Tunnelling and Underground Space Technology 98 (2020) 103299

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

Shaking table test on flexible joints of mountain tunnels passing through normal fault

Y.S. Shen[a], Z.Z. Wang[b,*], J. Yu[b], X. Zhang[a], B. Gao[a]

[a] *Key Laboratory of Transportation Tunnel Engineering, Ministry of Education, Southwest Jiaotong University, Chengdu, PR China*
[b] *School of Civil Engineering, Dalian University of Technology, Dalian, PR China*

ARTICLE INFO

Keywords:
Mountain tunnel
Flexible joint
Fault movement
Seismic motion
Shaking table test

ABSTRACT

Tunnels often suffered severe seismic damage when passing through the active fault in high intensity earthquake area. The fault movement might be divided into fault movement and seismic motion under the strong earthquake action, and both of them could have the significant influence on the stability of tunnel structure. To improve the seismic performance of the mountain tunnel through fault, a design idea or method of the between sectional tunnel structures with the flexible joint were put forward to run through the active fault and verified or analyzed by using the shaking table test. Firstly, the typical seismic damage characteristics of the tunnel passing through the fault were analyzed after Wenchuan earthquake; secondly, the sectional tunnel linings with the flexible joint were designed in the active fault zone under the strong seismic motion, and the basic theory of this design method was presented in detail. Thirdly, the scaled model shaking table test was carried out to study the seismic performance of flexible joints of tunnels under the normal fault action, and some key parameters of the test was designed, including similarity relationship, boundary condition, sensor layout, input earthquake wave and flexible joint design. The test results showed that the joints between sectional linings could make structure localize damage rather than global damage, and compared to seismic motion, the fault movement suffered more serious damage for the tunnel structure. The tunnel lining at hanging wall was more susceptible to damage or destroy than that at the footwall under the normal fault action, and the flexible joint could adapt to the differential deformation of fault during the strong earthquake. Lastly, the dynamic response of the tunnel lining demonstrated that the upper-structure of the tunnel mainly suffered the severe seismic load, while the lower-structure might experiences the imposed deformation of fault movement under strong earthquake motion. So the design method of the sectional tunnel lining with the flexible joint would be applied to tunnel structure design to improve the adaptive deformation ability of tunnel structure through active fault.

1. Introduction

For a long time, the underground structure has been generally considered to suffer a lower level of damage in comparison with the surface structure during an earthquake (Asakura et al., 2007). The tunnel engineering project will be prior to be recommended due to the advantages of shortening lines, smoothing the curve of traffic lines and resisting geological hazards and earthquake disaster (Yan et al., 2020a, 2020b). However, tunnels located in the active fault area are easily vulnerable to damage by shear deformation under strong ground motion (Kun and Onargan, 2013). A lot of tunnels are designed or constructed in China Western and inevitably cross through active fault zones in mountainous area with some disasters. Therefore, the damage mechanism of the tunnel through fracture zone should be firstly demonstrated under the strong ground motion, and some seismic design method need to be studied to improve the seismic performance of the tunnel running through fault zone in the high intensity earthquake area.

A number of related researches have been carried out to investigate the damage mechanism and seismic design method for tunnels crossing the fault section including numerical simulation (Anastasopoulos et al., 2008; Wang and Zhang, 2013), theoretical analysis (Zhang et al., 2018) and model tests (Su et al., 2019; Wang et al., 2019a, 2019b).

Researches have shown that the most severe earthquake damage occurs in fault fracture zones, followed by tunnel entrances and public road sections (Lai et al., 2017; Yu et al., 2016). Yu et al. (2018, 2019) investigate the seismic response of long tunnels, built-in non-homogeneous ground, subjected to sinusoidal shear motions and derived an analytical solution for the longitudinal bending stiffness of a segmental

* Corresponding author.
E-mail address: wangzhengzheng@dlut.edu.cn (Z.Z. Wang).

https://doi.org/10.1016/j.tust.2020.103299
Received 1 June 2019; Received in revised form 26 December 2019; Accepted 13 January 2020

liner, typically used on tunnels built with a shield next year. Yang et al. (2013) found the non-linear failure process of tunnel-fault system, it could be divided into five main stages: Strain localization, fracture initiation, crack acceleration, spontaneous crack growth and stability by qualitative classification of strain and fracture behavior during the strong earthquake. Zhang et al. (2017) analyzed the effects of different fault thicknesses and locations on tunnel deformation, stress and plasticity. Liu et al. (2015) through the fault displacement test of different dip angles, found that the range of the fracture shear the zone increased with the decrease of the fault dip angle. Yuan et al. (2019) found that the horizontal component contributed more to the dynamic response of the structure than the vertical component at the same time. Huang et al. (2017) found that the tunnel seismic passing through the fault decreased correspondingly with the increase of the incident angle. Baziar et al. (2014) studied the influence of tunnel location, tunnel depth, tunnel stiffness and soil relative density on the reverse fault tunnel. Baziar et al. (2016) proposed that the interaction mechanism between tunnel and soil should be considered in the tunnel design near the active fault zone. Zhao et al. (2019) found that the articulated design could mitigate damage for the tunnel lining due to fault movement. Xin et al. (2019) proposed a composite lining design through the active fault tunnel structure based on the analysis of earthquake disasters, and analyzed the seismic and damping effects of the structure by using three-dimensional numerical simulation method.

These studies mainly focused on the seismic damages mechanism, internal force analysis and dynamic stress response for tunnel structure closed to the fault zone by means of the shaking table test, while the flexible joints between sectional tunnel linings were seldom designed nearby the fault fracture zone in the high intensity earthquake area.

Under the strong ground motion, some induced faults might happen fault movement and seismic motion, and this coupling effect can cause some severe damage for tunnel structure and surrounding rock. So the objective of this paper presents a design idea or method of flexible joint between sectional tunnel linings through active fault under the strong ground motion. Firstly, the seismic damages modes or characteristics of tunnel structure across the fault fracture zone are demonstrated in Wenchuan earthquake; Secondly, the flexible joint design method of the sectional tunnel structure is proposed to adaptive imposed deformation by fault dislocation and seismic motion at the active fault area; thirdly the high-performance shaking table test of tunnel engineering is carried out to verify the reasonability and feasibility of the new flexible joint crossing through the active fault zone in strong earthquake, and the dynamic response and the deformation characteristics of the sectional tunnel lining is analyzed during the strong earthquake excitation. The research results can provide a reference for the seismic design of mountain tunnels across active fault zone.

2. Field investigation and analysis of tunnel damage through fault zone

The 2008 Wenchuan earthquake occurred in Wenchuan County, Sichuan, China. The epicenter was at Yingxiu town with a depth 14 km. The maximum peak ground acceleration (PGA) exceeded 1.0 g. The earthquake caused about 320 km rupture along the Longmenshan Fault Zone by thrusting with a dextral component (Wang and Zhang, 2013). A lot of tunnels near the epicenter (less than 30 km) suffered extremely severe damage during the Wenchuan earthquake, especially in those faults or fracture zones.

At the Longxi tunnel on the Dujiangyan-Wenchuan expressway, there was a F8 fault closed to the portal, where the tunnel lining suffered extremely severe damage during the earthquake within 100 m from the F8 fault, the steel rebar of lining was distorted or the lining was collapsed, and the pavement suffered severe longitudinal and transverse dislocations or uplifts with more than 30 cm high (Shen et al., 2014), as shown in Fig. 1.

At the Jiujiaya tunnel on the Jianjiaya-Qingchuan highway, the tunnel passing through the F1 and F4 faults suffered extremely severe damage during Wenchuan earthquake. For under-construction tunnel, the surrounding rock closed to work-face was susceptible to destroy or collapse and the typical seismic damage of lining included various kinds of lining cracks (longitudinal, transverse and circumferential cracks), spalling, collapse, rupture, reinforcing steel bar distortion, and so on, as shown in Fig. 2. At the same time the secondary disasters had crucial influence on the stability and safety of tunnel lining under the main shock and aftershock actions.

In summary, when the earthquake happened, the induced active fault might dislocate abruptly at first and then the earthquake motion occurred. So the tunnel structure closed to the poor geological condition or fault zone were easily vulnerable to damage due to the imposed deformation of the soft and hard rock during the strong earthquake. The fault dislocation had a crucial influence on the stability of surrounding rock or made the stratum instability, which was an important cause of tunnel lining damage or collapse during the earthquake motion. Therefore, the special tunnel structure should be adapted to the imposed deformation induced by fault dislocation under the strong ground motion.

3. Design idea of sectional tunnel lining with flexible joints through fault

Based on the deformation and damage characteristics of the tunnel structure through fault in Wenchuan earthquake, the seismic motion effect zone for a tunnel crossing through fault is divided into fault affected the zone and fault dislocated zone, as shown in Fig. 3. The strong ground motion characteristics should be taken into account to analyze the dynamic response of tunnel structure at the fault affected the zone (Fig. 3, nd), while at the fault dislocated the zone (Fig. 3, Lm) both the ground motion characteristic and the imposed displacement caused by fault dislocation should be considered.

Especially at the fault dislocated zone, the imposed deformation under fault movement might cause the tunnel lining dislocation. When the strong earthquake happens, the seismic motion can make tunnel lining severe damage, even tunnel completely destroyed, as shown in Fig. 4. So the special seismic anti-fracture and damping energy dissipation measures for tunnel structure should be designed during the earthquake (Fig. 5), in order to mitigate tunnel structure damage probability or try to make structure localize damage.

Base on the allowable longitudinal deflection or angular distortion of tunnel structure and the fault movement characteristics (Fig. 3), the design idea of sectional tunnel lining with flexible joints is put forward to pass through a large active fault area, that is, tunnel lining along longitudinal direction is divided into several sectional tunnel linings, and the flexible joints are installed between the sectional tunnel linings and linked like a piece of chain hinge, as shown in Fig. 5. Due to the flexible joints designed between sectional linings, the longitudinal deformation shape of tunnel structure shows an ideal step-like shape under the imposed deformation action (fault movement), and there happens the relative movement and shear deformation at those joints between sectional linings. Every sectional tunnel lining is only allowed small longitudinal displacement ($\Delta\delta$) during the fault movement.

$$\Delta\delta = \frac{\Delta u_1 + \Delta u_2}{n} \tag{1}$$

where $\Delta\delta$ is displacement of every sectional tunnel lining, Δu_1 is displacement of fault at hanging wall, Δu_2 is displacement of fault at footwall, n is the number of sectional tunnel lining. All symbols are showed in Fig. 3.

So it is minimum cost of joint damage or destruction to cut off the axial transmission of seismic motion, and to avoid the lining structure damage. The flexible joint design method can improve the adaptive deformation ability of tunnel structure through active fault.

For the flexible joints design method, above all, it is important issue

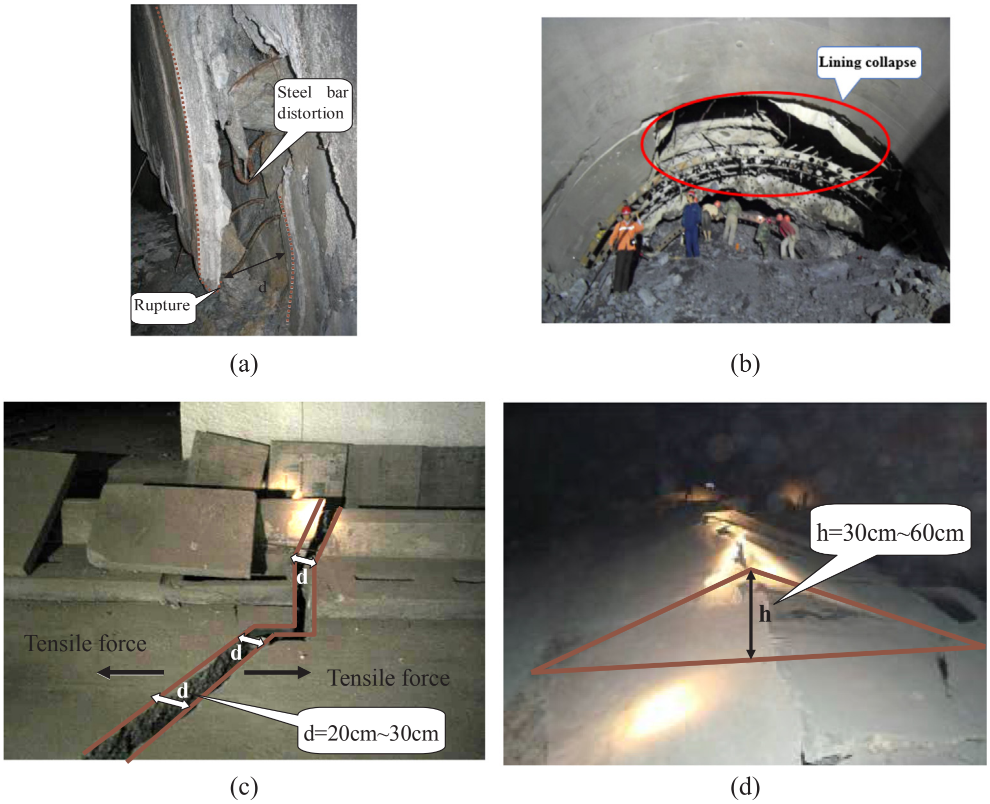


Fig. 1. Damage patterns of tunnel lining in Longxi tunnel. (a) Rupture of Longxi tunnel lining; (b) Tunnel lining collapse; (c) Transverse shear fracture; (d) Longitudinal uplift for pavement.

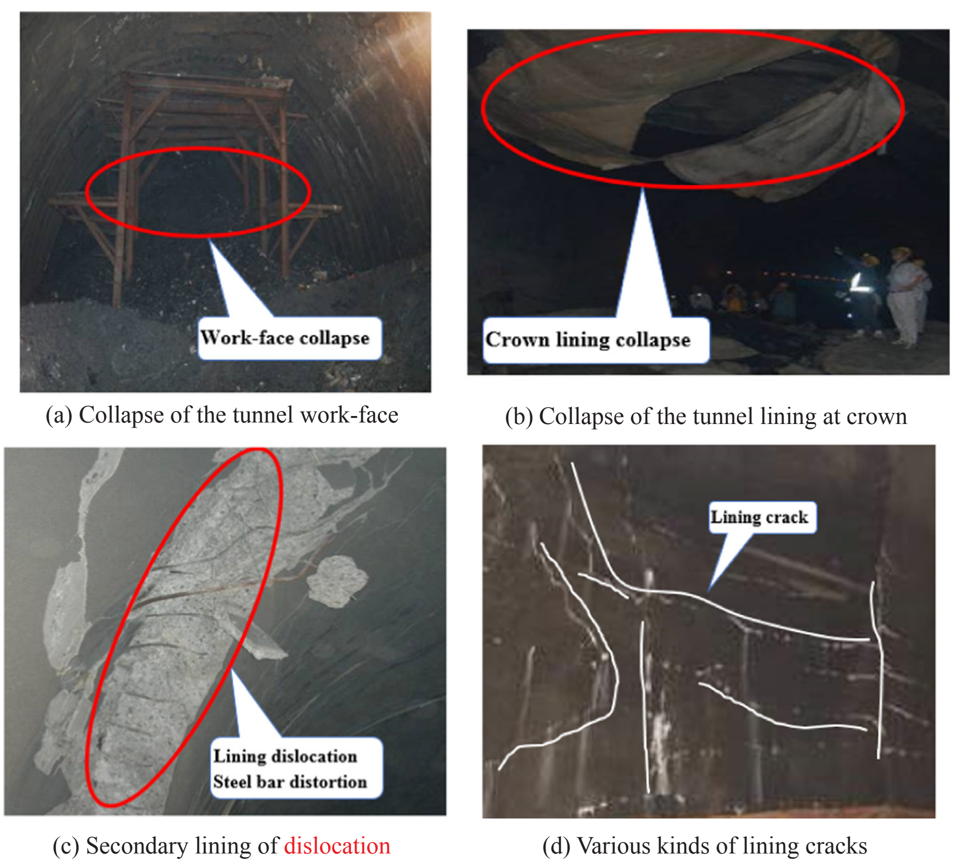


Fig. 2. Ling damage mode of Jiujiaya tunnel. (a) Collapse of the tunnel work-face; (b) Collapse of the tunnel lining at crown; (c) Secondary lining of dislocation; (d) Various kinds of lining cracks.

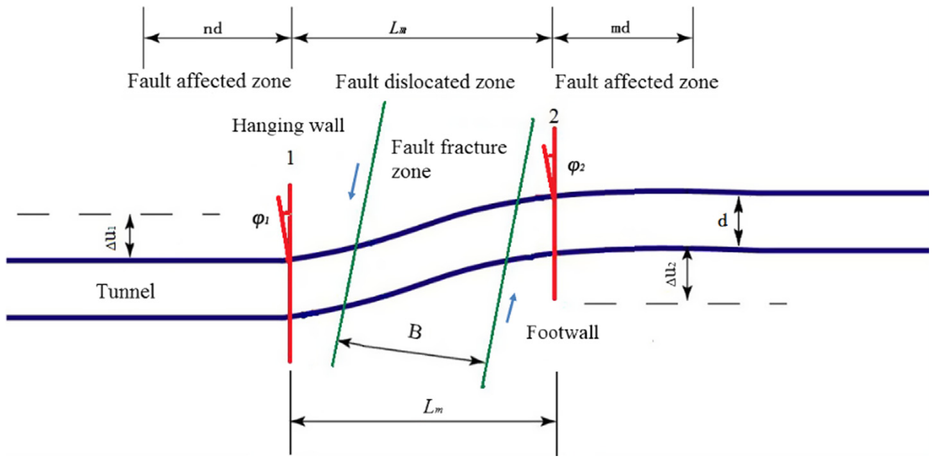


Fig. 3. Sketch map for affected partition of tunnel structure through fault.

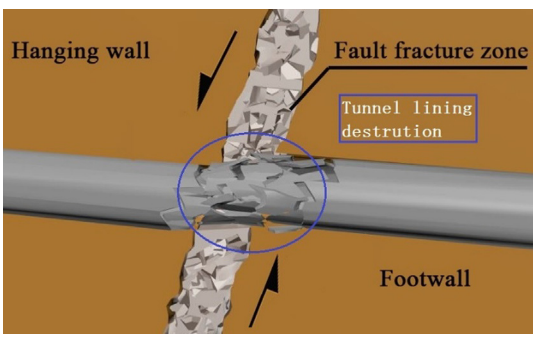


Fig. 4. Sketch map for tunnel lining destruction under the normal fault movement.

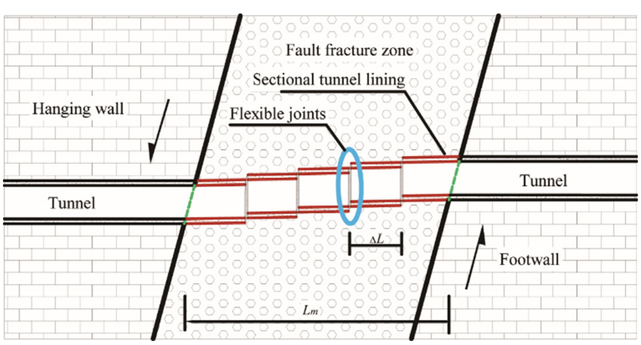


Fig. 5. Sketch map of sectional tunnel lining with joints under the normal fault movement.

that how to design the parameters of both sectional tunnel lining and joints. And these parameters mainly depend on the characteristics of fault movement and seismic wave. The flexible joints need to adapt to the imposed deformation of sectional tunnel linings due to its own flexibility and ductility, which can keep every sectional tunnel lining relatively independent in the fault fracture area. The earthquake energy release will mainly focus on the flexible joints during the fault movement, in order to keep the stability and safety of tunnel structure under the strong earthquake.

4. Experimental method and apparatus

In order to verify the reasonability or feasibility of the sectional tunnel lining with flexible joints design method during the earthquake, the scaled model shaking table test was carried out for tunnel running across the fault zone.

4.1. Shaking table

A model test was conducted at the National Engineering Laboratory for Technology of Geological Disaster Prevention in Land Transportation at Southwest Jiaotong University, and some parameters of shaking table was shown in Table 1.

4.2. Model box design

In the test, the rigid model box was designed to simulate the inclined fault movement with dip angle 82 degrees under the earthquake motion, and it was divided into two parts: hanging wall box and footwall box, as shown in Fig. 6. The hanging wall of model box could move freely in the vertical direction with 10 cm displacement by using four jacks, while the footwall was fixed on the base plate raft. The dimensions of model box were 2.5 m long, 2.5 m wide and 2.0 m high. At the same time the modal analysis of rigid box (first order natural frequency) was carried out to avoid the resonance between box and model material, which met the shaking table test requirements during the strong seismic motion.

Table 1
Parameters of shaking table.

Affiliated Institution	National engineering laboratory for technology of geological disaster prevention in land transportation
Table size (unit: m × m)	8.0 × 10.0
Frequency range (Hz)	0.1–50
Degree-of-freedom	six
Maximum weight (t)	160
Maximum displacement(mm)	Horizontal direction: ± 800; vertical direction: ± 400
Maximum velocity(mm/s)	Horizontal direction: ± 1200; vertical direction:800
Maximum acceleration(g)	Horizontal direction:1.2; vertical direction:1.0
Maximum overturning moment (t·m)	600

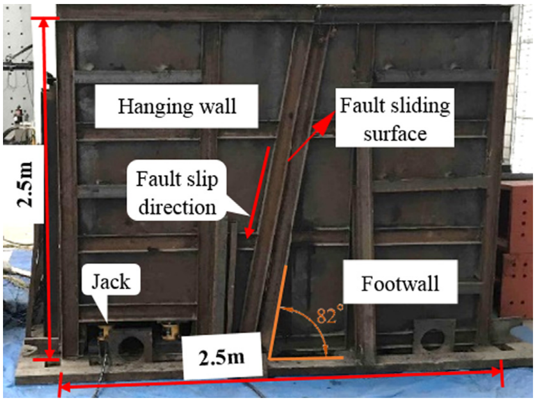


Fig. 6. Shaking table model box with fault.

Based on the test results of Bathurst et al. (2007), the polystyrene foam with 100 mm thick was installed inside of model box in order to absorb vibration energy and reduce the boundary effect of the model box. Meanwhile a layer of gravel was laid to increase the friction action at the model box bottom.

4.3. Tunnel description

The Longxi tunnel (Chengdu-Wenchuan expressway) is located only 2 km from the epicenter of Wenchuan earthquake in Sichuan province, and this mountainous tunnel with a length of 3.7 km was severely damaged during the earthquake. Longxi tunnel runs through an active fault (F8) and the hanging wall is sandstone and the footwall is mudstone with a little sandstone. This F8 fault is a non-causative fault and has a dip angle of 82°. The F8 fault fracture zone with about 10 m in width is filled with some broken rock mass. The tunnel has a horseshoe shape with excavated dimensions of 11.90 m in width and 9.69 m in height. The thickness of the secondary and primary lining is 50 cm and 20 cm, respectively. The concrete used for the secondary support and primary lining is C30-grade and C20-grade, respectively (the grade is consistent with the Chinese Code for Design of Concrete Structures, 2002). The support and lining geometric parameters of the Longxi tunnel is shown in Fig. 7.

4.4. Similarity relationship and similar material of model test

Taking into account the dimensions of tunnel structure, the scaled model shaking table test is carried out in the laboratory with a geometric similarity ratio of 1/30 and Young's modulus similarity ratio of

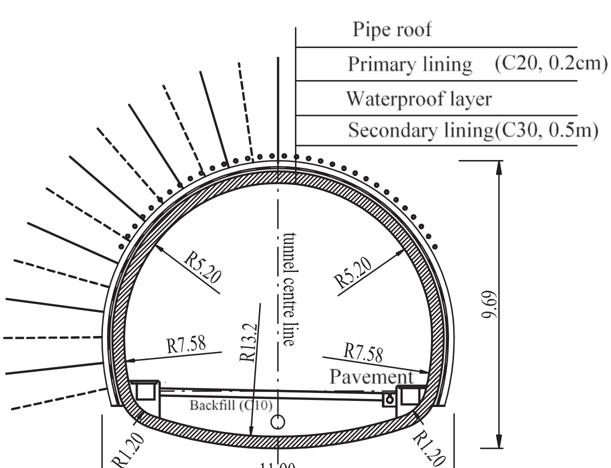


Fig.7. Cross-section of tunnel structure for test (unit: m).

1/45, and other physical parameters are obtained from the Table 2. After several matching tests, the similar material for surrounding rock is a mixing material of fly ash, river sand and waste engine oil, with the percentage ratio 50:40:10, while that of tunnel lining is a kind of precasting structure of water, gypsum, diatomite, quartz sand and barite, with the component and weight ratio 1:0.6:0.2:0.1:0.4. The mechanical parameters of both similar materials and surrounding rock are shown in Table 3.

4.5. Design of sectional tunnel linings with flexible joints for model test

Based on the seismic damage characteristics of Longxi tunnel structure in Wenchuan earthquake, the tunnel was divided into 8 sectional linings along the longitudinal direction and connected by using flexible joints, as shown in Fig. 8. The tunnel was made of four sectional linings (C,D,E,F) with 10 cm in length to pass through the fault dislocated zone, then two sectional linings (B, G) with 20 cm in length were designed at fault affected zone, finally two sectional tunnel linings (A, H) with 80 cm in length were located at far from the fault. The fault fracture zone was designed about 10 cm in width and both sectional lining D and E located at the fault dislocated zone. The steel wire mesh was bonded each other at joint between the sectional models and those joint gaps were filled with plaster, then the high elasticity rubber belt with 50 mm in width and 3 mm in thickness was stuck outside of joint to ensure joints flexibility between the sectional models, as shown in Fig. 9. The physical and mechanical parameters of joint were listed in Table 4.

4.6. Sensors layout

In order to research the dynamic characteristics of displacement and strain of tunnel lining under seismic motion and fault movement action, some displacement sensors were installed at tunnel crown, as shown in Fig. 10a and b. Strain gauges were mainly located in the larger dynamic stress response of the tunnel, and there were three main monitoring sections (2-2, 3-3 and 4-4) arranged to analyze the dynamic response of tunnel structure at fault dislocated zone, as shown in Figs. 10c and 8. In addition, two auxiliary monitoring sections (1-1 and 5-5) were installed simultaneously at the fault affected zone, as shown in Figs. 10d and 8.

4.7. Test progress and input earthquake wave

The scaled model shaking table test didn't simulate the tunnel excavation and the prefabricated lining was directly displaced into the model box. The whole model test was divided into two stages both the fault movement test and the seismic motion test by using shaking table. The former was that the hanging wall of model box was slid downward by using four jacks to simulate the normal fault movement, as shown in Fig. 11. At first, the model box was lifted and fixed by the jacks, and then those similar material was filled into the model box. Secondly, after the experiment preparation was completed, the oil pressure switches of four jack were turned on simultaneously, and the hanging wall of the model box slid down 50 mm instantly to complete the fault dislocation process. The latter the model box would be fastened at shaking table to simulate the earthquake excitations. The ground is dislocated by 1.5 m nearby F8 fault after Wenchuan earthquake in 2008 (Cui et al., 2017). According to the similarity relationship ratio, the dislocation distance should be set at 50 mm.

The dynamic response of the tunnel crossing through fault was simplified to be subjected to fault movement first and then to seismic motion in the tests. And this procedure could truly reflect the seismic shaking state acting to the model.

The Maoxian earthquake wave (EW component) was taken as an input seismic motion for shaking table test, which was recorded at the bedrock station during Wenchuan earthquake, with the peak ground acceleration (PGA) of earthquake wave 0.3 g, as shown in Fig. 12. Based

Table 2
Physical parameters and similarity relationship of model test.

parameters	Similarity relationship	Similarity ratio	Physical parameters	Similar relationship	Similarity ratio
Geometry	c_l	30	Stress	$c_\sigma = c_E$	45
Elastic modulus	c_E	45	Strain	c_ε	1
Density	$c_\rho = c_E/c_l$	1.5	Time	$c_t = c_l^{1/2}$	0.183
Cohesion	c_c	45	Frequency	$c_f = c_l^{-1/2}$	5.5
Friction angle	c_φ	1	Acceleration	$c_a = c_E c_l^{-1} c_\rho^{-1}$	1

Table 3
Physical mechanic parameters of tunnel lining and surrounding rock.

Object	Item	Density (kg/m^3)	Elastic modulus (MPa)	Poisson's ratio	Cohesion (kPa)	Internal friction angle (°)
Surrounding rock	Prototype	2200	2700	–	729	32
	Model	1467	60	–	16.5	32.3
Similarity ratio		1.5	45	–	44.2	1
Fault zone	Prototype	1800	900	–	180	25
	Model	1200	20	–	4	25
Similarity ratio		1.5	45	–	45	1
Secondary lining	Prototype	2400	30,000	0.25	–	–
	Model	1600	680	0.25	–	–
Similarity ratio		1.5	44.1	1	–	–

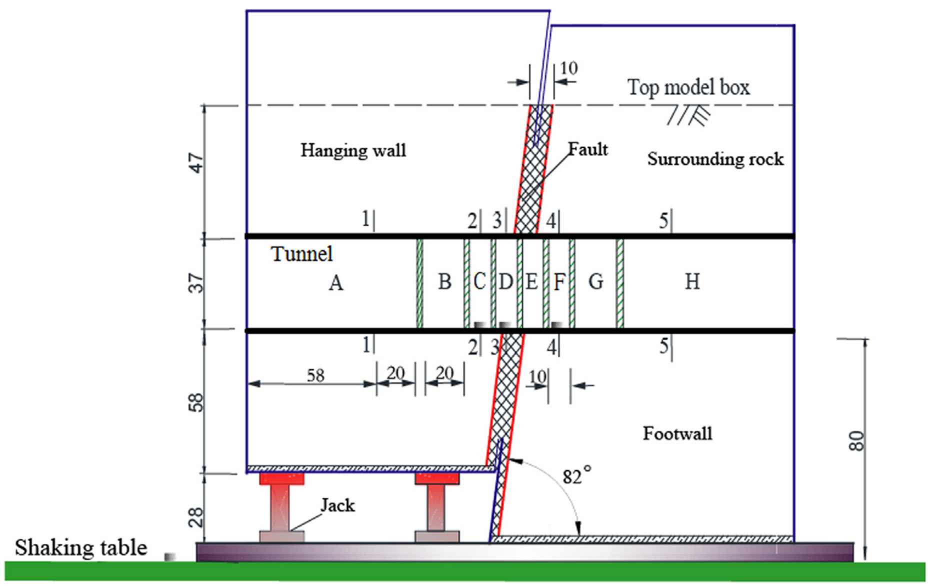


Fig. 8. Distribution of monitoring section and sectional tunnel lining for model box (unit: cm).

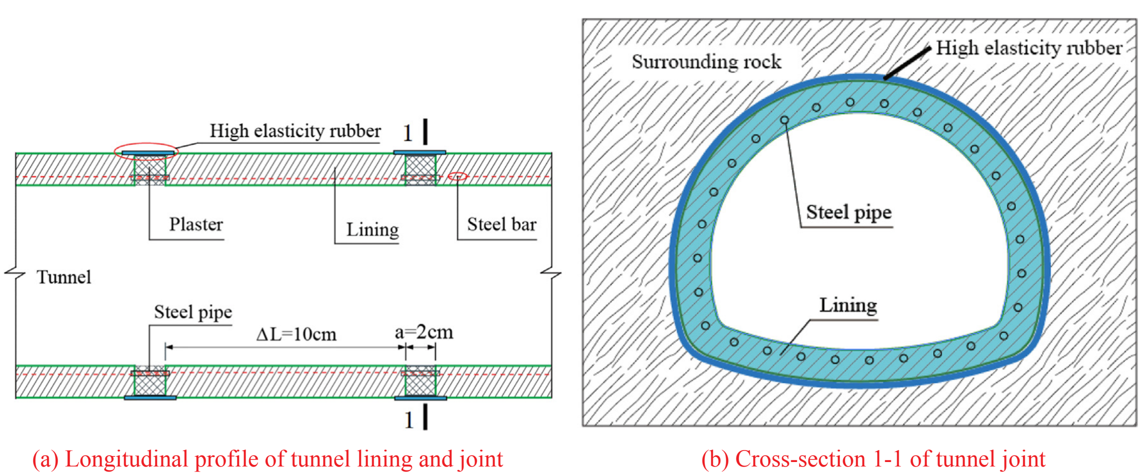


Fig. 9. Sectional tunnel lining with flexible joints.

Table 4
Physical mechanic parameters of flexible joint.

Object	Density (kg/m^3)	Elastic modulus (GPa)	Poisson's ratio
Rubber	850	0.16	0.25
Steel wire	7800	200	0.3

on the time similarity ratio (1:5.5), the earthquake wave record was scaled in amplitudes with the duration of 25 s. The seismic loading was carried out stepwise by shaking table, with the PGA of earthquake wave 0.3 g and 0.4 g. The input seismic wave was perpendicular to the tunnel axis in the shaking table test.

5. Model test results and discussion

5.1. Damage analysis of sectional tunnel lining

5.1.1. First stage normal fault movement

In this stage, the hanging wall of model box was abruptly dip offset downward 50 mm long to simulate the normal fault movement at between sectional lining C and sectional lining D.

Fig. 13 presented the longitudinal deformation characteristic of sectional tunnel linings after fault movement. The imposed deformation happened at sectional tunnel lining C and D crossing the fault zone, which was the main cause of lining C and D damage. The tunnel deformation mainly occurred at the hanging wall due to normal fault and the maximum displacement value was 41 mm at monitoring point d1. But the fault movement had the greatest influence on sectional lining B or C, not sectional lining A, because those sectional tunnel linings away from the fault zone moved as a whole along sliding surface and experienced small imposed deformation. So it was necessary to design the flexible joints between sectional tunnel linings adapting to the deformation of fault movement, especially nearby active fault zone.

As could be seen from the Fig. 14, the sectional tunnel lining C appeared the typical lining uplift and longitudinal fracture at the invert closed to fault zone, and there appeared an obvious dislocation between sectional lining C and D during the normal fault movement. Other sectional tunnel linings were vulnerable to lining falling (only at joints) and some cracks at crown or arch shoulder. Far from the fault, sectional tunnel lining A and H with one crack at invert were not almost susceptible to damage, and the entire tunnel structure still kept a good bearing capacity after the fault movement. Therefore, it was necessary to adopt a flexible joint design between tunnel linings to improve the aseismic performance of tunnel structure, meanwhile those sectional tunnel lining with flexible joints could make the structure localize damage to improve the dislocated performance of whole tunnel through

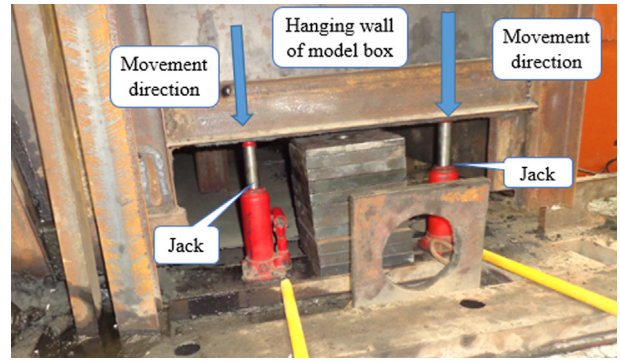


Fig. 11. Four jacks of hang wall bottom for model box.

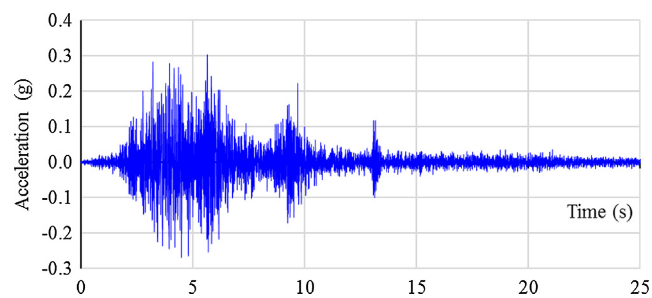
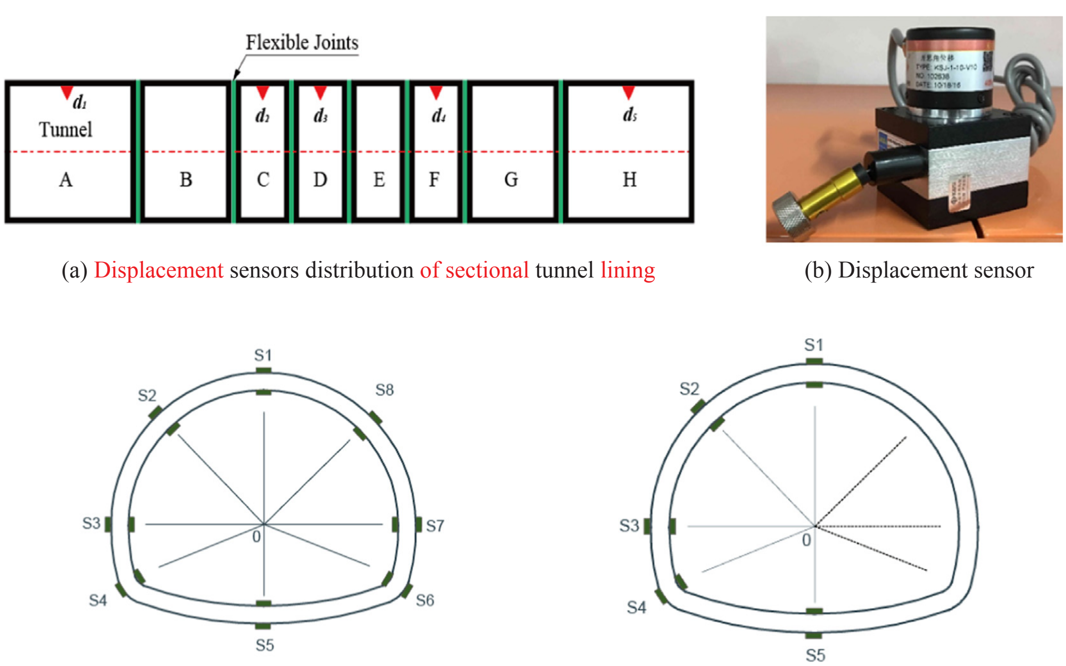


Fig. 12. Input earthquake wave recorded from the bedrock.



(a) Displacement sensors distribution of sectional tunnel lining

(b) Displacement sensor

(c) Strain gauges distribution of sections 2-2, 3-3 and 4-4

(d) Strain gauges distribution of monitoring sections 1-1 and 5-5

Fig. 10. Sensors layout of monitoring section for sectional tunnel lining.

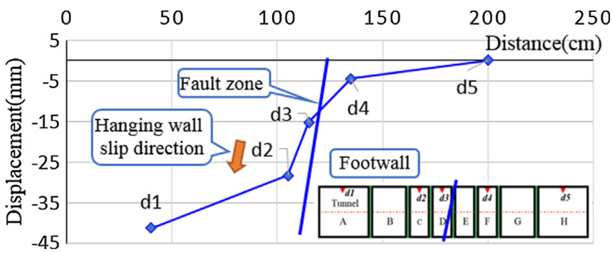


Fig. 13. Longitudinal deformation curve for sectional tunnel linings after fault movement.

active fault.

5.1.2. Second stage shaking table test

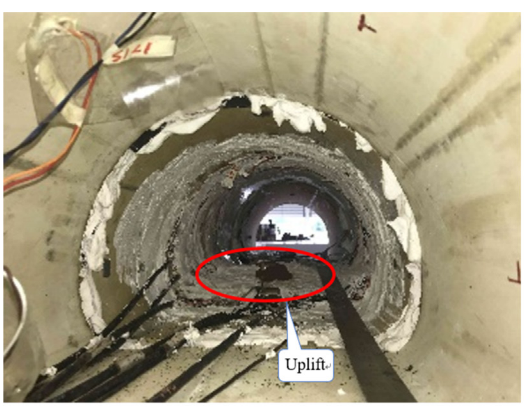
After normal fault movement, the scaled model shaking table test was excited by the Maoxian earthquake wave (EW component) with a PGA of 0.4 g. It was observed that the tunnel lining closed to the fault zone suffered severe damage and the entire invert of sectional tunnel lining A was uplifted 20 mm high at hanging wall, which had significant influence on the bearing capacity of the entire tunnel structure, as shown in Fig. 15a. And three cracks appeared at the invert for sectional tunnel lining H of the footwall (Fig. 15b). And there appeared an obvious dislocation with about 40 mm high between sectional tunnel lining D and E at fault dislocated zone, as shown in Fig. 15c. All flexible joints between the sectional tunnel linings closed to fault were crushed and dislocated, The sectional tunnel lining C occurred fracture in the center of invert and there appeared many cracks at both sidewall feet, as shown in Fig. 15d.

From Figs. 14 and 15, it showed that the tunnel structure was more serious damage at hanging wall than at the footwall during the seismic motion, and those flexible joints designed could mitigate tunnel structure failure probability and make structure localize damage rather than global damage, especially in fault dislocated area. So it was an effective measure to reduce the seismic damage by designing more sectional tunnel linings with flexible joints at the fault dislocated area. If tunnel lining through active fault was damaged during the strong earthquake, the tunnel operation was in a good state by repairing joints or one or two sectional linings.

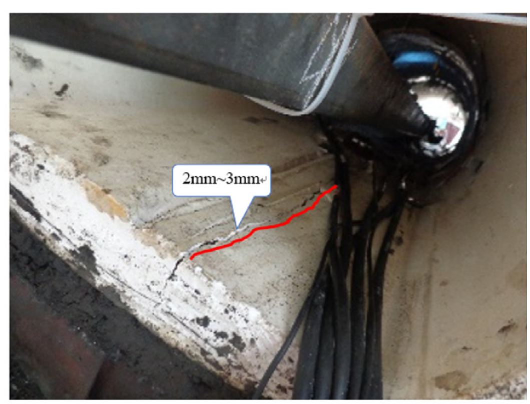
5.2. Dynamic response for tunnel lining during earthquake

Based on the dynamic deformation characteristics of tunnel structure under the strong earthquake, the tunnel lining was easily suffered large deformation at diagonal direction (Shen et al., 2014). In this paper, the monitoring points of the arch shoulder outside and sidewall foot inner side would be focused to analyze the dynamic response of sectional tunnel lining with joints during the scaled model shaking table test.

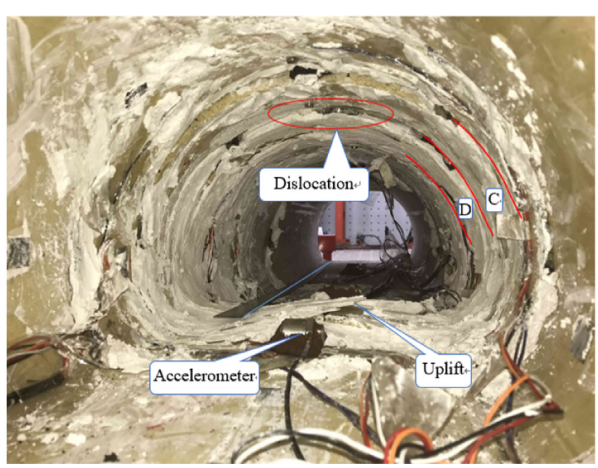
Fig. 16 presented the strain time-history curve of lining at left sidewall foot for different monitoring sections. It was shown that after the largest excitation test case with a PGA of 0.4 g, the variation tendency of input acceleration wave (Fig. 12) was in good agreement with the strain response of tunnel structure (Fig. 16). The maximum strain values of lining at monitoring section 2-2 and 3-3 reached 106με and 103με at time of 5 s, respectively, while the strain values of lining far from the fault were small during the earthquake. The minimum strain value of lining sidewall foot was −93.4με at time of 5 s in monitoring



(a) Section A

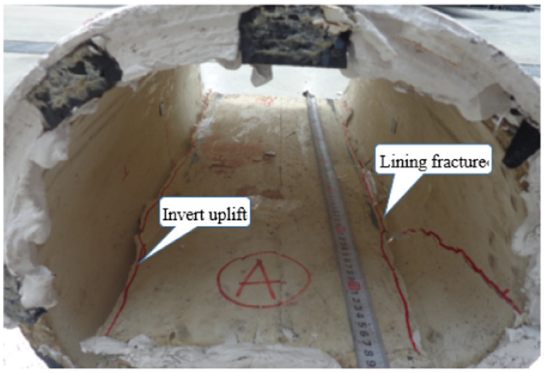


(b) Section H

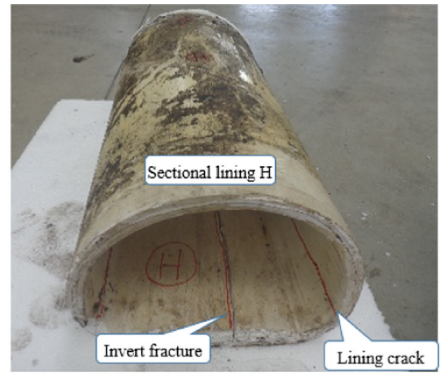


(c) Sections C and D

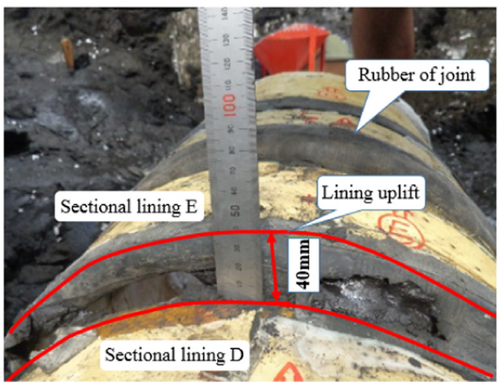
Fig. 14. Cracking distribution of tunnel lining after normal fault movement.



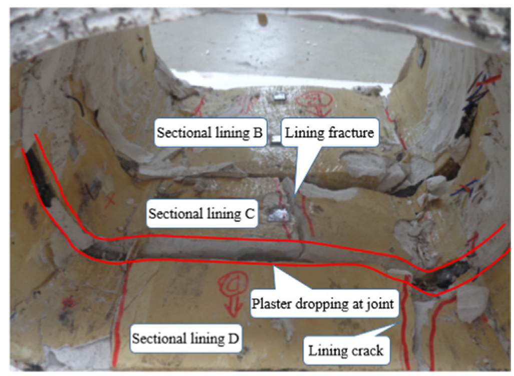
(a) Section A at hanging wall



(b) Section H at footwall



(c) Sectional tunnel lining uplift



(d) Sectional lining B,C and D

Fig. 15. Failure mode of tunnel lining after shaking table test.

section 3-3. The tunnel invert at monitoring section 2-2 and 3-3 was exactly located at the hanging wall bottom and in the fault fracture zone, respectively, where there was a larger imposed deformation and stress concentration than any other positions under the normal fault movement (Fig. 17). So at the sidewall foot, the sectional tunnel lining closed to fault would suffer more seismic load compared to tunnel structure far from fault.

Fig. 18 presented the strain time-history curve of tunnel lining at tunnel arch shoulder for different monitoring sections. The variation tendency of input acceleration wave showed bad agreement with the strain response of tunnel structure, as showed in Figs. 12 and 18. The maximum positive strain value of lining was 230με (at time 5.4 s) at monitoring section 1-1 of hanging wall far from the fault, while the strain value of lining closed to fault was about 44.2με at time 5.4 s. And the minimum negative strain value of lining sidewall foot was −125με at monitoring section 3-3. So the tunnel lining closed to fault was mainly subjected to compressive stress, while the lining far from the fault was the tensile stress at the tunnel arch shoulder. The strain response of tunnel lining nearby fault experienced a typical alternation of the compressive and tensile stress in the diagonal direction during the shaking table test.

Figs. 17 and 19 presented the peak strain value of shorter sectional linings with 10 cm in length was less than that of those longer sectional linings (80 cm in length). After fault movement, all monitoring sections had existed some residual strains, as shown in Table 5. And the final residual strain values of different monitoring points had a little change before and after acting on seismic motion for tunnel model. The peck strain values of arch shoulder for different monitoring sections were twice that of sidewall foot, which indicated that the upper-structure of tunnel (arch shoulder) experienced more severe dynamic response compared to the lower-structure of tunnel lining (sidewall foot). Therefore, the shorter sectional tunnel lining could more effectively reduce the stress concentration and decrease dynamic response of tunnel structure under strong earthquake action.

From this shaking table test, the maximum and minimum strain value distribution of tunnel lining showed a good agreement with the tunnel damage characteristics in shaking table test, while it was different with tunnel seismic damage without some flexible joints (Figs. 1b and 2b). Cui et al. had studied a very similar model tunnel without the joints under similar loading conditions and tunnel structure suffered severe damage nearby fault zone (the maximum strain value 223.6 με) (2017). So it was demonstrated that the several sectional tunnel linings with flexible joints could mitigate dynamic response of structure and improved the aseismic performance of entire structure in high intensity earthquake area. But the specific design of the joints under different situations and comparison of the standard lining and proposed designs still need to be further studied.

6. Conclusions

Based on seismic damages analysis of these typical tunnel passing through the fault after Wenchuan earthquake, a design idea or method of the between sectional tunnel structures with flexible joints was proposed and verified using the shaking table test. The following conclusions could be drawn from this study:

(1) Tunnels were found vulnerable to severe rupture or dislocation or collapse at active fault zone under the strong earthquake, and there tunnel structure would experience two-stage seismic damages with fault movement and seismic motion during earthquake.
(2) The different length of sectional tunnel linings with the flexible joints was designed to apply to the large active fault area under the strong earthquake, and the joints could make structure localize damage rather than global damage. So the flexible joints could

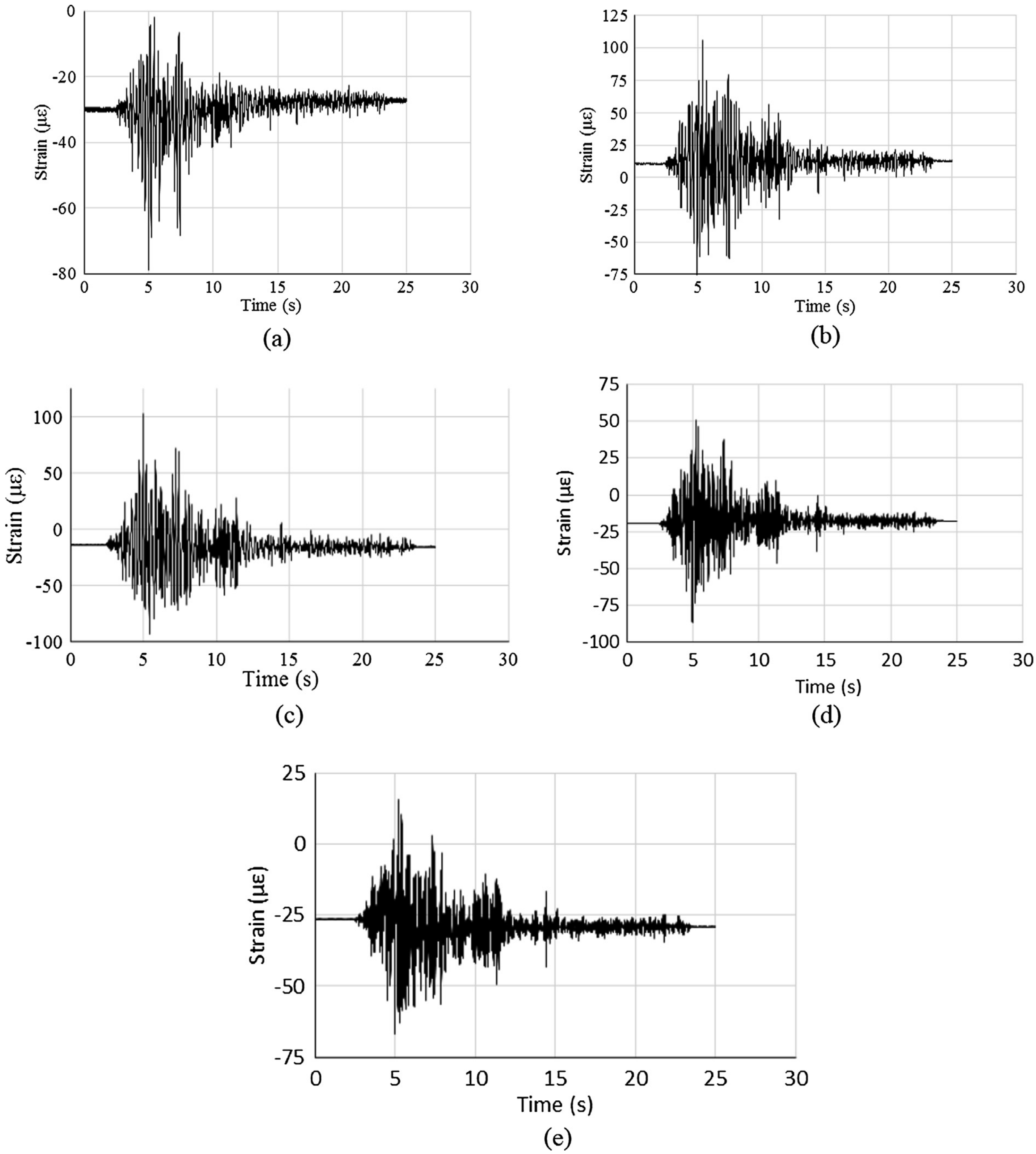


Fig. 16. Strain time-history curve of lining at left sidewall foot for different monitoring sections. (a) Strain time-history curve of lining at section 1-1; (b) Strain time-history curve of lining at section 2-2; (c) Strain time-history curve of lining at section 3-3; (d) Strain time-history curve of lining at section 4-4; (e) Strain time-history curve of lining at section 5-5.

effectively adjust the stress distribution of surrounding rock to reduce tunnel seismic damage.

(3) Based on shaking table test, the fault movement suffered more serious damage for the tunnel structure than seismic motion, and the tunnel structure at hanging wall was more vulnerable to lining fracture or dislocation compared to the footwall. And compared with tunnel lining without joint, almost sectional tunnel linings with joints were damage in the fault zone, but those flexible joints were easily to repair after the earthquake and could effectively avoid global damage of tunnel lining.

(4) From the strain response analysis of tunnel structure, the peck strain values of arch shoulder for different monitoring sections were twice that of sidewall foot, the upper-structure of tunnel could experience more seismic loads, while the lower-structure was more vulnerable to the imposed deformation of fault movement. So the flexible joints design of tunnel structure was recommended to apply to the fault fracture zone in the high intensity earthquake area. This article analyzed qualitatively the performances of the proposed joints based on specific loading cases (i.e. one faulting deformation scenario and one shaking motion) due to the limitations of the test conditions. The specific design of the joints under different situations and comparison of the standard lining and proposed designs still need to be further studied, but the design of the joints, and many of the conclusions of this research are generally hopefully applicable to other similar tunneling projects.

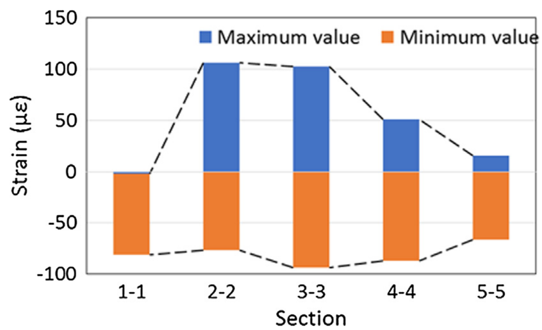


Fig. 17. Strain maxima and minima of sidewall foot for different monitoring sections.

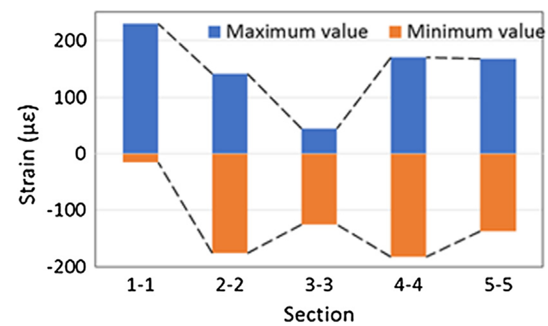


Fig. 19. Maximum and minimum strain values of arch shoulders for different monitoring sections.

CRediT authorship contribution statement

Y.S. Shen: Conceptualization, Writing - original draft, Writing - review & editing. **Z.Z. Wang:** Methodology, Formal analysis, Validation, Funding acquisition. **J. Yu:** Software, Data curation. **X. Zhang:** Software, Data curation. **B. Gao:** Supervision, Funding acquisition.

Declaration of Competing Interest

We declare that we have no conflict of interest.

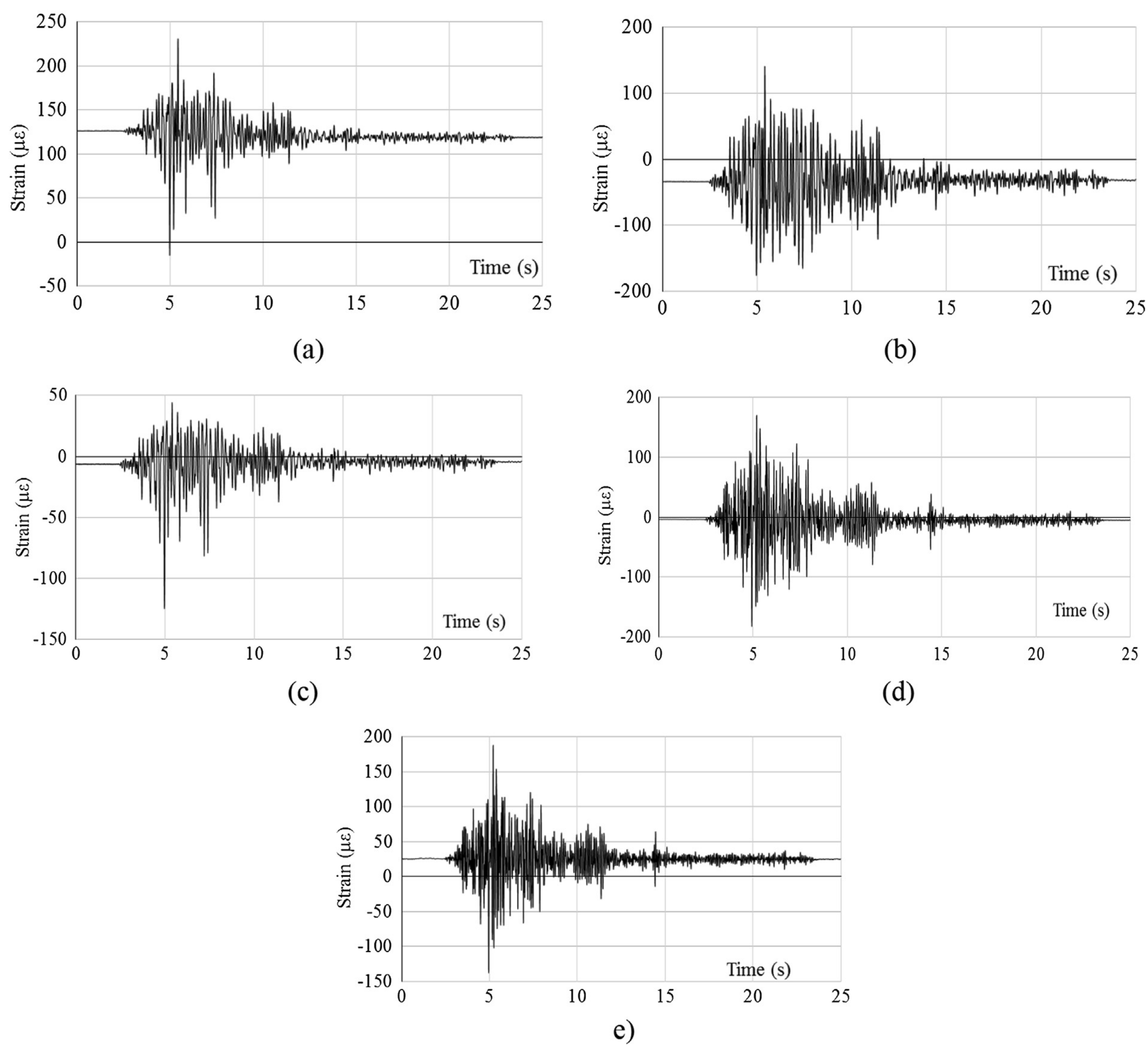


Fig. 18. Strain time-history curves of tunnel lining at left arch shoulder for different monitoring sections. (a) Strain time-history curve of lining at section 1-1; (b) Strain time-history curve of lining at section 2-2; (c) Strain time-history curve of lining at section 3-3; (d) Strain time-history curve of lining at section 4-4; (e) Strain time-history curve of lining at section 5-5.

Table 5
Residual strains of monitoring points in different monitoring sections (unit: με).

Position	Monitoring sections					Remarks
	1-1	2-2	3-3	4-4	5-5	
Arch shoulder	126.2	−33.8	−6.6	−4.6	26	Before seismic motion
	118.5	−32.5	−4.8	−5.2	24.3	After seismic motion
Left sidewall foot	−30.7	10.4	−14.4	−19.3	−26.4	Before seismic motion
	−27.8	12.1	−16.7	−17.8	−29.1	After seismic motion

Acknowledgements

The authors appreciate the support from the National Natural Science Foundation of China (No. 51778540 and 51678501 and 51778539), the National Key Research and Development Program of China (2016YFB1200401 and 2019YFC0605104), and Key Laboratory Open Funds of Transportation Tunnel Engineering of Ministry of Education of China (Grant No. TTE2017-05).

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