°, tunnel damage is mainly caused by flexure in the footwall, and when the dip angle is 45° and 60°, tunnel damage is caused by combing bending and shearing force in the footwall and fault zone. With the decrease of dip angle, the longitudinal damage range increase, which indicates the increase of fault influence range. This conclusion is also being proved by Lin[37]. For inactive fault, the smaller angle between the fault and axial direction of the tunnel is, the more obvious the development of cracks[24]. The smaller the fault dip angle is, the greater the adverse effect of the fault on a tunnel, and the larger the fault influence range is. Therefore, when the tunnel inevitably needs to cross the fault, the largest angle should be chosen to cross.

3.3.2. Width of fault. From the damage investigation, it can be found that the width of fault much influences the tunnel damage. Cui[38] investigated the influence of different fault width on earthquake damage of tunnel. The numerical simulation results indicated that the wider the fault is, the more severe the tunnel will be damaged when the fault dislocated. While for the tunnel crosses inactive faults, the width of fault only determine the influence range of fault, the influence of fault width on the seismic response of tunnels on both sides of the fault is not obvious[39]. In general, the wider the fault, the more adverse the safety of the tunnel across the fault. Therefore, when crossing the fault, the tunnel should be constructed from the place with a narrow fault width.

3.3.3. Property of surrounding stratum. Lin[37] used numerical simulation to study the influence of soil properties of thrust fault on tunnel failure, indicated that soil with higher stiffness and friction angle would induce more serious damage to tunnel lining. Du[39] analyzed the influence of different rock properties on fault-crossing tunnel response and concluded that the larger the difference of medium property between fault and surrounding rock, the more serious the shear failure of the tunnel when crossing fault. Zhao[27] built a 3D numerical model with inclined fault and investigated the seismic response of fault-crossing tunnel. The results indicated that the greater the difference between the mechanical properties of surrounding rock and fault, the stronger the seismic response of tunnel in the fault area. The failure of a fault-crossing tunnel is caused by the different properties of surrounding rock and fault, which lead to different seismic responses between them, and then the tunnel is damaged due to the non-uniform deformation. Therefore, reducing the material property difference between surrounding rock and fault is an effective method to reduce the tunnel seismic damage.

4. Aseismic Measures of Tunnel cross Fault
In general, there are three main philosophies for tunnels to reduce earthquake damage: enhance the properties of surrounding strata, set up aseismic devices and improve the performance of tunnels. However, as the failure mechanism of the fault-crossing tunnel is still under research, the targeted seismic measures need to be further studied. Hashash[8] proposed some design strategies for tunnels crossing active faults: if large displacements are concentrated in a narrow zone, retrofit design will most likely consist of enlarging the tunnel cross section across and beyond the displacement zone, and if fault displacements are small or distributed over a relatively wide zone, providing articulation of the tunnel liner with ductile joints is an effective approach to accommodate fault displacement. Shahidi and Vafaeian[60] classified three probable aseismic measures for fault-crossing tunnels; excavating a larger diameter section to provide enough space for faulting, the isolation technique and the method of flexible
joints. Considering the response and failure mechanism of fault-crossing tunnels, four kinds of aseismic measures are discussed in the present section.

4.1. Buffer layer
Buffer layers are capable to reduce the dynamic loads transmitted from surrounding rock to tunnel lining, and then reduce the relative deformation of tunnel lining, as shown in Figure 1. At present, the feasibility of buffer layer in portal section and body part of tunnel have been verified by some researchers, and the material of buffer layer vary from foam concrete to rubber\(^\text{[41-45]}\).

![Fig.1 buffer layer](image)

Some researches have been carried out to analyze the feasibility of setting buffer layer in fault-crossing tunnels reducing the adverse impact of faulting. Cui\(^\text{[46,47]}\) conducted a series model tests and investigated the damping effect of the buffer layer under normal faulting, and obtained an optimal thickness of the buffer layer. Wang\(^\text{[48]}\) proved that setting a buffer layer in the fault section of tunnel can effectively reduce the acceleration response and strain response of the tunnel lining and then reduce tunnel damage. And the suitable location of the buffer layer in a fault-crossing tunnel was discussed by Cui\(^\text{[49]}\), which is between the primary lining and secondary lining.

A buffer layer set between the lining and the surrounding rock can absorb seismic energy through the deformation of layer material itself, reducing the surrounding rock pressure transferred from surrounding rock to the lining, and then reduce the relative deformation of lining. Thus, seismic damages are alleviated. And the damping layer materials include foam concrete, rubber, and asphalt, etc.

It’s an effective way of reducing seismic response of the tunnel by installing a buffer layer between the primary and the secondary lining. But due to its relatively weak stiffness, buffer layer has certain limitations under static conditions. At the same time, setting a buffer layer cannot reduce the tunnel damage when the fault dislocates. Thus, the buffer layer is suitable for inactive faults but not active faults.

4.2. Fiber concrete
Fiber-reinforced concrete has been a widely used durable material in ground structures or as primary support in underground structures in form of shotcrete. These kind of concrete improves the mechanical properties of concrete, such as compressive strength, tensile strength, ductility, etc. Due to the good performance of fiber-reinforced concrete compared with ordinary concrete, more and more scientists consider to apply it as earthquake resistance material in underground structures.

Xin\(^\text{[49]}\) conducted shaking table tests to analyze the performance of polypropylene fiber concrete lining under earthquake loading. The results showed polypropylene fiber allows tunnel lining to generate smaller deformations and strains to resist deformations of surrounding rock, which is more suitable to be applied in the sections of tunnel lining with larger deformation. Cui\(^\text{[51]}\) used fiber-reinforced concrete instead of ordinary concrete as tunnel lining to study the anti-fault effect of the tunnel under fault dislocation and proved that fiber reinforced concrete can effectively improve the shear resistance of tunnel.

Fiber reinforced concrete can improve the seismic performance of fault-crossing tunnel lining. However, as a passive resistance measure, fiber reinforced concrete does not reduce the shear force caused by fault dislocation or the soil pressure caused by stratum deformation. Therefore, this method needs to be
combined with other aseismic measures to mutually reduce the tunnel damage.

4.3. Flexible joints
Considering the failure mechanism of the fault-crossing tunnel discussed above, the flexible joint is a suitable aseismic measure to make the tunnel adapt to fault dislocation, as shown in Figure 2. Some researches indicated that segmental tunnel lining has the ability of more deformation to dissipate the effects of faulting than continuous one\cite{35}. It proves that for fault-crossing tunnels, increasing the overall longitudinal flexibility of the tunnel may reduce the influence from fault dislocation. Shock absorption seam is one of the flexible joints used in tunnel damping. It is reported that some researches focus on the reasonable distance between shock absorption seams by Cui\cite{52}.

![Fig. 2 flexible joints](image)

Xu\cite{43} applied the flexible joint to the tunnel portal section and verified the effect of flexible joint on the seismic reduction of the tunnel. Ma\cite{13} used a 3D discrete-continuum coupling approach to investigate the performance of a cross-active-fault tunnel with flexible joints. The results showed that the tunnel lining with flexible joints will be more flexible to accommodate the displacement and reduce the stress imposed on the lining segments. Yan\cite{53} proposed a steel reinforced rubber joint with flexibility and ductility and used model test and numerical simulation to verify the effectiveness of flexible joint under normal faulting. The results showed that the tensile damaged area of the lining with joints was obviously smaller than that of the lining without joints. The same flexible joint was used by Shen\cite{18} in the analysis of tunnel crosses displaced secondary fault. The result showed that the structure with flexible joint are with localized damage rather than global damage.

The work described above has emphasized the applicability of flexible lining in a fault zone, and little attention has been paid to the materials of flexible joints and the construction in specific projects. Therefore some scholars have done exploratory work in this field. Zhao\cite{54} analyzed the mechanical characteristics of a new type of plastic concrete and applied it on the flexible joint of fault-crossing tunnels. By numerical simulation, the effectiveness of the plastic concrete has been verified.

The fundamental principle of flexible joint is that, on the one hand, the tunnel lining within a certain range of fault is divided into several sections by the joints, so that the lining of each section is relatively independent; on the other hand, due to the materials with relatively low stiffness and strength in the connection sections, the fault dislocation is mainly absorbed by the deformation of joints. It will not only reduce the stress of each lining segment but also increase the overall flexibility of the tunnel within the fault influence range. Even if the fault is dislocated, the existence of flexible joints will limit the damage of tunnel to a limited area and then avoid the overall damage, and reduce the cost of maintenance and repair.

For the wide faults that may have large dislocations, the flexible joints can effectively reduce the shear failure caused by dislocation. However, because of the damping concept of the flexible joint is to distribute the fault dislocation to each joint with a maximum deformation on average, the application of the flexible joint is limited when the fault width is small.

4.4. Grouting
Grouting is an effective way to reduce tunnel damage caused by uneven response of the tunnel due to
non-uniform stratum. Researches focus on the aseismic effect of grouting measures for the tunnel at the interface between soft and hard rock have been carried out by some scholars, as shown in Figure 3. Wang\textsuperscript{[55]} carried out numerical simulation and proved the effectiveness of different kinds of grouting measures in reducing the seismic response of the tunnel at the interface between the soft and hard rock. Wang\textsuperscript{[44]} analyzed anti-seismic effect of grouting on fault-crossing tunnel and concluded that grouting reinforcement can effectively control the settlement of arch crown and the convergence of sidewall, meanwhile, the full ring interval grouting is better than that of full ring contact grouting.

For the tunnel crossing inactive fault, the main factor of earthquake damage is that the property of surrounding rock and fault is quite different, resulting in the inconsistency of seismic response, and the nonuniform response causes the nonuniform deformation of the tunnel and then lead to destruction. So, grouting reduces the property difference between fault and surrounding rock and fundamentally reduce the uneven deformation of the tunnel. At the same time, strengthening the surrounding rock can improve the tunnel performance under static conditions. However, grouting cannot reduce the fault displacement, nor the tunnel damage caused by fault displacement. Hence the grouting method is only suitable for tunnels crossing inactive fault.

4.5. Enlargement of tunnel cross-section

Enlarging the tunnel across-section can disperse the shear effect of fault to a longer range, so as to reduce the local damage and provide enough space for the tunnel to deform, as shown in Figure 4. Xin\textsuperscript{[56]} conducted a series of shaking table tests to study the operating mechanism of enlarging tunnel cross-section in fault-crossing tunnel. The results showed that the enlarged section absorbs most of the ground motion energy to protect the safety of the internal tunnel. The core concept of enlarging tunnel is to expand the tunnel section properly, and when the fault is dislocated, the pre-expanded area can offset the reduction of clearance caused by fault dislocation, and ensure the effective clearance area to maintain the basic function of the tunnel or to maintain enough space for repairment of the tunnel. While the fault width is wide with possible large dislocation, the over-excavation amount required to enlarge tunnel across is enormous. At the same time, a larger across of the tunnel is adverse to the stability of the tunnel under static conditions. So, it would be uneconomical in this situation.
4.6. Summary
All the aseismic measures discussed above have good aseismic effect for fault-crossing tunnels, but different aseismic measures have their own serviceability. The buffer layer can reduce the relative deformation of lining caused by surrounding rock, which is suitable for tunnels crossing inactive fault. Due to its own good mechanical property, the fiber concrete can improve the seismic performance of tunnel lining. The flexible joint can reduce the tunnel stress and damage by allowing the relative dislocation of linings, which is suitable for tunnels crossing wide active fault. Grouting can reduce the uneven deformation of surrounding stratum and then reduce tunnel damage, which is suitable for tunnels crossing inactive fault. Enlarging tunnel cross-section can provide enough space for the tunnel to deform and reduce local damage, which is suitable for tunnels crossing narrow active fault.

Some evaluations have been carried out for different aseismic measures. Some researches indicated that the buffer layer is more effective than the flexible joint in tunnel cross inactive fault[57]. And some studies showed that for the tunnels cross inactive fault or fault with limited dislocation, enlarging the tunnel across is better than flexible joint and buffer layer in damping effect[58]. However, the geological situation in practical engineering is usually more complicated than that assumed in laboratory research, and single aseismic measures often cannot meet the engineering needs. Therefore, the ideal aseismic design should first verify the fault status, accurately estimate the possible displacement, and then combine the advantages of different aseismic measures, set up composite aseismic measures at the place where the tunnel crosses the fault zone. Some completed fault-crossing tunnel projects were designed by a combination of various aseismic measures. For instance, the Claremont hydraulic tunnel in San Francisco adopted two aseismic measures, i.e. enlarging tunnel across and setting flexible joints. The Kalongla tunnel of Motuo highway enlarged the tunnel across, set flexible joints and used foam concrete as the buffer layer.

5. Conclusions
In this paper, a wide collection of seismic damage investigation and literature reporting seismic response and aseismic measures of the fault-crossing tunnels have been reviewed. And the conclusions are as follows:
1. The area where the tunnel crosses the fault is one of the most vulnerable part of the tunnel in earthquake. This section might be damaged severely in the earthquake. Transverse cracks, inclined cracks, spalling of lining, shear failure and collapse of the tunnel might happen after an earthquake.
2. The seismic damage mechanisms of the tunnel crossing active fault and inactive fault are different. Tunnels crossing active fault are damaged by the shear caused by fault dislocation. And tunnels crossing inactive fault are damaged due to the non-uniform movement of different parts of the tunnel caused by the different seismic responses between fault and surrounding rock. Although the failure of the tunnel crossing active fault is primarily caused by fault dislocation, the influence of earthquake wave propagation cannot be ignored indiscreetly.
3. Influence factors of fault-crossing tunnels include earthquake parameters, structural status, and geological condition. The fault activity is the determining factor that affects the failure mode of a tunnel. The incident angle of the seismic waves is a crucial factor affecting the seismic response of fault-crossing tunnels, but the influence mechanism remains to be studied. The increase of tunnel depth and fault width or the decrease of fault dip angle could lead to more damage to the fault-crossing tunnel. The relative stiffness of tunnel and surrounding stratum determines the response of fault-crossing tunnel, so the increase of tunnel longitudinal stiffness and the difference between fault and surrounding rock, or the decrease of tunnel transverse stiffness would cause severer damage of tunnel.
4. At present, the effective aseismic measures for fault-crossing tunnels consist of setting a buffer layer between the tunnel and surrounding rock, using fiber concrete instead of normal concrete, setting flexible joints between each tunnel section, grouting around the tunnel and enlarging tunnel across. Each seismic measure has its unique advantages and applicable conditions. In the rational seismic design of fault-crossing tunnels, the fault activity should be first verified, and the possible fault movement should be estimated as accurate of possible. Then, according to the geological conditions and engineering requirements, a combination of multiple seismic measures should be adopted.
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