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ORIGINAL ARTICLE

Characteristics of seismic disasters and aseismic measures of tunnels in Wenchuan earthquake

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Abstract Over the past few years, accompanied by big and frequent earthquakes, more attention was paid to the tunnel earthquake resistance. To reduce tunnel seismic damage and explore the reasonable aseismic measures, the tunnel earthquake disaster investigation was employed to analyze and summarize the tunnel seismic damage on the basis of Wenchuan earthquake. Fifty-two tunnels near the epicenter of Sichuan Province were investigated: Only 7 tunnels did not show structure damage, 6 tunnels suffered the most serious damage, and the rest appeared damage to various extents. It indicates that most serious seismic damage happens to fault fracture zone, followed by entrance and common section of the tunnel. Additionally, the results display that the typical seismic damage of tunnels is lining cracking, collapsing, dislocation, construction joints cracking, and uplifting of invert, and usually lining cracking and collapsing account for a larger proportion. Therefore, the tunnel aseismic design should emphasize the fault fracture zone and tunnel entrance. Tunnel design should adopt the composite lining structure with shock absorber and whole chain alternative grouting to prevent the lining cracking and collapsing in the seismic fortification zone.

Keywords Tunnel · Earthquake resistance · Seismic damage · Disaster investigation · Wenchuan earthquake

Introduction

The destructive effects of earthquakes from the surface to deep underground weakened rapidly, therefore, compared with the ground buildings, tunnels and underground structures usually have a better seismic performance, and their seismic capacity improves with the increase in tunnel depth. However, in the recent 100 years, the earth entered a new active seismic period, and many earthquakes with high magnitude occurred, such as Tokyo earthquake with magnitude of 8.3 in 1923, Tonghai earthquake with magnitude of 7.8 in 1970, and Hanshin earthquake with magnitude of 7.2 in 1995 (Liao and Guo 2012). Consequently, different damage happened to those tunnel structures experienced large earthquakes, and much attention was paid to study tunnel seismic damage and aseismic measures.

The Wenchuan earthquake happened on May 12, 2008, with the magnitude of 8.0, resulted from Longmen Mountain thrust nappe pushing southeastward with anticlockwise shearing, as shown in Fig. 1. Its epicenter was located at the intersection of Yingxiu Town and Xuankou Town in Wenchuan County of Sichuan Province, at 31.01° N and 103.42° E, with focal depth of 29 km, as shown in Fig. 2. This earthquake was of great destructive. Tunnels suffered from large-scale structure damage in Sichuan, Gansu, and Shaanxi of China (Chen et al. 2012). The earthquake economic losses doubled about every 10 years owing to the development of the world economy; thus, the seismic resistance of underground structures gradually became an important project.

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Fig. 1 The position and causes of the Wenchuan earthquake

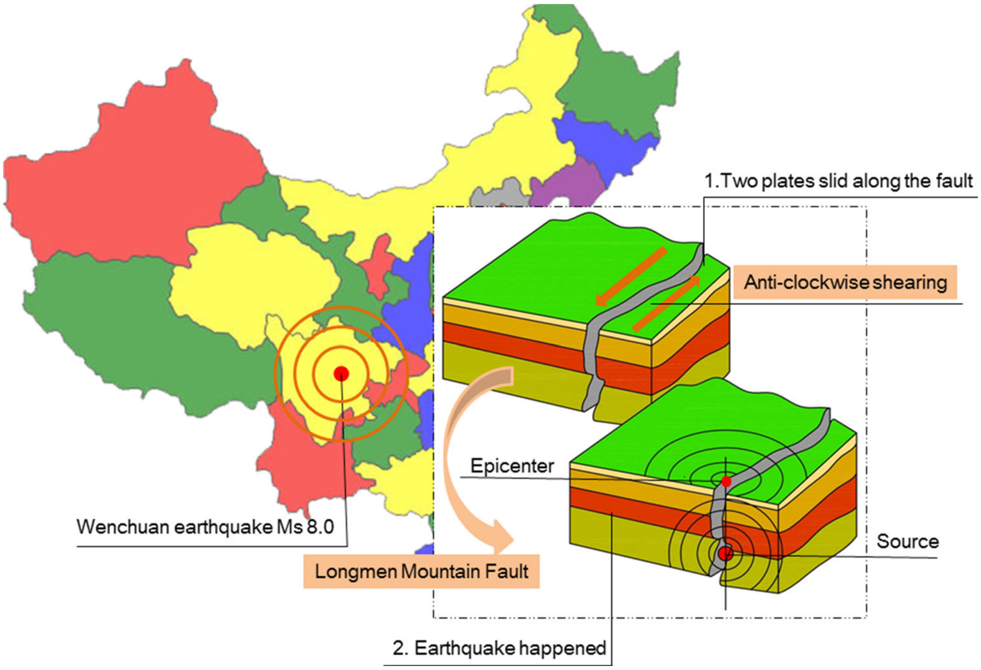
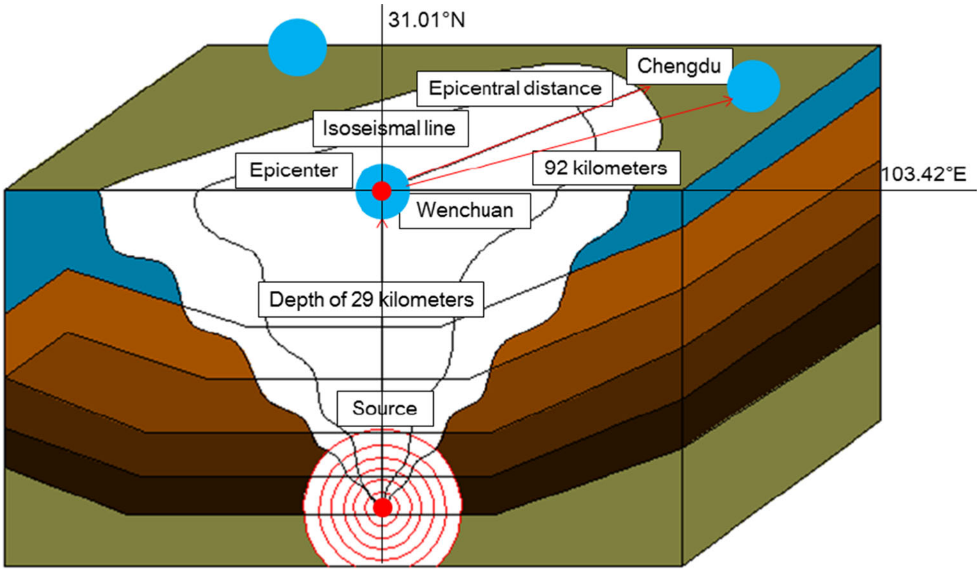


Fig. 2 The epicenter and focal depth of the Wenchuan earthquake



A large amount of data statistics and numerical simulation have been carried out to address the tunnel seismic damage and aseismic measures in recent years. For data statistics, Guo et al. (2010) analyzed the causes for damage of buildings and tunnels in the Wenchuan earthquake. Li (2011) made a summary of damage characteristics and aseismic constructions about mountain tunnels in Wenchuan earthquake. Cui et al. (2011, 2013a, b, c) summarized the structure damage of each tunnel section by dividing the tunnel into sections in the Wenchuan earthquake. In terms of numerical simulation, Genis (2010) considered the seismic damage patterns of tunnel along the axis through the 3D dynamic based on DEM method. Yu et al. (2016a) took advantage of FLAC-3D to conduct numerical simulation for the seismic damage of Longxi tunnel and analyzed the theoretical causes of tunnel seismic damage. For aseismic measures, Gao et al. (2005) summarized two shock absorption measures and aseismic situation of underground structures. Gao et al. (2009) launched a comparative study on different grouting methods for reducing seismic damage.

The aforementioned work analyzed and summarized tunnel seismic damages and earthquake resistance without systematic comparison of seismic damages and perfect aseismic measures. Therefore, this paper took into account the influencing factors of tunnel seismic damages, divided the tunnels into sections, summarized and classified the difference in tunnel structure damages, analyzed the causes of seismic damages, and proposed the corresponding aseismic measures and shock absorption methods for different seismic damage based on Longxi tunnel, Zipingpu tunnel, Baiyunding tunnel, Longdongzi tunnel, Youyi tunnel, and Shaohuoping tunnel with the most serious damage in the Wenchuan earthquake.

Summary of tunnel damage

Statistics of tunnel damage

The structure damage of tunnels in the Wenchuan earthquake mainly happened in mountainous area. Seismic damage of 52 highway tunnels was detected and collected by Sichuan Provincial Transport Department Highway Planning, Survey, Design and Research Institute after the big earthquake (Tao and Jiang 2014). Results indicated that 11.5% of the tunnels suffered from extremely serious damage, 5.8% heavy damage, 19.2% intermediate damage, and 44.2% slight damage, and only 19.3% of the tunnels showed obscure seismic damage.

Tunnels near the epicenter suffered from the most serious seismic damages, for example the Longxi tunnel, Zipingpu tunnel, and Longdongzi tunnel of Dujiangyan-Yingxiu Expressway, Shaohuoping tunnel of Yingxiu-Wenchuan Expressway, Baiyunding tunnel, and Youyi tunnel of G213 Expressway, as shown in Fig. 3.

The relationships between fault fracture zone and tunnels are shown in Table 1. These tunnels were perpendicular to fault fracture zone approximately, and their seismic design intensity were all VII and lower than the actual intensity in Wenchuan earthquake; meanwhile, they reflected serious damage which was quite different from the current cognition of tunnel seismic damage (Chen and Zhuang 2011).

Seismic damage patterns

Tunnel structure damage, including slope instability, lining cracking, collapsing, and dislocation, fracture of tunnel portal, uplifting of invert, and fault slip were significant in Wenchuan earthquake, as shown in Fig. 4. The most common tunnel seismic damage patterns were lining collapsing and dislocation of tunnel (Ma et al. 2016). The probability evaluation and reasons of different seismic damage patterns are shown in Table 2.

Influencing factors of tunnel seismic damage

Seismic intensity

Seismic intensity was divided into twelve grades in China on the basis of tremor. The degree of building damage, the level of seismic ground motion parameters, and the release of the earthquake energy increased with intensity level (GB/T 17742-2008) (2008). The intensity distribution of the Wenchuan earthquake is shown in Fig. 5. The tunnels that suffered from serious seismic damage were concentrated in the area of the intensity above VI, and statistics of structure seismic damage in portal section were mainly conducted between intensities VI and XI. The seismic damage of highway tunnel portal and outside the tunnel portal mainly occurred in the area of intensity IX and above (Luo et al. 2017), as shown in Table 3.

Results showed that structures outside of the tunnel were greatly affected by the secondary disaster, the influence of earthquake inertia force was significant (Dikmen 2016), and little seismic damage happened to side and front slopes in

Fig. 3 Positions of the tunnels around the Wenchuan County

Table 1 The relationship between fault fracture zone and tunnels around the Wenchuan County

Tunnel name	Tunnel length (m)	Design intensity	Actual intensity	Relationship with fault fracture zone
Longxi tunnel (LX)	3674.5	VII	XI	Near orthogonal
Zipingpu tunnel (ZPP)	4096	VII	X	Near orthogonal
Longdongzi tunnel (LDZ)	1047	VII	XI	Skew
Shaohuoping tunnel (SHP)	450.5	VII	XI	Skew
Youyi tunnel (YY)	406	VII	X	Skew
Baiyunding tunnel (BYD)	950	VII	X	Near orthogonal

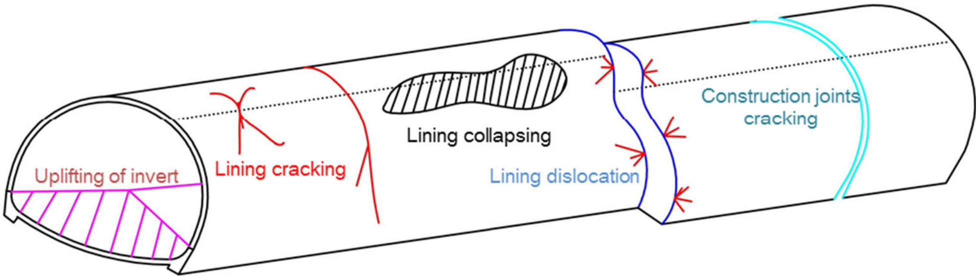


Fig. 4 Seismic damage patterns of the Wenchuan earthquake

Table 2 The percentage and causes of tunnel seismic damage patterns

Damage patterns	Causes of seismic damage	Percentage of seismic damage (%)
Slope instability	Rock and soil failure	22
Lining cracking	Interaction between rock mass and underground structures	19
Portal failure	Failure of rock, vibration effect	16
Lining collapsing	Tensile failure of high-frequency vibration wave	10
Lining dislocation	Dynamic interaction between rock and underground structures	5
Uplifting of invert	Dynamic interaction between rock and underground structures	11
Construction joints cracking	Fault tectonic activity	9
Others		8

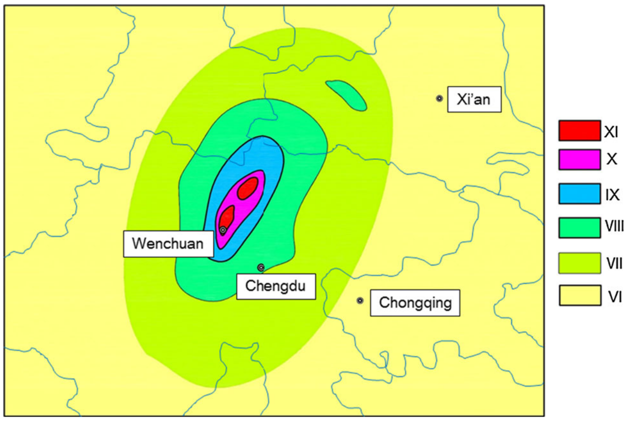


Fig. 5 Seismic intensity distribution of the Wenchuan earthquake

Table 3 Earthquake intensity and portal seismic damage

Tunnel name	Design intensity	Side slope	Portal
Xiaoqiuguan tunnel	VII	No	Smash
Feixianguan tunnel	VIII	No	Smash
Caopo tunnel	IX	Collapse	Crack
Baiyunding tunnel	X	Collapse	Crack

intensities VII and VIII. Seismic damage under the intensities of IX and X was mainly caused by the secondary geological disaster, including cracking of tunnel portal, and collapsing and slumping of the mountain tunnels. Besides, the seismic damage of tunnel portal, side and front slopes, and open cut tunnel was mainly owing to the earthquake inertia force (Xue et al. 2015), while lining structure of tunnel portal in soft rock mainly resulted from the earthquake inertia force and forced displacement (Wang and Zhang 2013).

Usually, tunnels cannot be destroyed below the earthquake intensity of VII. A few tunnel construction joints and tunnel entrances will slightly crack in intensity of VII. Lining structures cracking, water seepage, and secondary disasters will happen in intensity of VIII. Severe lining structures cracking, concrete spalling, and even collapsing of lining structures will happen in intensity of IX. Collapsing of lining structures will increase in intensity of X. Rock mass will crush and tunnel will collapse in intensity of XI. The quantity and scale of seismic damage broaden as the seismic intensity increases (Lai et al. 2017).

Rock classification

The overall seismic damage of tunnels was not serious under the better state of rock mass. The lining cracking and collapsing of secondary lining had a bearing on the actual support of tunnels, so the correlation to the rock mass classification was not indicated. According to the "Code for Design of Road Tunnel (JTG D70-2004)" (2004), the basic quality index (BQ) of rock mass was determined by the degree of rock hardness and integrity. The rock mass was divided into six grades. The lining dislocation and construction joints cracking were bound up with the actual construction quality and monitoring of construction; however, tunnel seismic damage reduced when the rock mass was in better condition, as shown in Table 4.

As a whole, seldom tunnel seismic damage occurs in the impact rock mass; however, different seismic damage often happens to tunnels in the weak rock mass, especially in rock mass grade of V. Therefore, the corresponding aseismic measures for tunnel lining support should be adopted under the worse quality of rock mass.

Epicentral distance

Tunnel seismic damage depended on epicentral distance in Wenchuan earthquake. Seismic energy decreases gradually with the transmission of seismic wave, and the tunnel seismic damage declines with the increase in epicentral distance. Considering the longitude and latitude (λ_0, φ_0) of epicenter and that of observation station (λ, φ), the epicentral distance Δ could be calculated by these methods (A_Z is azimuth angle, and A is the semimajor axis of the earth): horizontal coordinate method, geocentric latitude method, Bren formula method, Gauss mid-latitude formula method, and Robbins method. Hu (1987) compared these methods and reported that the relative error of Robbins method was below 0.007% when the epicentral distance was calculated with the azimuth angle between 40° and 140°, so Robbins method was adopted to calculate the epicentral distance of the Wenchuan earthquake.

Table 4 The rock mass and disasters distribution of six tunnels

Rock mass classification	V	IV	III	II
Length of seismic damage (m)	370	245	87	34
Proportion of seismic damage (%)	20.6	13.7	4.8	1.9

The Robbins method:

$$ctgAz = (\cos\varphi_0 tg\varphi_s - \sin\varphi_0\cos\Delta\lambda)/\sin\Delta\lambda$$

$$\Delta = N_e\delta\left\{1+\frac{\delta^2}{6}h^2(1-h^2)+\frac{\delta^3}{8}gh(1-2h^2)\right. \\ \left. +\frac{\delta^4}{120}\times\left[h^2(4-7h^2)-3g^2(1-7h^2)\right]-\frac{\delta 5}{48}gh\right\} \tag{1}$$

where $Ne = A/\sqrt{1-e^2\sin^2\varphi_0}$, $Ns = A/\sqrt{1-e^2\sin^2\varphi}$, $tg\varphi_s = (1-e^2)tg\varphi + e^2\frac{N_e\sin\varphi_0}{N_s\sin\varphi}$

$$\sin\delta = \sin\Delta\lambda\cos\varphi_s/\sin A_z,\ h^2 = \varepsilon\cos^2\varphi_0\cos^2 A_z, \\ \varepsilon = e^2/(1-e^2),\ g^2 = \varepsilon\sin^2\varphi_0 \\ \sin\Delta\lambda\cos ecAz = (\cos\varphi_0 tg\varphi_s - \sin\varphi_0\cos\Delta\lambda)/\cos Az \tag{2}$$

The statistics of highway tunnels by epicentral distance in the Wenchuan earthquake are shown in Fig. 6. It indicates that with the increasing epicentral distance (Lai et al. 2015), the number of tunnels and seismic damage reduces. The tunnel was in a dangerous state with epicenter distance below 40 km, and half of them appeared serious seismic damage. The tunnel appeared a small amount of seismic damage with epicenter distance above 100 km. Seldom earthquake damage in the tunnel appeared with the epicentral distance of 300 km.

Tunnel depth

Tunnel depth refers to the vertical distance between the top of the tunnel excavation section and the natural ground. The research data indicated that with the increase in tunnel depth, tunnel seismic damage decreased, and compared with shallow tunnel, deep tunnel seemed to be safer. However, LX tunnel was an exception in the Wenchuan earthquake, where deep mountain tunnel suffered from heavy damage for the first time, the secondary lining collapsed on a large scale, and some cavities crumbled away. This thoroughly overturns the view: "There are no tunnels with a depth of over 300 m which suffers from serious damage" (Liao and Guo 2012). So the statistics and analysis of deep tunnel seismic damage in the Wenchuan earthquake were of great significance. The statistics of tunnel seismic damage in the Wenchuan Earthquake by tunnel depth less than 500 m are shown in Table 5. Results showed that the shallow tunnels had serious seismic damage with tunnel depth of 25 m, and seismic damage decreased with the increase in tunnel depth; meanwhile, tunnel showed little seismic damage with tunnel depth above 500 m.

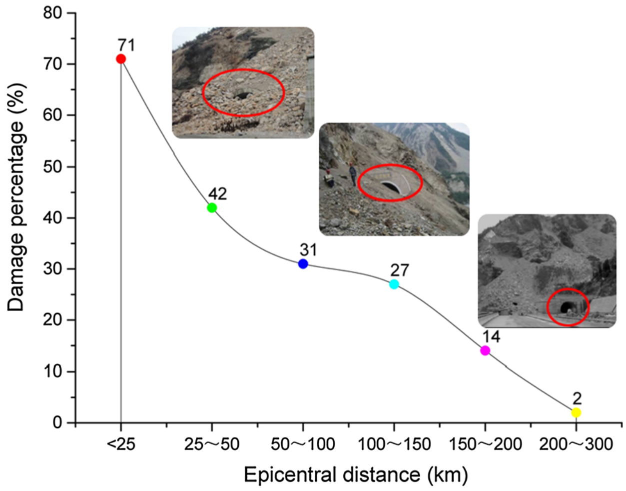


Fig. 6 Epicentral distance and tunnel seismic damage

Analysis of damage characteristics and mechanism of different tunnel structure sections

Different paragraphs of the tunnel earthquake disasters reflected a very large gap. The common tunnel was divided into three sections: tunnel structure in portal section, tunnel structure in fault fracture zone, and tunnel structure in common section (Cui et al. 2013b). Therefore, the structure of tunnel portal was divided into shallow tunnel structure and deep tunnel structure, as shown in Fig. 7.

Tunnel structure in portal section

Owing to shallow depth, and poor geological conditions, tunnel portal section was easily affected by external factors. And the intensity level of the Wenchuan earthquake was high, so there was much secondary seismic damage. Tunnel portal section suffered from the most serious seismic damage except fault fracture zone. In terms of lithology, the lining structure of tunnel portal section could be divided into soft rock lining and hard rock lining, and soft rock portal section can also be divided into shallow-buried soft rock section (S) and soft rock transition section (T) (Ye et al. 2012), as shown in Fig. 8. The tunnel structure seismic damage of portal section was closely related to the softness of surrounding rock. The damages of hard rock tunnel section were slight, while the structure of soft rock tunnel portal section suffered from heavier seismic damage (Cui et al. 2013a). The statistics of structure seismic damage for portal section of six tunnels, namely LX tunnel, ZPP tunnel, BYD tunnel, LDZ tunnel, YY tunnel, and SHP tunnel according to the extent of soft and hard surrounding rock, are shown in Table 6.

The seismic damage of soft rock tunnel portal section mainly included lining cracking, which accounted for about 50%, followed by collapsing of secondary lining without lining dislocation. Construction joints cracking accounted for about 6%, and hard rock tunnel portal section suffered little seismic damage. For example, Zaojiaowan tunnel and Maojiawan tunnel with hard lithology and complete granite suffered almost no seismic damage. Because seismic fortification was conducted in the construction of shallow-buried section of soft rock tunnel portal, collapsing of secondary lining did not appear. However, collapsing of secondary lining which occurred in the transition section of soft rock tunnel portal was due to high seismic intensity and no reinforcing bars. Tunnel portal, side and front slopes, and open cut tunnel structure were blocked and destroyed by falling rocks.

Tunnel structure in fault fracture zone

The tunnel structure in fault fracture zone suffered from the most serious damages in the Wenchuan earthquake, and it included dislocated fault fracture zone and in situ fault fracture zone. The tunnel structure in dislocated fault fracture zone suffered from heavier damage than that of in in situ fault fracture zone, as shown in Fig. 9. Lining cracking, lining collapsing, lining dislocation, construction joints cracking and other damage appeared in the tunnel structure of dislocated fault fracture zone, while no seismic damage such as collapsing of secondary lining, tunnel lining collapsing occurred in in situ fault fracture zone. Tunnel lining and collapsing of secondary lining were the most serious seismic damage (Cui et al. 2013c). Table 7 shows the statistics of seismic damages for four different tunnels in fault fracture zone with different grades of rock mass.

Table 5 Tunnel depth and tunnel seismic damage

Tunnel depth (m)	Damage number				Damage percentage (%)
	Light	Intermediate	Serious	No	
<25	14	9	10	24	58
50–100	2	1	2	12	29
10–200	3	0	1	6	40
20–300	3	2	1	13	32
30–500	4	3	0	4	14

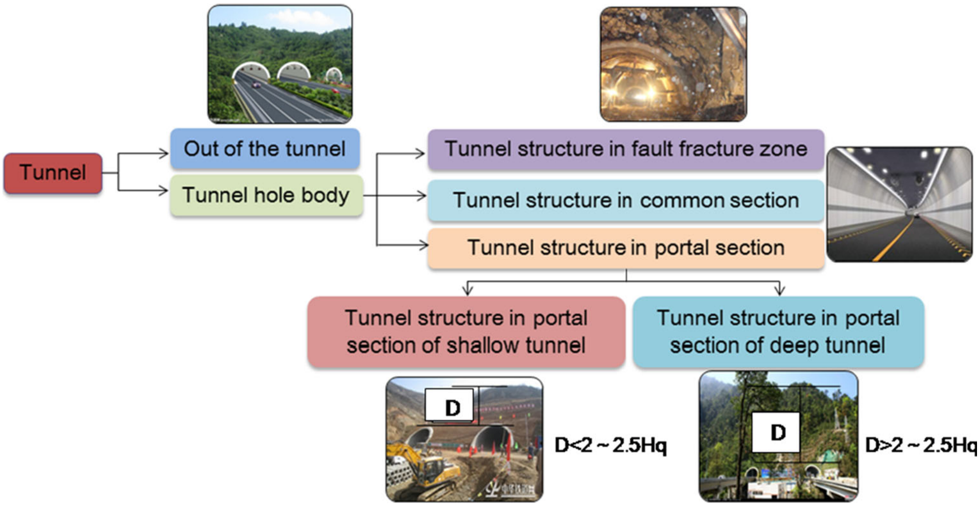


Fig. 7 Detailed tunnel structure division (*D* tunnel depth, *hq* load equivalent height)

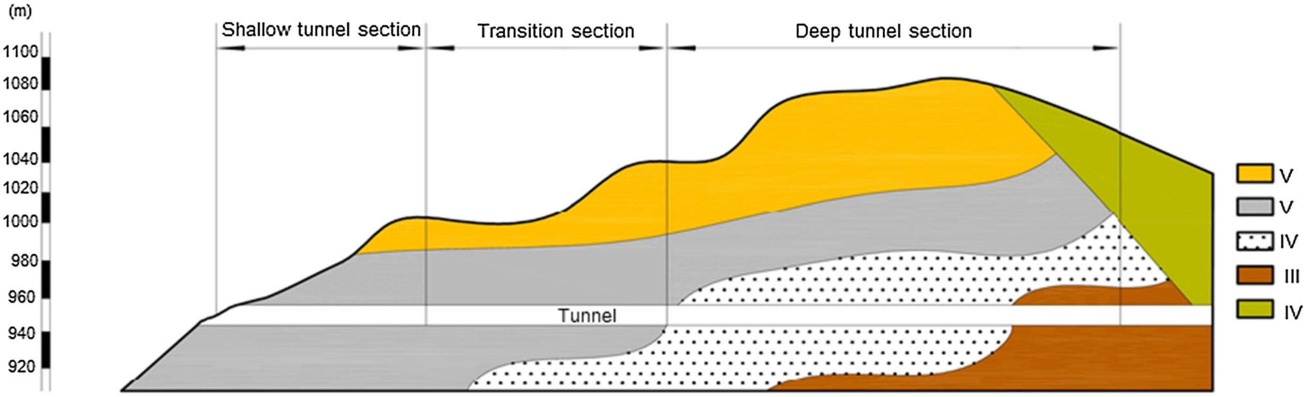


Fig. 8 The division of tunnel portal section

Table 6 Detailed seismic damage of entrance section

Damage pattern	Lining cracking		Lining collapsing		Lining dislocation		Construction joints cracking	
Tunnel section	Length (m)	Percentage (%)	Length (m)	Percentage (%)	Length (m)	Percentage (%)	Length (m)	Percentage (%)
S	508	63.9	0	0	15	1.8	49	6.2
T	601	54.1	37	3.3	5	0.5	72	6.5
Hard rock	1195	63.6	37	1.9	35	1.8	128	6.8

Fault dislocation was the main cause of tunnel structure seismic damage in fault fracture zone, and soft rock mass in the upper wall and footwall of fault fracture zone was another cause of tunnel structure seismic damage in fault fracture zone (He et al. 2014). And the width of fault fracture zone also exerted an influence on tunnel seismic damage. The lining cracking of LDZ tunnel, LX tunnel, and BYD tunnel accounted for a high proportion, and collapsing of secondary lining accounted for the same proportion. Therefore, for the rock mass with different grades and geological conditions, the reinforcement of primary support and secondary lining should depend on the actual situation (Li 2011).

The tunnels passing through fault fracture zone in the Wenchuan earthquake area included “Wide fault fracture zone without dislocation,” “Narrow fault fracture and dislocation,” and “Wide fault fracture zone and dislocation” (Anastasopoulos and Gazetas 2010). LX tunnel was located in the wide fault fracture zone, its lining cracking was the most serious, and collapsing of secondary lining accounted for a high proportion; tunnel rock mass was seriously damaged too. Therefore, tunnels in dislocated fault fracture zone were the key section of seismic fortification (Chen and Wei 2013). Tunnels in wide dislocated fault fracture zone suffered from much serious seismic damage, which could result in collapsing of secondary

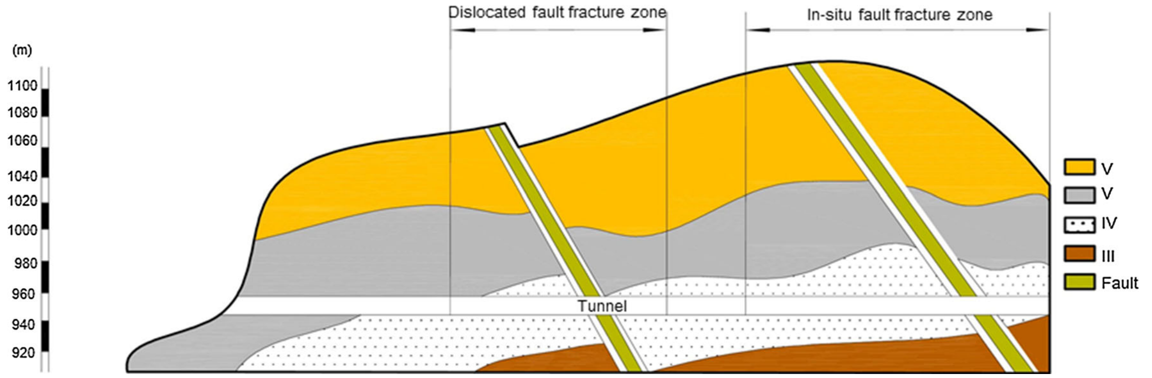


Fig. 9 The division of tunnel structure in fault fracture zone

Table 7 Detailed seismic damage of fault rupture zone

Rock mass	Lining cracking		Lining collapsing		Lining dislocation		Construction joints cracking	
	Length (m)	Percentage (%)	Length (m)	Percentage (%)	Length (m)	Percentage (%)	Length (m)	Percentage (%)
II (LDZ tunnel)	142	46.1	47	15.3	4	1.3	0	0
III (LX tunnel)	55	53.9	25	24.5	0	0	26	25.5
IV (BYD tunnel)	255	45.9	238	42.8	15	2.7	6	1.1
V (YY tunnel)	344	32.4	153	14.5	19	1.8	25	2.4

Table 8 Detailed seismic damage of common section

Rock mass	Lining cracking		Lining collapsing		Lining dislocation		Construction joints cracking	
	Length (m)	Percentage (%)	Length (m)	Percentage (%)	Length (m)	Percentage (%)	Length (m)	Percentage (%)
II	178	27.9	159	24.9	55	8.6	2	0.3
III	376	13.1	80	2.8	260	9.1	66	2.3
IV	1308	22.3	171	2.9	31	0.5	199	3.4
V	258	22.41	127	11.2	205	18.1	32	2.8

lining, so it was also the key of seismic fortification. Tunnels in in situ wide fault fracture zone suffered from slight seismic damage such as secondary lining cracking and other small damage. Tunnels in wide dislocated fault fracture zone and narrow dislocated fault fracture zone required both horizontal and longitudinal seismic fortification. And cross-sectional seismic fortification could be provided for tunnels in in situ wide fault fracture zone (Chen et al. 2014d).

Structure of common tunnel section

Fault fracture zone and portal structure were the area with relatively concentrated tunnel seismic damages. Before the Wenchuan earthquake, it was widely believed that general section suffered without seismic damages, and there was less study on the seismic damage mechanism of common section (Cui et al. 2013c). The tunnel structure seismic damage in common section mainly included lining cracking, dislocation, uplifting of invert, and construction joints cracking. The rock mass classification for tunnels in earthquake area was from II to V, as shown in Table 8.

The seismic damage of common tunnel section mainly occurred in the section with homogeneous soft rock, the soft rock part at the intersection of soft rock and hard rock, and the section with rock mass defect, and there was no serious seismic damage such as tunnel lining collapsing, collapsing of secondary lining in general (Lai et al. (2016e)). The secondary lining adopted plain concrete with big deformation, and that behind the lining structure was incompact, and other defects appeared in construction; seismic damage may also occur due to high-intensity earthquake, such as lining cracking, uplifting of invert, lining dislocation, construction joints cracking. When the rock mass grades of general tunnel section were II, IV, and V, lining cracking was more serious, and the uplifting of

Table 9 Cracking of lining structure

Tunnel name	Length of lining cracking (m)	Percentage of lining cracking (%)
LX tunnel	208	34.9
LDZ tunnel	142	46.1
JJY tunnel	35	50.7

invert occupied a large proportion, so the lining strength should be reinforced in this section. Meanwhile, the invert should be set flexibly in combination with the actual geological condition, instead of being set only in the weak geological condition (Lai et al. 2016a). When the rock mass classification was III, tunnel seismic damage was not quite serious, but the lining dislocation was higher than that of surrounding rock of other grades, so construction supervision should be strengthened to ensure construction quality. For the seismic damages of general tunnel section of homogeneous surrounding rock, the general tunnel section of hard rock suffered from no seismic damage basically, common tunnel section of soft rock suffered from heavier damages, and lining structure was greatly affected by earthquake inertia force followed by forced displacement. The seismic damages of common section with rock mass defect were mainly caused by earthquake inertia force, and forced displacement exerted a small influence (Wang et al. 2003).

Analysis of typical seismic damage characteristics and mechanism

Most of the damaged tunnels in the Wenchuan earthquake were built between 1990 and 2005, and they all adopted shotcrete–bolt support. It is a kind of support which combines shotcrete, bolt, and steel fabric shotcrete. And different kinds of the shotcrete–bolt support and the combination of several structures can be adopted based on the stability of different surrounding rocks. Shotcrete–bolt support is featured by timeliness, tightness, suppleness, reinforcement inside surrounding rock, and flexibility of support combination and time setting (Li et al. 2015).

It is mainly designed by engineering analogy method that directly determines the parameters of shotcrete–bolt support and its construction according to engineering investigation, and in combination with the experience of similar engineering completed. For some simple small-span engineering, the engineering analogy method can be applied separately. However, under most circumstances, especially for the underground engineering with complicated terrain and less experience, just using the engineering analogy method cannot ensure the reliability and reasonableness of design, and it should combine with other methods. Lining cracking, collapsing of secondary lining, lining dislocation, construction joints cracking and other seismic damage occurred in Wenchuan earthquake (Li et al. 2016). Different seismic damage was caused by different factors, so aseismic measures should be taken based on the specific seismic damage.

Lining cracking

The lining cracking in Wenchuan earthquake was the common seismic damages and accounted for a large proportion of the tunnels seismic damages in earthquake area. For the lining cracking of LX tunnel and LDZ tunnel, the typical characteristics and cracking causes of lining cracking are summarized in Table 9.

Lining cracking occurred on a large scale of LX tunnel, and the collapsed concrete block destroyed construction machinery and ventilation facilities, and an annular crack of 1–30 mm wide was formed on the road due to the lining cracking and dislocation. The internal lining of LDZ tunnel was shattered greatly and formed an annular crack about 10–20 mm wide on the road. LX tunnel and LDZ tunnel were located in Longxi Town of Dujiangyan City on the left bank of Minjiang River, and both of them passed through fault, anticline, and other unfavorable geology, with similar supporting measures. There were two kinds of lining cracking: distinct cracking along certain direction, uncertain direction cracking; and flake-like, as shown in Figs. 10 and 11.

As the commonest tunnel seismic damage, lining cracking mainly results from earthquake inertia force (general in section of tunnel portal) and forced displacement (near the interface of soft and hard rock at tunnel portal), as shown in Fig. 12. Concrete exfoliation is always accompanied by reticular fracture or lining crush. The directional lining cracking often occurs due to tension and shear action, flake-like crack is always caused by bending and deformed lining, and reticular crack results from the pressure and shear under the earthquake action as well as repeated movement (Pei et al. 2015).

Collapsing of secondary lining

Collapsing of secondary lining is one of the most serious damages of tunnels except the lining cracking and collapsing of tunnel. It appeared in most tunnels of the Wenchuan earthquake. With regard to BYD tunnel and YY

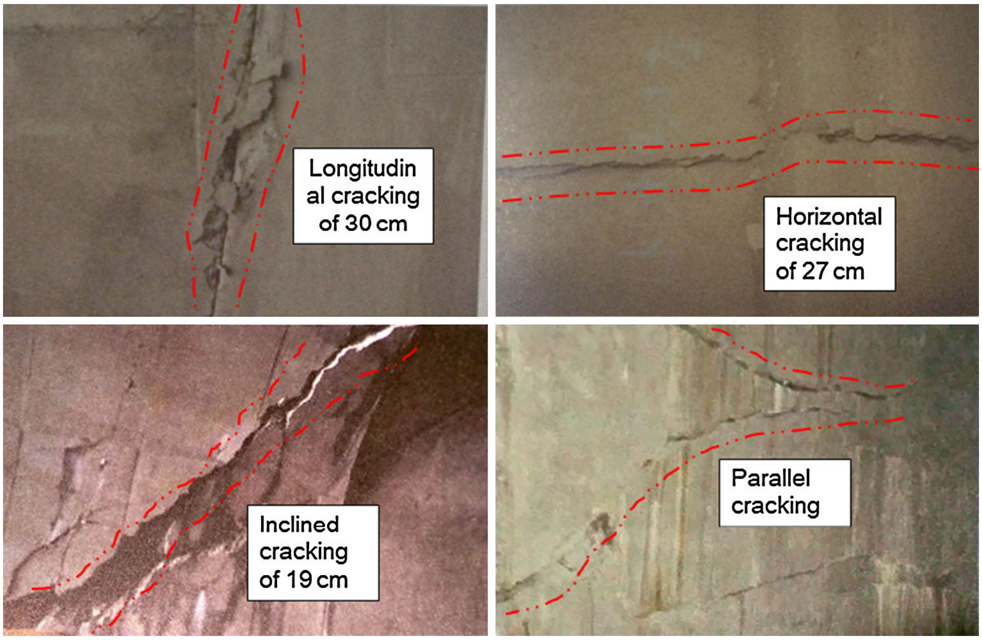


Fig. 10 The tunnel structure directional cracking (Cui et al. 2011)

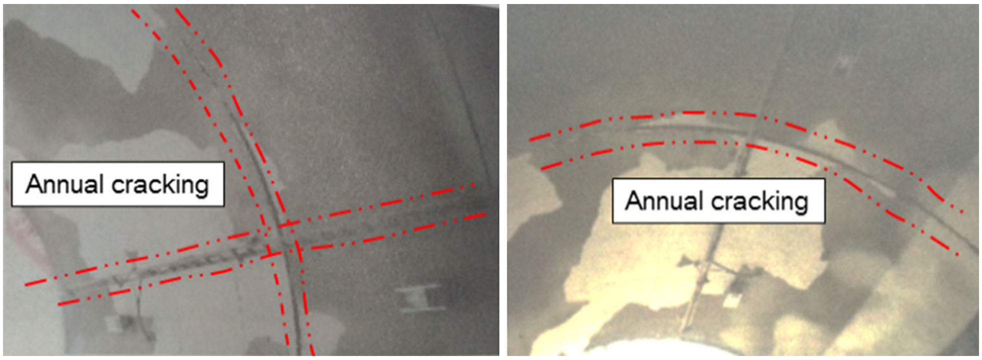


Fig. 11 The lining structure annual cracking (Chen and Zhuang 2011)

tunnel, the summary of typical characteristics and causes for collapsing of secondary lining is shown in Table 10.

Located in the massif between Zhichanggou and Xiaotaogou in heavy-hilly area, YY tunnel was a deep tunnel (Shen et al. 2008). There were emptied coal mines, rock weathering, relaxation, and other unfavorable geological conditions in the areas that the tunnel passed through; thus, the secondary lining completely collapsed. The lining collapsing of the two tunnels showed massive falling-off on a large scale, and it was difficult to restore. Hence, it must be reinforced again, the secondary lining should be strengthened, and the opportunity for implementation of secondary lining should also be grasped, so as to avoid the similar seismic damage, as shown in Fig. 13.

Collapsing of secondary lining is related to epicentral distance, fault, supporting structure, construction factor, etc. Most tunnels emerge collapsing of secondary lining without reinforcement of the secondary lining due to insufficient intensity and structure instability during earthquake (Alija et al. 2013).

Lining dislocation

During the Wenchuan earthquake, the lining dislocation of tunnels occupied a little proportion in seismic damage of tunnels, but caused a great hazard, which was difficult to improve and restore. It mainly occurred on the interface of surrounding rocks and interfaces with changed lining section. With regard to LX tunnel and LDZ tunnel, the summary of the characteristics of lining dislocation and dislocation causes is shown in Table 11.

For LX tunnel, though the lining dislocation occupied a little proportion, it was serious at portal section, with dislocation of 20 cm; and the lining dislocation of LDZ tunnel

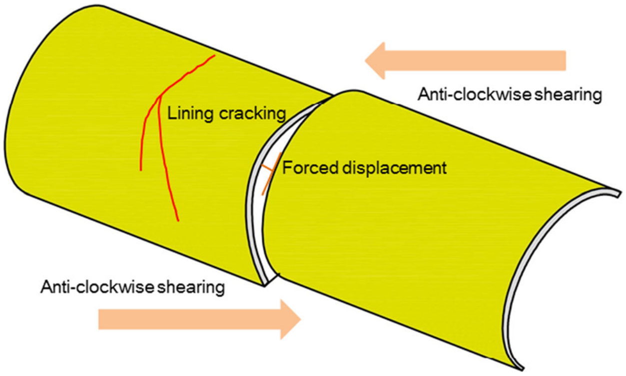


Fig. 12 The forced placement and anticlockwise shearing due to internal force

was as much as 15 cm. Hence, the lining dislocation of tunnel occupied a little proportion, but it was difficult to be handled in later period, as shown in Fig. 14.

The causes of lining dislocation include: unreasonable trolley structure leads to failure in resisting the deformation caused by exogenic actions such as concrete; in case of great difference in workability of concrete of same label, the shrinking percentage of concrete would differ. Therefore, the performance of concrete mixing each time is basically different. The lining dislocation results from the improper selection for concrete of tunnels in collapsing area (Mao et al. 2011).

Construction joints cracking

Construction joints cracking was an inevitable problem in tunnel seismic damage. During Wenchuan earthquake, the seismic damage happened to tunnels in numerous mountainous areas. With regard to construction joints cracking of ZZP tunnel and BYD tunnel, the specific statistics and the causes are analyzed, as shown in Table 12.

For ZZP tunnel, the construction joint basically cracked, and some form annular cracks with the width of 5–70 mm; for BYD tunnel, the construction joints within the tunnel all cracked, and crack width even reached up to 10 mm for the part with serious damage, and the tunnel showed annular crack and longitudinal crack. The construction joints cracking was inevitable in the seismic damages of tunnels. During Wenchuan earthquake, the construction joints cracking had a large proportion in special terrain condition. The specific damage condition is shown in Fig. 15.

The structural causes for construction joints cracking: mortar leakage, hydration reaction insufficiency of concrete, resulted in concrete strength reduction in concrete. It was too fast for concrete grouting due to settlement of concrete, earthquake loading, and mainly caused by the defects in construction quality, etc., during the constructions (Chen et al. 2010).

Uplifting of invert

Uplifting of invert was one of the common seismic damage of highway tunnel which happened to numerous mountainous areas (Luo et al. 2016). The specific statistics and the causes for LX tunnel (V) and LDZ tunnel were analyzed, as shown in Table 13.

Uplifting of invert in the left line of LX tunnel was 100%, the uplift reached to over 30 cm, and the longitudinal cracking reached to 30 cm wide in serious damage section. The uplifting of invert reached to 22.1% in LDZ tunnel, as shown in Fig. 16.

The invert can improve the supporting structure of upper part and constitute a whole tunnel with secondary lining. It is a reinforced concrete structure and can effectively resist the counter-force from the lower layer of tunnel (Konagai et al. 2009). The main reasons for uplifting of invert were lack of knowledge about rock mass, which resulted in broken and uplifted rock mass because of insufficient bearing capacity for rock mass in terms of support parameters. Earthquake caused water seepage of formation, and water swelled of rock mass. The degree of uplifting of invert was related to the swelling coefficient of rocks and the temperature of water seepage; for example, the mudstone became soft because of water and then showed reduction in bearing capacity, which resulted in uplifting of invert and deformation.

Aseismic measures and shock absorption measures

There are two ways to reduce seismic damages of highway tunnels, including aseismic measures and shock absorption measures (Yan et al. 2016). During the Wenchuan earthquake, the seismic damage of typical tunnel structures include lining cracking, collapsing of secondary lining, lining dislocation, construction joints cracking, uplifting of invert, and different aseismic measures can be taken for different seismic damage.

Table 10 Collapsing of secondary lining

Tunnel name	Length of collapsing of secondary lining (m)	Percentage of lining collapsing (%)
BYD tunnel	14	48.3
YY tunnel	50	100
LX tunnel	305	51.3

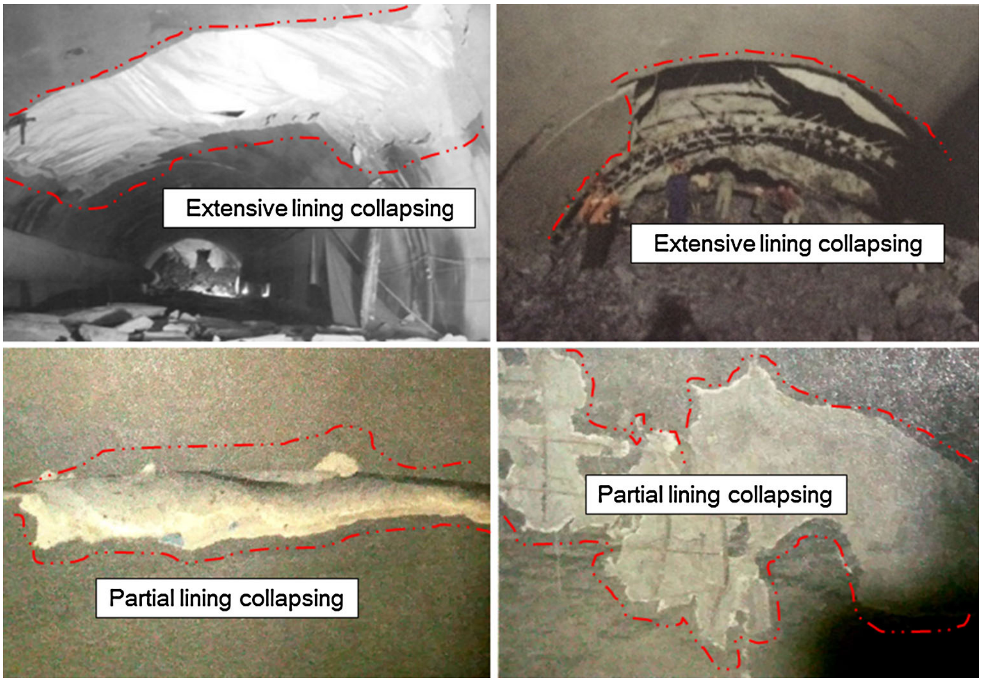


Fig. 13 The collapsing of secondary lining (Yu et al. 2016a)

Table 11 Lining dislocation of the secondary lining

Tunnel name	Length of lining dislocation (m)	Percentage of lining dislocation (%)
LX tunnel	30	0.5
LDZ tunnel	4	1.3

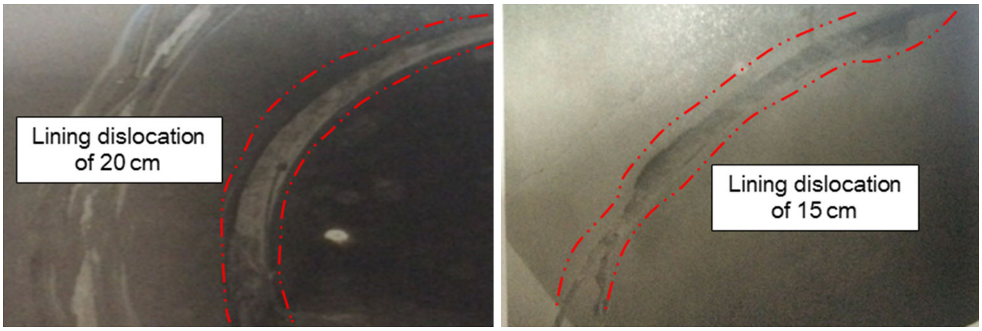


Fig. 14 The lining structure dislocation (Mao et al. 2011)

Table 12 The construction joints cracking

Tunnel name	Length of construction joints cracking (m)	Percentage of construction joints cracking (%)
ZPP tunnel	9	0.3
BYD tunnel	4	13.8

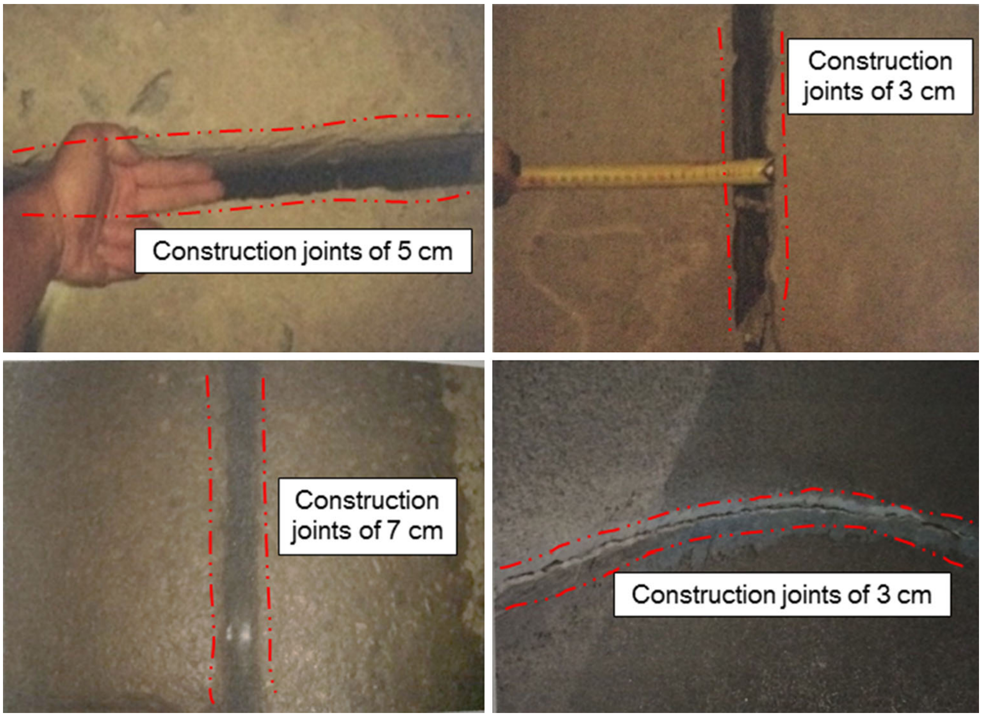


Fig. 15 The construction joints cracking (Chen et al. 2010)

Table 13 The uplifting of invert

Tunnel name	Length of uplifting of invert (m)	Percentage of uplifting of invert (%)
LX tunnel	42	100
LDZ tunnel	68	22.1

Aseismic measures

Aseismic measures for tunnel sections

1. The tunnel portal should locate in place with good geological condition and mountain stability. If the portal needs to pass through the unstable underlay, it should reduce the excavation height of side and face upward slope and take measures of spray anchor net and protective side wall (Wang et al. 2016).When the portal is located at the place of falling rocks, enter the tunnel in advance and measure the open cut tunnel to ensure the stability of tunnel portal. End wall tunnel portal has the weakest seismic capacity and easily causes cracks, so bamboo-truncating portal and ring frame tunnel portal should be adopted to reduce the damage of earthquake in tunnel portal (Bathurst et al. 2007), as shown in Fig. 17. Reinforced concrete structure should be adopted for open cut tunnel; also the mortar rubble shall be adopted for backfill.
2. When the tunnel locates in the fault fracture zone, reinforced concrete structure should be adopted for the secondary lining, the auxiliary construction should be strengthened, composite lining structure profile of curved wall and invert should be adopted for fortification section, deformation joint and seismic joint should be set between lining structures, and the cavity behind lining should be seriously avoided (Lai et al. 2016c), as shown in Fig. 18. Besides, in case of cavity, concrete mortar should be filled in accordance with construction procedures strictly, so as to reduce disturbance of rock mass.

Aseismic measures for tunnel structure damage

1. Lining cracking occupied a high proportion in tunnel seismic damage during the Wenchuan earthquake, which proved the complexity of engineering analogy method in practice. Secondary lining cracking occurred because of the combined action of instantaneous

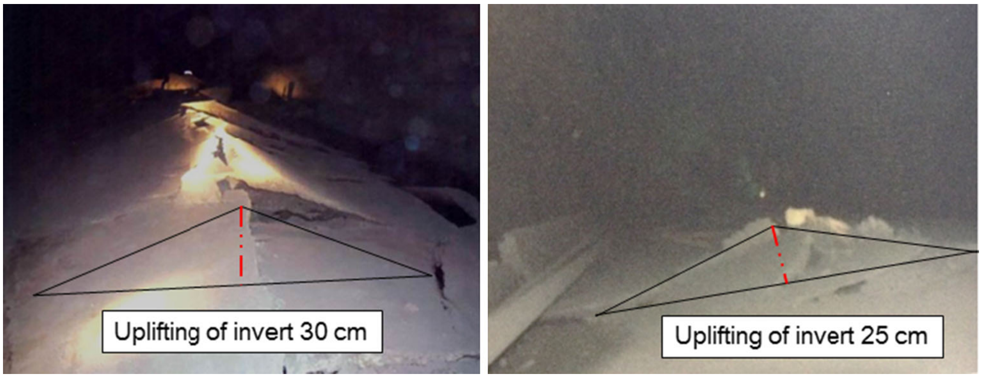


Fig. 16 The uplifting of invert (Yu et al. 2016b)

Fig. 17 The bamboo-truncating portal and ring frame tunnel portal

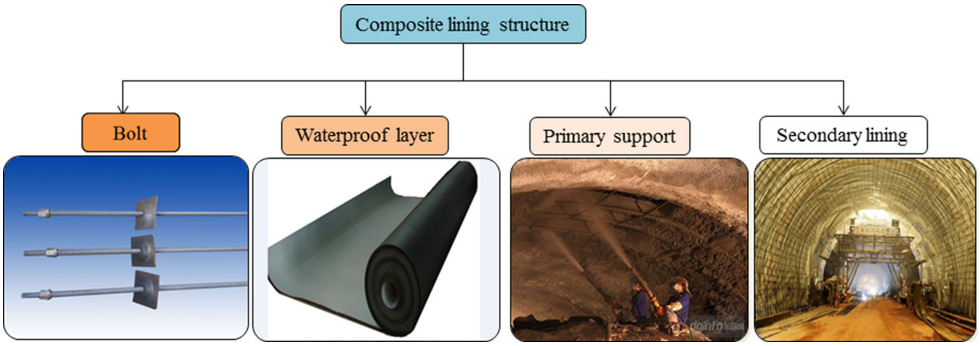


Fig. 18 The compositions of composite lining structure

earthquake load, and the dead load reached the maximum bearing capacity in the ultimate limit state of bearing capacity. It mainly owed to the lining of concrete (Yu et al. 2013), which, ultimately, resulted from the intensity deficiency and unsuitability for grade of concrete. Therefore, during shotcrete–bolt design and engineering analogy, it is suggested that the proper grade of concrete should be selected by considering the seismic code and combine the tunnel secondary lining cracking in the Wenchuan earthquake, and also construction process should be strictly executed to prevent such seismic damage.

2. During the Wenchuan earthquake, collapsing of secondary lining all had no reinforcements, and the seismic damage of reinforced concrete structure was obviously lower than that of plain concrete structure which indicates the necessity of reinforcement for lining. For example, the collapsing of secondary lining was 100 m in the LX tunnel without reinforcement (Yu et al. 2014), which was mainly because the large-scale geological condition of the tunnel was not fully considered. Hence, during design of tunnel, the preliminary geological and topographical condition should be fully considered and also the relevant

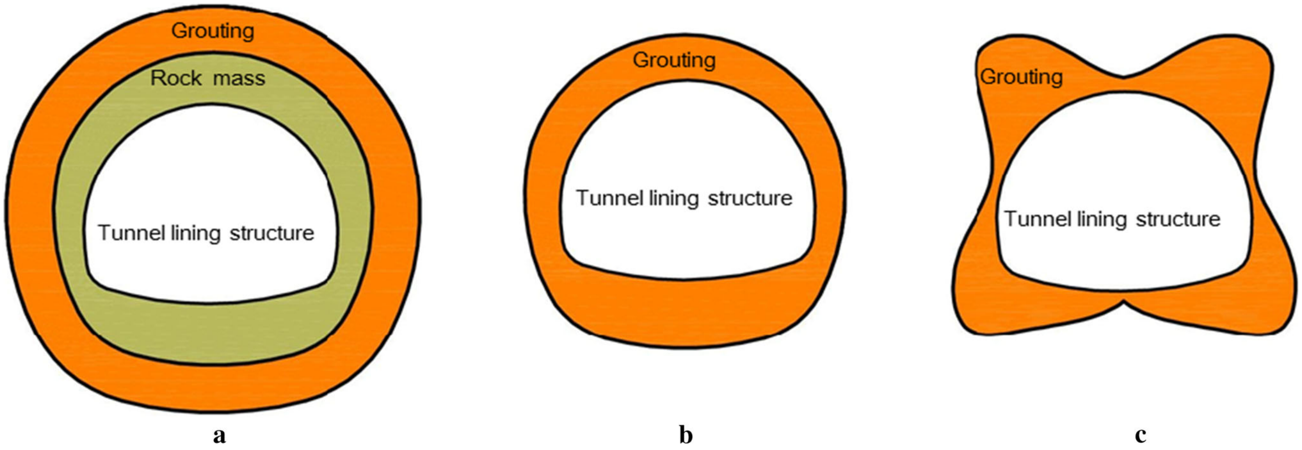


Fig. 19 The three different grouting measures (Gao et al. (2009). **a** Whole chain alternative grouting. **b** Whole chain touch grouting. **c** Local grouting

regulations should be strictly executed to ensure the strength of lining.

3. Secondary lining dislocation only accounted a little proportion in the seismic damage of tunnel during the Wenchuan earthquake, but secondary lining dislocation was difficult to be handled. During construction, template should be processed in accordance with requirements strictly, touch panel should be operated in accordance with welding process and firmly welded, and hard wood should be selected for processing of peg with size as required. The poured concrete and contact surface of templates should be treated before the comparison with templates. During violation of concrete, the vibrator should not vibrate the template, so as to avoid the damage to template. During construction, it should timely replace the template of damaged pattern, meanwhile the form fixer should be careful and responsible, and strictly perform the installation order (Hwang and Lu 2007).
4. There are several measures to prevent the fracture of construction joint: Select qualified raw material, construct in strict accordance with construction proportion, and control the usage of water and cement; in the geological condition, ensure the design of controlled blasting, optimize drilling and blasting parameters, and control the usage; grasp the opportunity of secondary lining, and the lining should be basically stable on the rock mass during preliminary support deformation (Jiang and Zhao 2015).
5. The preventive measures for uplifting of invert are: strengthen monitoring and measurement and analyze monitoring information (settlement); ensure waterproof and drainage design in tunnel and prevent the base of invert from being soaked; enhance the process connection and management to ensure the construction quality of invert; enhance the drainage of foundation pit; and adjust and enhance the construction parameters, so that the bottom of invert has sufficient rigid constraint and can effectively resist the stress produced by water absorption of rock.

Shock absorption measures

1. The shock absorption measures of tunnel include change in structure, such as reduction in quality by adopting light aggregate concrete to increase the strength, adopting steel fiber concrete to increase damping, adopting polymer concrete to reduce the rigidity, and adopting shotcrete–bolt net support and steel fiber reinforced concrete. When change in tunnel structure is impossible, the shock absorption can be realized by setting damping device, setting shock absorber between lining and rock mass, setting plate-type shock absorption layer between lining and rock mass, and pressing and injecting shock absorption materials between lining and surrounding rock (Chen et al. 2014b). The rock mass can be reinforced to reduce the uniform seismic deformation due to different rock mass conditions. Gao et al. (2009) proposed three grouting reinforcement ways: whole chain alternative grouting, whole chain touch grouting, and local grouting for the rock mass treatment of tunnel, as shown in Fig. 19, and also drew a conclusion that the grouting and reinforcement of rock mass could improve tunnel stress.
2. When tunnels pass through fault fracture zone, the shock absorption layer should be set between primary support and secondary lining, as shown in Fig. 20. Also, reasonable reduction in the rigidity of tunnel

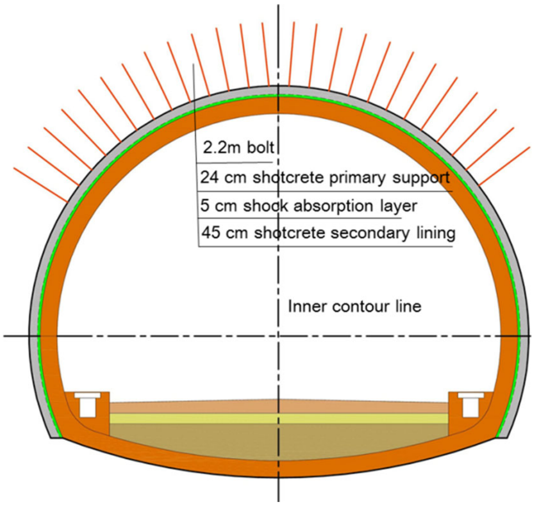


Fig. 20 The composite lining structure with shock absorption layer

lining is beneficial for shock absorption, which can significantly reduce peak value of maximum and minimum stress, and exert no effect on lining displacement (Chen et al. 2014c).

Discussion

Comparison of seismic damage between ground structure and tunnel structure during the Wenchuan Earthquake

Earthquake wave includes transverse wave, longitudinal wave, and surface wave. The longitudinal wave spreads fastest, followed by transverse wave and surface wave. The transverse wave makes the ground shake violently. Transverse and longitudinal waves generate surface wave on the surface after meeting, and the amplitude of surface wave is long and powerful. The building damage is mainly affected by transverse and surface wave, so the ground structures suffer from more serious seismic damage than the underground structure during the Wenchuan earthquake. And ground structures mainly reflected in fracture of constructional column of masonry structure, cracking of bearing wall, breakage of stairs, collapsing of walls, destruction of frame column and beam of reinforced concrete frame structure, cracking of the joint of individual wall body and column, cracking of filling wall, etc. (Hashash et al. 2001). The buildings of brick–concrete structure suffered from so serious damage that they collapsed completely. While frame structure basically showed good structure, that of frame and brick–concrete structure was basically in perfect condition and had no damage, as shown in Fig. 21.

Ground structure is directly affected by the seismic transverse wave, but since tunnel suffers from significant restraining effect of foundation and rock mass, the dynamic effect of underground structure generally does not reflect the impact of self-seismic characteristics (Lai et al. 2016d). While the ground structure can significantly reflect the impact of self-seismic characteristics, ground structure suffers more serious seismic damage and even directly collapsed, completely lost bearing capacity, and resulted in structure failure and casualties. On the contrary, tunnels suffer from slighter seismic damage, lining cracking, and secondary lining collapsing. Therefore, seismic fortification of ground structure is stricter than that of tunnel. Since the seismic damage of tunnel is difficult to be recovered, the earthquake proof of tunnel should be strictly treated during design and construction period (Yu et al. 2016a).

Comparison of Hanshin Earthquake in Japan and the Wenchuan Earthquake

Characteristics of seismic damage in Hanshin Earthquake

The Hanshin earthquake in Japan happened on January 17, 1995, with the epicenter in Awaji Island of Hyogo Prefecture. It was an earthquake of magnitude 7.3 of Richter scale which occurred directly beneath the city. Japan agreed that earthquake would not happen in this district; the district was lacking preventive measures and disaster relief system, thus leading to a large number of casualties and economic loss. It is of great significance in earthquake history of Japan and has aroused the attention of Japan earthquake science, urban architecture, and traffic prevention, and tunnel, as an infrastructure with more seismic damage, was investigated and researched by Japanese experts.

During the Hanshin earthquake, highway tunnel, sewage tunnel, communication line tunnel, power line tunnel, etc., suffered from damage of different degrees. Figure 22 showed the cracking form and sketch of a sewage tunnel; the tunnel had the diameter of 3.5 m and depth of 9–14 m. The soil layer was alluvial sand and clay sediment, and also annular cracking and longitudinal cracking occurred during secondary lining.

In terms of mountain tunnel, the Rokko tunnel of Sanyo Shinkansen suffered from the seismic damage during the Hanshin earthquake. The Rokko tunnel led to Osaka, 16,235 m long, and passed through several active faults of Rokko fault system. On the inner cement walls of the Rokko tunnel, there were three cracks as long as dozens of meters (Wang et al. 1998a).

In terms of shield tunnel, the cable tunnel of the Edogawa, Sannomiya central zone, in the downtown of Kobe had completed the excavation for the whole section, and

Fig. 21 The seismic damages of the superstructure. **a** Framework structure. **b** Frame masonry structure

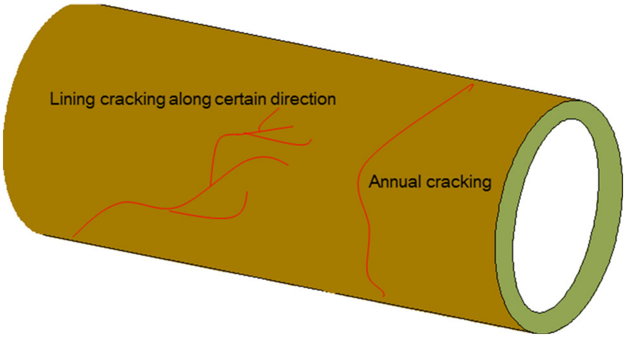


Fig. 22 The cracking of lining structure in Hanshin earthquake

basically completed lining installation. The tunnel had the diameter of 4.9 m, the lining thickness of 20 cm, and the depth of 11–15 m. It was found from the inspection that there were cracking with length of 90 cm and width of 0.2 mm in the shaft section, partial breakage of lining transition section without structure failure, collapsing of numerous buildings nearby, and opened cracking of ground (Yu et al. 2016b).

Comparison of seismic damage of tunnel between Hanshin earthquake and Wenchuan earthquake

The Hanshin earthquake in Japan was similar to the Wenchuan earthquake in China; both of them happened in the districts where were believed no earthquakes, so no seismic fortification was considered, then the serious tunnel seismic damage happened. The Wenchuan earthquake had greater magnitude and more energy than the Hanshin earthquake, so the seismic damage of tunnel was more serious. After the earthquakes, the tunnel lining also showed annular cracking and longitudinal cracking, and even falling of pieces, and tunnels in fault fracture zone all suffered from serious seismic damage and produced long and obvious cracking (Chen et al. 2014a). Thus, the seismic fortification at early stage is very important (Wang et al. 1998b; Lai et al. 2016b), and it is necessary to have a full understanding of the geological environment of tunnel and ensure good quality in seismic fortification during tunnel design and construction periods, so as to prevent seismic damage to tunnels.

Perfection of seismic code for tunnel

Through the statistics about seismic damage of tunnel in Wenchuan earthquake and the comparison of seismic damages with ground structure, the suggestions for the relevant regulations of Specifications of Earthquake Resistant Design for Highway Engineering (JTG B02-2013) (2013) are: for tunnels in meizoseismal area, the increasing in thickness of lining and tunnel rigidity is inaccurate; the earthquake intensity adopted for seismic design of tunnel refers to the Seismic Design of Buildings (GB 50011-2010 2010), but the tunnels are underground, so the actual earthquake parameter is less than that and the relevant adjustment should be made in combination with actual condition; and static method similar to ground structure is adopted for the seismic design of tunnel, but actually, the calculation results are too conservative and cannot reflect the actual situation.

The suggestions for the relevant regulations of tunnel in Code for Design of Road Tunnel (JTG D70-2004) (2004) are: cavities behind the lining are strictly prohibited and should be filled with concrete mortar; the lining properly increases when tunnel passes through fracture; at the junction of soft rock and hard rock, seismic joint should be set in combination with settlement joint and expansion joint; and curved wall lining with invert should be adopted for tunnel lining of weak surrounding rock, but the seismic content of highway tunnel should be supplemented in Guidelines for Design of Highway Tunnel (JTGT D70-2010) (2010).

Concluding remarks

1. The influencing factors of tunnel seismic damage contain seismic intensity, rock mass classifications, epicentral

distance, and tunnel depth. Along with the increase in the seismic intensity, reduction in the integrity of rock mass, and decrease in epicentral distance and tunnel depth, the proportion and severity of seismic damage of tunnel increase; on the contrary, the seismic damage reduces.
2. The seismic damage of tunnel in dislocated fault fracture zone, soft rock transition section, and soft rock shallow tunnel section is serious, while that of hard rock tunnel is slight. Seismic damages to typical tunnel structure contain lining cracking, collapsing of secondary lining, lining dislocation, construction joints cracking, uplifting of invert, etc.
3. Lining cracking and construction joints cracking are caused by earthquake inertia force and forced displacement. Lining dislocation and uplifting of invert are caused by uneven expansion of concrete. Lining collapsing results from non-reinforcement for secondary lining, and the main fortification measure is to adopt composite lining structure with concrete curved wall.
4. The shock absorption measures for tunnel are mainly to set shock absorption layer and grouting treatment for the rock mass. The annular grouting can improve the stress of tunnel, while shock absorption layer can buffer the forced displacement of tunnel in great earthquake and then reduce the seismic damages to tunnel.
5. Relative to ground structures, tunnels suffers from lighter seismic damage and will not be completely collapsed and lose the integrity. The seismic fortification of tunnel focuses on the improvement in lining form and the way of grouting, while that of ground structures focuses on change in buildings structure and selection of lightweight building materials.

Earthquake, as a natural disaster that cannot be completely predicted, leads to multiplied losses along with the rapid development of the world economy. Most regions in the world belong to seismic fortification area; thus, the study on seismic fortification of tunnel is of great importance, and also the study will promote the development of new material application and structure pattern innovation on the basis of lining structure and support pattern.

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