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Analysis on the Earthquake Damages Characteristics of Tunnel through Fault Zone

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Abstract: The factors and types of earthquake damages to tunnel through fault zone are analyzed and concluded based on the research on earthquake damage data of tunnel through fault zone in previous great earthquakes. The results indicate that tunnels through fault zone with complex geological conditions, high geo-stress and poor surrounding rock quality are main earthquake damage parts and controlling areas. The main factors which affect tunnel earthquake damage consist of seismic intensity, seismic fortification code, and construction quality of tunnel and activity of fault zone, all of which jointly affect the extent of earthquake damage to tunnel. Ductility lining structure which shall be adopted to fault zone and extended section of tunnel to avoid tunnel entire collapse; The types of earthquake damage to tunnel through fault zone at fractured zone mainly consist of dislocation of tunnel lining, longitudinal/transverse cracking of lining, chipping or peeling of lining, bulging of floor, and entire collapse of lining and surrounding rocks. The research results mentioned plays an important role in the understanding of earthquake characteristics of tunnel through fault zone, and will provide precious basic data to the practical seismic design and construction of tunnel crossing fault.

***Keywords:** Tunnel through fault zone; earthquake damage characteristics of tunnel; factors of earthquake damage to tunnel; types of earthquake damage to tunnel*

1. Introduction

Tunnel has superior earthquake resistance, but, when the tunnel pass through fault zone, the lining structure of fault zone is easily damaged in earthquake due to the poor quality of surrounding rocks[1][2]. Severe tunnel damage frequently occurred in tunnel due to the fault zone in all previous great earthquakes. In the great earthquake of M8.3happened in San Francisco, US in 1906, the catchment tunnel in San Andreas dam which transversely passes through the fault zone was seriously damaged after the earthquake, with a partial displacement value of 2.4m, and the tunnel Wright No. 1 with a burial depth of 214m had track bulging and sleeper fracture, the horizontal displacement value of the tunnel was even up to 1.37m [2]. In the great earthquake of M7.9 in happened Tokyo, Japan in 1923, the tunnel though fault zone was heavily damaged, and the tunnel section with large quality difference of surrounding rock and large stratigraphic fluctuation even had worse damage, most of the damage were numerous cracks in lining of tunnel and severe deformation of lining[3].In the M7.3 earthquake happened in North Izu Islands of Japan in 1930, the Tanna railway tunnel under construction had a horizontal displacement of 2.39m and a vertical displacement of 0.6m at the fault zone of Tanna tunnel because of the earthquake, and there are a great numbers of cracks at the side walls of the main tunnel [3]. The earthquake of M7.6 happen in Kern County, California in 1952caused severe earthquake damage to four tunnels on South Pacific Railway through White Wolf fault fractured zone, and the transverse displacement at one side wall of Tunnel No. 4 was up to 50cm [3]. The earthquake of M7.2 happened in Hanshin, Japanin 1995 caused heavy damage to over 10% of mountain tunnels, wherein the Shanyang Shinkansen Malacca Tunnel had a lot of cracks in lining of the tunnel at the section transversely passing through active fault system, there were 10+ meter cracksat 3 parts, the distribution of earthquake damage in Malacca Tunnel was shown in graph 1 [4]. The Chi-chi earthquake of M7.3 happened in Taiwan, China in 1999, the heavily damaged part was up to 25%, the medium damaged part was 20%, while the slight damage part was 55% after the research on 44 damaged tunnels within 25km to seismogenic fault in middle part of Taiwan, in which the water tunnel in Shek Kong dam caused heavy diastrophism damage to the lining of tunnel at fracture zone because of passing through Chelongpu fault, the vertical deformation of the tunnel was 4.0m and the horizontal deformation was up to 3.0m, and the entire tunnel was damaged as shown in graph 2[5]. The "5.12" great earthquake of M8.0 happened in Wenchuan, China in 2008 ,which resulted in severe damage to Longchi tunnel and Longxi tunnel at fault zone, and the earthquake damage to tunnel caused by fault zone on Du-wen expressway was shown in Table 1[6]-[8].

In conclusion, tunnel through fault zone is the underground construction structure which is easily damaged in earthquake, and fault zone section is the controlling part for earthquake fortification of tunnel.

Therefore, this article, in combination with the earthquake damage to fault zone in previous great earthquakes, provides precious basis for earthquake fortification to practical tunnel through fault zone by analyzing the influence factors of earthquake damage to tunnel and summarizing the earthquake damage types of tunnel.

***Table 1** Evaluation Form of Tunnel in Wenchuan Earthquake on Du-wen Expressway*

Class of Highway	Tunnel Name	Seismic Intensity	Fortification Standard	Poor Geological Condition	Major Earthquake Damage
Expressway	Zipingpu Tunnel	Ⅸ～Ⅹ	Grade Ⅶ	Gas and Fault	Cracking of lining, movement and dislocation of lining
	Longdongzi Tunnel	Ⅸ～Ⅹ	Grade Ⅶ	Fault	Cracking and leakage of lining, movement and dislocation of lining
	Longxi Tunnel	Ⅸ～Ⅹ	Grade Ⅶ	Gas and Fault	Cracking and leakage of lining, severe dislocation of lining
Wolong Line	Shaohuoping Tunnel	Ⅸ～Ⅹ	Unknown	Fault	Cracking of lining
Second Grade Highway	Longchi Tunnel	Ⅷ～Ⅸ	Unknown	Gas and Fault	Roadbed bulging, cracking, dislocation and leakage of lining
	Zaojiaowan Tunnel	Ⅷ～Ⅸ	Unknown	Fault	Cracking and dislocation of lining, damage of appurtenance
	Chediguan Tunnel	Ⅷ～Ⅸ	Unknown	Fault	Cracking of lining, partial dislocation of lining
	Taoguan Tunnel	Ⅸ～Ⅹ	Unknown	Fault	Cracking of lining, damage of appurtenance
	Caopo Tunnel	Ⅸ～Ⅹ	Unknown	Fault	Cracking and leakage of lining
	Dankanliangzi Tunnel	Ⅸ～Ⅹ	Unknown	Fault	Cracking of lining

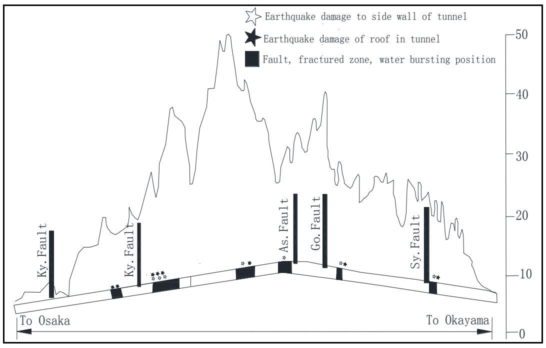

***Figure 1** Longitudinal Distribution of Earthquake Damage to Malacca Tunnel*

***Figure 2** Earthquake Damage to Water Tunnel of Shek Kong Dam*

2. Influence Factors of Earthquake Damage

Practice has proved that, under smaller seismic intensity, the underground construction structures (tunnel, underground workshop and so on) with preferable surrounding rock conditions have a better earthquake resistance than structures on the ground. Earthquake damage to tunnel generally happens to the parts with complicated geological conditions such as poor quality of surrounding rocks and large change of formation condition. It is known from research that the main factors which influence earthquake damage to tunnel through fault zone mainly include seismic intensity, ground stress and tunnel buried depth, etc., and meanwhile, the surrounding rock quality of tunnel is one of the most important factors that influence the earthquake damage to tunnel due to the apparent dependence and tracing ability of tunnel structure to surrounding rocks.

2.1. Seismic Intensity

Sunil Shama and Willian R. Judd [9] made collection and statistics to a great numbers of earthquake damage to tunnel, the result indicated that most of the earthquake damage happened to the earthquakes greater than magnitude 7, and the damage degree of tunnel in earthquake was heavier when the earthquake magnitude is greater, so the seismic intensity has decisive influence to earthquake damage to tunnel. LI Tianbin[10] had researches on various tunnels on Du-

Wen expressway in “512”Wenchuan Earthquake and proved that the earthquake damage to tunnel was much stronger when the epicentral distance to Wenchuan Earthquake is shorter; for instance;ShaohuopingTunnel and Longxi Tunnel which were near to epicenter location had a seismic intensity greater than IX-X, and the earthquake damage was much more severe; the tunnel damage became more heavier with the shortening to epicentral distance on highway section of Du-Wen expressway, and please see table 2 for the seismic intensity to tunnel site and damage degree of earthquake damage to tunnel.

From the table 2, the earthquake damage to tunnel and seismic intensity basically had certain correspondence, the greater the seismic intensity in tunnel was, the heavier the earthquake damage to tunnel was. But research to earthquake damage found out that seismic intensity was not the only influence factor to earthquake damage degree to tunnel, and earthquake damage was also related to many other factors such as surrounding rock conditions, earthquake fortification measures to tunnel, lining forms, rigidity, and seismic wave propagation, etc.

2.2. Surrounding Rock Conditions of Tunnel

Practice has proved that structure of tunnel had apparent tracing ability and dependence to surrounding rocks, therefore, the engineering geological conditions of surrounding rock would influence the earthquake damage characteristics of tunnel. In “5.12”Wenchuan Great Earthquake, the surrounding rocks of tunnel from Dujiangyan to Yingxiu section on the National Highway No. 213 were mainly weak broken rocks such as sandstones and mud rocks, so the earthquake damage to tunnel on that section was severe; instead, the surrounding rocks of tunnel from Yingxiu to Wenchuan section were mainly granites, and 7 tunnels on this section had relatively slight earthquake damage. Sunil Shama[9] had statistics on the earthquake damage under different surrounding rocks, and indicated that the superior surrounding rock could absorb greater earthquake energy and had better earthquake resistance. CHEN Zhengsun [11] and the others stimulated the earthquake response property of tunnel through fault fractured zone under difference surrounding rock conditions numerically, and the result indicated that the tunnel had largest internal force value when located at the interface of fault fractured zone.

Table 2 *Relationship between Earthquake Damage Degree to Tunnels and Seismic Intensity on Du-Wen Expressway*

Serial No.	Tunnel Name	Seismic Intensity	Length/m	Damage Degree
1	Zipingpu Tunnel	Ⅸ～Ⅹ	4081	Heavy Damage
2	Longdongzi Tunnel	Ⅸ～Ⅹ	1070	Heavy Damage
3	Longxi Tunnel	Ⅸ～Ⅹ	3691	Heavy Damage
4	Longchi Tunnel	Ⅸ～Ⅹ	1177	Heavy Damage
5	Shaohuoping Tunnel	Ⅸ～Ⅹ	450	Heavy Damage
6	Chediguan Tunnel	Ⅸ～Ⅹ	4026	Medium Damage
7	Futang Tunnel	Ⅸ～Ⅹ	2365	Medium Damage
8	TaoguanTunnal	Ⅸ～Ⅹ	625	Medium Damage
9	CaopoTunnal	Ⅸ～Ⅹ	759	Slight Damage
10	Dankanliangzi Tunnel	Ⅸ～Ⅹ	1567	Slight Damage
11	Zaojiaowan Tunnel	Ⅷ～Ⅸ	1926	Slight Damage
12	Maojiawan Tunnel	Ⅷ～Ⅸ	399	Slight Damage

2.3. Buried Depth of Tunnel

The buried depth of tunnel has apparent influence to earthquake damage, and the height of pillar at the upper side of the tunnel apparently influences the seismic oscillation of tunnel. Domestic scholars including LI Tianbin had research and statistics on all tunnels on Du-Wen expressway in 512 Wenchuan Great Earthquake and found out that the degree of earthquake damage to tunnel structure was related to both buried depth and surrounding rocks of tunnel at the same time, when the surrounding rock conditions were better, greater earthquake resistance obtained under difference buried depth, and the earthquake resistance was better when the buried depth was deeper under poor engineering geological conditions. CHEN Zhengxun and the others [11] found out the influence from buried depth and surrounding rock property of tunnel to earthquake damage to tunnel by research, the theory that earthquake damage reduced when depth of tunnel was increased can be explained by attenuation characteristics of Rayleigh Wave, and the research proved that the seismic internal force borne by lining structure was reduced along with the increasing of buried depth.

2.4. Seismic Measures of Tunnel and Forms of Lining Structure

The damage to tunnel is mainly reflected on the damage to supporting measures and corresponding appurtenances of the tunnel, so the supporting condition and the lining structure forms of tunnel have apparent influence to the earthquake damage characteristics of tunnel. The rigidity of tunnel structure has apparent influence to seismic oscillation of tunnel, the structure in earthquake absorbs more earthquake energy when the rigidity of tunnel lining is larger, and the structure generates relatively higher acceleration, stress and displacement value, which easily causes heavy damage. In “512”Wenchuan Earthquake in Sichuan province, the surrounding rocks of 3 tunnels from Dujiangyan to Yingxiu section were soft rocks with poor geological conditions, the tunnel lining was reinforced concrete, and the supporting structure had relatively large rigidity, therefore, much heavier damage happened to the tunnels in earthquake; while 7 tunnels from Yingxiu to Wenchuan section were located in firm surrounding rocks, the secondary lining was mostly plain concrete, and the lining rigidity was relatively weak, so the tunnel lining had relatively light damage in earthquake. It is known from above that the rigidity of tunnel lining structure has apparent influence to earthquake damage to tunnel, the tunnel lining structure bears relatively high earthquake energy when the lining rigidity is larger, and the tunnel is easily damaged; meanwhile, the earthquake damage to tunnel in Wenchuan earthquake also indicated that tunnel using ductile materials such as reinforced concrete would avoid heavy damage like collapse after earthquake, which was favorable to protect life and property safety.

2.5. Earthquake Fortification Standard

The earthquake damage in previous greater earthquakes proved that the earthquake fortification standard of tunnel had decisive influence to earthquake damage to tunnel, table 3 showed the summary on evaluation of earthquake disaster to tunnels under the jurisdiction of Chengdu Railway Bureau in Wenchuan earthquake, from the table we can learn that tunnels built in early ages without earthquake fortification standard or with low earthquake fortification standard were easily damaged in earthquake, and the damage was relatively heavy[12].

2.6. Construction Quality of Tunnel

Tunnel construction is thefinal step of achievements display of tunnel, which has decisive influence to the entire quality of tunnel. According to the record of Youyi Tunnel, the tunnel had 11 times of collapse in total, there were sections up to 340m long which needed secondaryreinforcement because of the overlarge sedimentation during construction, and the seriously sunk sections were up to 275m, between 166m and 457m, the collapse and sinking were mostly in tunnel section, and the section at Yingxiu was very severe. It is learned from the earthquake damage of Wenchuan earthquake that the thickness of secondary lining at some section was only about 10cm, such section had a severe earthquake damage (the severe damage located at 180-380m of entrance at Yingxiu section), and the Yingxiu section was severely damaged. The earthquake damage result indicated the apparent influence of construction quality to tunnel, high attention shall be paid to the quality control on tunnel construction especially in earthquake area with strong intensity, geological disaster mostly happened to the tunnel with tunnel construction at tough section, and the control on construction quality shall be paid with special attention.

2.7. Activity Feature of Fault Zone

The influence to tunnel structure from active fault zone mainly lies in two aspects, dislocation of active fault zone along fractured surface (namely dislocation problem) and changing dynamic response feature of tunnel through fault fractured zone (namely oscillation problem). Tunnel through active fault zone easily has lining dislocation along with many other damages such as cracking, the Zipingpu Tunnel, Longdongzi Tunnel, Longxi Tunnel and Longchi Tunnel on Du-Wen expressway all had massive damages after earthquake influenced by fault zoneof Longmen mountains.

3. Analysis on Types of Earthquake Damage to Tunnel through Fault Zone

From instances of earthquake damage to tunnel through fault fractured zone, it’s known that fault fractured zone was featured with poor geological conditions of surrounding rocks, stratum transited from soft rock to hard rock or from hard rock to soft rock, which are the concentrated sections of earthquake damage to tunnel. It is learned from data that the tunnel through fault fractured zone generally has the following types of damage [13]:

Table 3 *Summary on Evaluation of Earthquake Disaster under the Jurisdiction of Chengdu Railway Bureau*

c	Project	Location Relation to Epicenter in Wenchuan Earthquake	Seismic Intensity Classified Currently	Designed Fortification Standard	Major Damage to Existing Engineering and Equipment in Wenchuan Earthquake
1	Bao-Cheng Line	70~320km to Epicenter Wenchuan	VI~Ⅶ	No uniform earthquake fortification standard when Bao-Chengdu Line was built; the extended two	Arch walls of tunnel were partially cracked and peeled to fall down, the protection to slope at tunnel portal was cracked, which led to dangerous rock falling;

				lines are not greater than VI, except for Qingbaijiang in Chengdu which is VII.	
2	Guang-Yue Sub-line	About 50km to Epicenter	Ⅶ	Built in 1966, fortification standard unknown	Partial piers were damaged by collapsed objects, and tunnel portals were buried;
3	Cheng-Kun Line	70~500km to Epicenter Wenchuan	Ⅶ~Ⅸ	No uniform earthquake fortification standard; VI-VII for Emei, Chengdu, Vii-IX for remaining section, fortification available for all engineering works	Arch and side wall of lining in tunnel were cracked, slurry pouring out of foundation base, and the foundation base sunk;
4	Cheng-Yu Line	70~400km to Epicenter Wenchuan	VI~Ⅶ	Built in 1950's, no uniform national earthquake fortification standard available at that time, no fortification for all engineering works	Arch and side wall of lining in tunnel were cracked, slurry pouring out from foundation base, and the foundation base sunk;
5	Nei-Liu Line	250~600km to Epicenter Wenchuan	VI~Ⅶ	Low fortification standard for Neijing-Shuifu section, fortification of Vi-VII for Shuifu-Liupanshui section	①Cracking increased at arch wall of lining or lining cracking worsened ② New surrounding rock falling or dangerous rock falling formed at the slope of tunnel portal, and damage aggravated;
6	Xiang-Yu Line	340~460km to Epicenter Wenchuan	VIor less thanVI	Full line built in Dec. 1979, bridges designed in consideration of earthquake influence at that time	Cracking and dislocation of tunnel lining, water leakage and water bursting, slurry poured out from foundation base, serious dangerous rock falling at entrance and exit of tunnel;
7	Chuan-Qian Line	340~590km to Epicenter Wenchuan	VI or less thanVI	Built in July 1965without considering earthquake influence	Cracking and dislocation of tunnel lining, water leakage and water bursting, slurry poured out from foundation base, serious dangerous rock falling at entrance and exit of tunnel;
8	Yu-Huai Line	340~610km to Epicenter Wenchuan	VI or less thanVI	Earthquake fortification not considered in bridge engineering according to seismic intensity	Cracking and dislocation of tunnel lining, water leakage and water bursting, slurry poured out from foundation base, serious dangerous rock falling at entrance and exit of tunnel;
9	Hu-kun Line	510~680km to Epicenter Wenchuan	VI or less thanVI	Earthquake fortification not considered in bridge engineering according to seismic intensity	Gutter and lateral cracked and damaged, dangerous rock falling; 2Cracking and dislocation of tunnel lining, water leakage and water bursting, slurry poured out from foundation base, serious dangerous rock falling at entrance and exit of tunnel;
10	Sui-Yu Line	180~330km to Epicenter Wenchuan	VI or less thanVI	《Code for Seismic Design of Railway Engineering》（GBJ111-87）	Upper side of cutting slope collapsed or slipped with falling rocks, weathering flaking of cutting slope, embankment slope slipping down;
11	Da-Cheng Line	70~340km to Epicenter Wenchuan	VI or less thanVI	Earthquake fortification not considered in bridge engineering according to seismic intensity	Dangerous rock falling at some tunnel portals, longitudinal circular cracking of lining, concrete flaking of lining, water leakage in some tunnel, and slurry pouring out from foundation base;
12	Guang-Wang Line	About 200km to Epicenter Wenchuan	VI	No earthquake fortification considered	Arch ring and side wall of some tunnels cracking, foundation base damaged

3.1. Damage of liningby Shear Dislocation of Surrounding Rock ofthe Fault Zone

The tunnel structure of tunnel through fault zone has apparent dislocation at the fault fractured zone due to the apparent relative displacement difference of surrounding rocks during earthquake caused by apparently sudden change of preferable surrounding rocks and surrounding rock rigidity of tunnel through fault zone, and the lining has shear damage under fault zone. The followings are typical dislocation damage in earthquakes: the earthquake in San Francesco, US in 1906 caused dislocation damage to Tunnel Wright No. 1, and the horizontal dislocation was up to 1.37m; the earthquake in Izu, Japan in 1930 led to a horizontal dislocation of 2.39m and a vertical dislocation of 0.6m in Tanna Tunnel through fault zone of Tanna mountain, and the dislocation damage was severe; the earthquake in Hanshin, Japan in 1995 resulted in an apparent earthquake shear dislocation damage to the tunnel structure of Shanyang Shinkansen Malacca Tunnel after earthquake because of transversely passing through Malacca fault system; the fault zone had apparent dislocation damage along the construction joint and non-construction joint near F8 fault in Longxi Tunnel on Du-Wen expressway, the largest dislocation was up to 60cm, please see the damage type and damage to Longxi Tunnel in graphs 3-4.

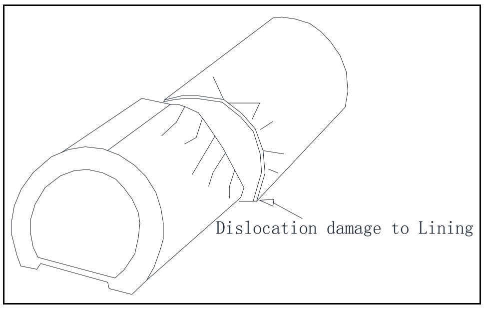

Figure 3 *Damage to Tunnel Lining caused by Shear Dislocation of Surrounding Rock*

Figure4 *Dislocation of Secondary Lining to Tunnel*

3.2. Inclined cracks, Transverse cracks and Longitudinal cracks of Tunnel Lining

Cracks of tunnel lining is one of the major damage features at tunnel through fault zone part, the tunnel structure is accompanied with lots of cracking damages during the fault dislocation, and the cracks of lining mainly include longitudinal cracks, transverse cracksand inclined cracks. The apparent earthquake damage characteristics are mainly inLongchi Tunnel, Longxi Tunnel, Longdongzi Tunnel and Jiujiaya Tunnel in Wenchuan earthquake, Sanyi Tunnel in Chi-chi earthquake, and the damage types are shown in graphs 5-8.

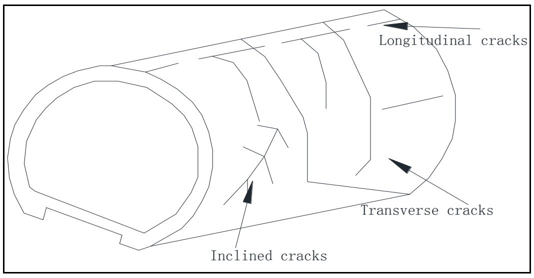

Figure 5 *Cracking damage to lining of tunnel through fault zone*

Figure 6*Damage to Side Wall of Longchi Tunnel*

Figure 7 *Side Wall Damage in Hole ofLongchi Tunnel*

Figure 8 *Side Wall Cracks in Longchi Tunnel*

3.3. Partial and Entire Falling of Lining Arch Ring, Bulging of Inverted Arch

By the influence of concentrated high stress of fault zone, collapse of both lining and surrounding rocks or falling of secondary lining happened during earthquake in tunnel through fault zone, heavy collapse of surrounding rocks generally leads to the sealing of tunnel portal, which is one of the most severe earthquake damage to tunnel, and please see graphs 9-12 for damage features. Entrance portal of Longxi Tunnel had tunnel collapse in poor surrounding rocks, and the collapse caused serious sealing of tunnel; and secondary lining at the upper side wall of tunnel body section of 1 LongdongziZuoxian tunnel was collapsed, which led to severe damage to tunnel.

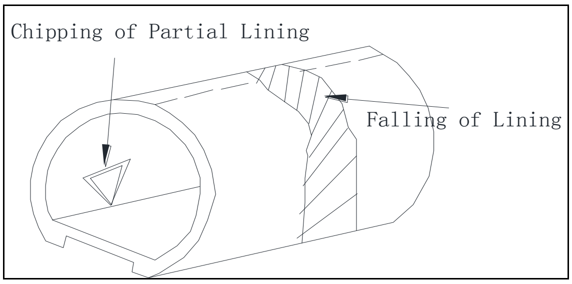

Figure 9 *Partial and Entire Falling Damage of Lining Arch Ring*

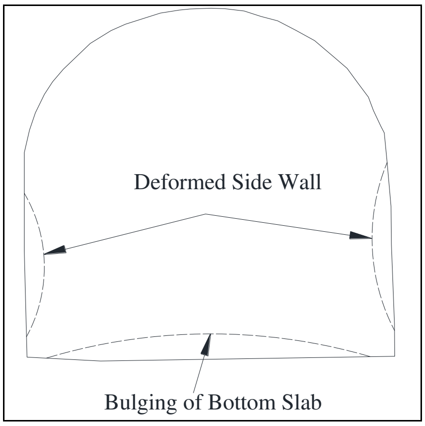

Figure10 *Bulging of Inverted Arch and Side Wall Damage of Lining*

Figure11 *Collapse and Leakage of Lining at Zuoxian Tunnel Body Section*

Figure 12 *Bulging and Cracking of Bottom Slab at Tunnel Body Section*

4. Conclusions and Enlightenment

This article made research and analysis on earthquake damage to tunnel through fault fractured zone, especially made classification and conclusion on earthquake damage to partial damaged tunnel in Wenchuan Great Earthquake, and analyzed thedamage influence factors of tunnel through fault fractured zone, also made summarization on earthquake damage types of tunnel, and the following conclusion are made:

(1) Fault fractured zone has significant influence to earthquake resistance of tunnel, the tunnel through fault zone is easily damaged and causes various secondary disaster, and the fault zone section is controlling part for earthquake resistance of tunnel, therefore, earthquake fortification measures shall be taken.

(2) Major factors which influence the damage to fault zone are seismic intensity of tunnel site, engineering geological condition of tunnel site, earthquake resistance design measures of tunnel, fortification standard and construction condition of tunnel and so on, and all factors decide the result of earthquake damage to tunnel jointly.

(3) The main earthquake damage types of tunnel through fault fractured zone include dislocation of tunnel lining, longitudinal/transverse cracks of lining, falling and peeling of lining, bulging of floor, and entire collapse of lining and surrounding rock, and many of the earthquake damages occurred in the damaged area of tunnel together.

(4) The influence area of earthquake damage to tunnel through fault zone consists of fault zone and the transition section within certain range of both sides of the fault zone, and the distance is the major range of earthquake fortification.

(5) Structure with better ductility shall be adopted to secondary lining at fault zone and within certain range of both sides, so as to avoid severe damage to tunnel in earthquake, such as entire collapse; and research to norm of tunnel through fault

fractured zone shall be strengthened, and implementation of the norm shall be carried out.

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