DAMAGE EVALUATION OF TUNNELS IN EARTHQUAKES

Fang Xiaoqing[1], Lin Junqi[2], Zhou Xiaolan[3], Liu Runzhou[4]

[1] *Post-graduate student, Institute of Engineering Mechanics, China Earthquake Administration, Harbin, China*
[2] *Professors, Dept. of Civil Infrastructure Engineering, Institute of Engineering Mechanics, CEA, Harbin, China*
[3] *Post-graduate student, Institute of Engineering Mechanics, China Earthquake Administration, Harbin, China*
[4] *Post-graduate student, Institute of Engineering Mechanics, China Earthquake Administration, Harbin, China*
Email: faxiaoqing@163.com; linjunqi@iem.net.cn; xiaolanzhiyang@163.com; eisci@163.com

ABSTRACT:
The state of art of tunnel earthquake damages and tunnel earthquake damage mechanism are briefly introduced in this paper. According to tunnel's traffic function and damage descriptions based on the investigation, tunnel damages are divided into five grades: no damage, minor damage, moderate damage, major damage and collapse, and their corresponding damage index range and characteristic values are defined. The materials of tunnels influenced in Kobe earthquake and Chi-Chi earthquake are collected in this paper, and the damage grades are determined based on the performance in the earthquake. After comparative analysis, the seismic intensity, overburden depth, rock classification, distance from faults and the tunnel length are chosen as the earthquake damage factors. A formula for tunnel seismic damage evaluation is deducted using these factors and the least square method and with the modification of construction time, seismic fortification intensity and portal stability. The damage of four tunnels is evaluated using the derived formula, and the results are the same with that of static and dynamic methods. It shows that the method provided in this paper is effective, reliable.
KEYWORDS: Tunnel; Earthquake; damage evaluation; damage mechanism; regression statistics

1. INTRODUCTION

Tunnels, being confined by the surrounding rock or soil, have long been assumed to have good anti-seismic ability. Thus in a very long time, the damage of tunnels do not take enough attention as the structures on ground. As the tunnel number and its seismic damage increased, this problem attracts the attentions of seismologists of all countries.

In 1923, Kanto earthquake in Japan, over 80% of the more than one hundred tunnels in the disaster area damaged. The brick and concrete linings of one tunnel sheared off and cracked and the movement of one arch wall reached 25cm. The cracks of another tunnel spread the entire hole, the tunnel bottom knobbed, reach to 1m, the shrinkage of cross section reached 50cm. In 1971, St Fernando earthquake of USA, five tunnels damaged. Among them, one tunnel close to Sylmar fault damaged in linings and sheared off, one vertical displacement reached to 2.29m, accompany with bending crack. Another tunnel appears long and wide cracks in the lining. In 1978, an earthquake in Japan, tunnels also be seriously destroyed, the lining cracked, the vault concrete spill, steel enforcement cut off, the line cross section distorted, the width shorted about 0.5m, the bottom knobbed. In 1999, Chi-Chi earthquake of Taiwan, a lot of tunnels received moderate or severe damage. Because near to the fault, Chingshue tunnel collapsed, and the same to the tunnel located at Sta. 42k+537 of No.8 Highway.

China has earthquake frequently, the west area is more often. There are over one thousand railway and highway tunnels exactly located in this wide west region. As one of the most important constituents of the highway engineering, the tunnel destruction will be able to cause the transportation network intermitted, influencing the rescue and repair work after earthquake directly. Therefore, how to analyze the tunnel stability in earthquake areas and give its damage state under certain intensity quickly became an issue of all concerns.

2. STUDY ON DAMAGE EVALUATION OF TUNNELS

At the beginning of 20th century, Charles H. Dowding and Arnon Rozen (1978) observe 71 cases of rock tunnel response to earthquake motions, and 42 cases of them are damaged. Through study, they came up with the relationship of the tunnel damage level with the earthquake magnitude, intensity and epicenter. The tunnel is no damage when ground movement acceleration $\ddot{u}_g \leq 0.19$g and ground movement velocity $\dot{u}_g \leq 20$cm/s; The tunnel will be minor damage when 0.19g< $\ddot{u}_g \leq 0.5$g and 20cm/s< $\dot{u}_g \leq 80$cm/s; The tunnel will be severe damage when $\ddot{u}_g >0.5$g and $\dot{u}_g >80$cm/s.

After the study of tunnel seismic damage materials in Japan, Shunzo Okamoto arrived at the conclusion that: Tunnels over 50km far away from the epicenter do not be influenced; The tunnel sector of thick lining has bigger damage percentage, with thickness 40cm damage percentage is 82%, thickness 30cm is 38%, thickness 20cm is 16%. Under the different geological condition the damage percentage is: the hard rock 16%, the soft rock 40%, the joint development rock 44%, and the earth 61%. The earthquake safety of tunnel is mainly controlled by the natural condition, when the natural condition is very bad, to increase lining thickness does not help matters, on the contrary, this will increase earthquake force and get opposite result, a more effective method is to reinforce the surrounding rocks.

Sunil Sharma and William R. Judd (1991) summarized some earthquake influences to the underground cave briefly. It collected 192 reports of underground cave behavior from 85 earthquakes throughout the world. The data had been assembled into a data base to determine some of the significant factors that may affect underground structure stability. And at last, they developed a correlation between peak ground acceleration at surface, overburden depth and damage which allow for preliminary assessment of stability of new underground structures.

Robert Rowe (1992) analyzed the influence of earthquake wave, hard rock, fault and liquefaction on tunnels. He brought forward that the tunnel safety index increase with the depth when the depth is lees than 500 meter; when tunnel crossing the active fault possibly has seriously but the partial destruction, the damage level is the function of fault displacement, the lining and the rock condition; tunnels in soft soil layer or soft rock layer is easier to get damage.

Changshi Pan (1996) summarized the tunnel earthquake damages and propose that: Tunnel through the fault or fault crushed zone would receive serious destruction in the earthquake, lining near the fault would sheared off in the transverse and vertical plane of the tunnel axial direction; Tunnels does not cross fault would also sheared off in transverse and vertical direction; The concrete lining spilling is due to over compression, the crack and the steel enforcement pull broke is the result of excessive stretch, which indicated that the lining had a great deformation in transverse under earthquake; The lining would have rotation in transverse under earthquake.

Yu-er Zhang (2003) proposed some tunnel damage characteristics in earthquake: The vibration deformation of subway tunnel with the restraint function of environmental media is obviously, and generally, the structure dynamic response does not displays the natural characteristic obviously; With earthquake load function, subway tunnel and its environmental media movement together; geological condition around the tunnel has important influence to its anti-seismic property; severe damage would happened at the sharply changes of section shapes and stiffness, such as portal and turning position; The tunnel damage form mainly is curving crack, vertical crack, concrete spilling and steel enforcement exposition, and so on.

Jin-Hung Hwang and Chih-Chieh Lu (2007) proposed a modified cross-section racking deformation (MCSRD) method which is simple and fast. It can automatically take into account the interaction between underground structure and the surrounding ground under seismic action, by using a 2-D finite difference method. It suggested that most of the tunnels in the gravel formation had a seismic capacity of JMA IV while tunnels in soft rock had a seismic capacity of JMA V.

3. DAMAGE MECHANISM OF TUNNELS

The damage of tunnels resulting from earthquakes is generally manifested in one or a combination of the following forms: (1) Damage by earthquake induced surrounding rock failure, such as liquefaction or landslides at tunnel portals; (2) Damage from fault displacement; (3) Damage from ground shaking or ground vibration. The potential of tunnel damage from ground failure may be evaluated through established geotechnical analyses, geological exploration, and testing. Careful sitting can avoid this problem. Tunnel displacement by fault movement usually results in serious damage. Similar to ground failure, sitting to avoid intersection with active faults can minimize this problem for new tunnels. It was found that most of the tunnel damage from fault movement was caused by unavoidable location of tunnels across faults. Damage from ground shaking differs from the preceding two sources of potential damage.

The tunnel would present three kind of deformation under the seismic motion: compression and tension deformation, longitudinal deformation and shear deformation. The tunnel damage situation related to three aspects: the earthquake the tunnel experience, the deformation character around the tunnel and the anti-seismic ability of the tunnel structure.

The tunnel endure different earthquake load for its different position, which has something to do with the fault displacement, earthquake source or epicenter. Earthquake wave weakens gradually as it disseminates for the wave diffusion and the earth damping. Therefore, the little distance to the displacement fault or epicenter, the stronger the earthquake load is.

When regarding to the relationship between the around geology and tunnel structure, the tunnel will deform along with the site deformation if the around geology is firm, otherwise, the tunnel will resist some deformation of site. In addition, the plastic area expansion for the collapse or too great deformation in construction would also cause the tunnel site to be weak, and will cause the vibration larger when the earthquake wave comes. If the tunnel structure can not resist the earthquake load it will be damaged.

3 THE DAMAGE EVALUATION METHOD OF TUNNELS

3.1 The damage grade and damage index

The tunnel damage grade evaluated mainly according to the tunnel traffic function and its damage investigation. The tunnel damages are divided into five grades: no damage, minor damage, moderate damage, severe damage and collapse, and their corresponding damage index ranges are [0, 0.2], (0.2, 0.4], (0.4, 0.6], (0.6, 0.8] and (0.8, 1], and the characteristic values are 0.1, 0.3, 0.5, 0.7 and 0.9. The damage grade can be defined as: a) no damage, the lining of tunnel may have small cracks, but no falls of rock, can be safely use; b) minor damage, the road surface may sink slightly, the tunnel lining have small cracks, the fall of rock locally, and it can restore to normal use by slight repair; c) moderate damage, there are a lot of cracks in lining; many fallings of rock, the road surface may sink obviously. The traffic are blocked, it can restore to normal use after repairs; d) severe damage, there are a great deal of cracks in its lining, falls of big rocks, the road surface may sink severely. The tunnel can not be use unless thorough repairs; and e) collapse, serious crack and deformation in its lining, the tunnel structure collapsed partially, must be reconstructed.

3.2 The tunnel seismic damage examples

There were more than one hundred tunnels in the disaster area in Kobe earthquake. Tunnels in the intensity 10 areas were damaged in different levels, and there were several tunnels major damaged for crossing fault zones, also there many tunnels were damaged in the intensity 9 areas, and only little tunnels were damaged in intensity 8 areas. Generally speaking, tunnels in intensity 7 areas are not being damaged. In Chi-Chi earthquake, 44 tunnels in intensity 9 areas were damaged, and in low intensity areas the tunnels are safe.

In this study, the materials of 27 damaged tunnels in Kobe earthquake and 7 tunnels in Chi-Chi earthquake are collected, and the intensity were adjusted according to Chinese intensity. The damage grade of each tunnel and corresponding damage index are decided according its damage and the damage grade definition described above. The data are listed in Table 3.1.

Table 3.1 the damage tunnels in earthquakes

No	Intensity	Tunnel	Lengths (m)	overburden depth (m)	rock	Whether through the fault	Damage grade
1	10	Rokko	16250	460	hard rock	Yes	severe
2	10	Kobe	7970	272	hard rock	Yes	moderate
3	9	Nagasaka	625	20	soft rock	No	minor
4	10	Toyama	141	4~8	soft rock	Yes	severe
5	10	Kaigesan	253	2~1125	soft rock	Yes	severe
6	8	Arima	450	6~435	hard rock	No	minor
7	8	Gosha	115	40	hard rock	No	minor
8	10	Kitakshi	6983	350	hard rock	Yes	severe
9	10	Keihaku	1743	20~250	hard rock	Yes	severe
10	9	Maiko-noboli	3293	4~50	hard rock	No	moderate
11	9	Maiko-kudari	3250	4~50	hard rock	No	moderate
12	10	Nubiki	3032	260	soft rock	No	moderate
13	10	DainiNubiki	3032	240	hard rock	No	minor
14	9	Seikotsudaini	207	40	hard rock	No	minor
15	10	Shinkobe	6910	330	hard rock	Yes	moderate
16	10	dainikobe	7175	330	hard rock	Yes	moderate
17	8	Yekana	1245	145	soft rock	No	minor
18	9	Rokoyama	2843	280	hard	No	minor

					rock		
19	10	Rokoyama	452	67	hard rock	No	minor
20	10	Higashitakara-1	364	62	hard rock	No	minor
21	10	Higashitakara-2	362	59	hard rock	No	minor
22	10	Nishitakura-1	347	42	hard rock	No	minor
23	10	Nishitakura-2	244	42	hard rock	No	minor
24	9	Takakura-1	538	86	hard rock	No	minor
25	9	Takakura-2	579	87	hard rock	No	minor
26	9	Getsnmi-1	236	43	hard rock	No	minor
27	9	Getsnmi-2	228	34	hard rock	No	minor
28	7	Doufu tunnel	647	6~50	soft rock	No	no damage
29	7	Miaoli tunnel	982	4.5~50	soft rock	No	no damage
30	7	Tonglu tunnel	331	6~26	soft rock	No	no damage
31	9	No.1sany-tunnel	7544	24~122	soft rock	Yes	severe
32	7	No.2sany-tunnel	260	3.5~50	soft rock	No	no damage
33	7	No.3sany-tunnel	517	2~21	soft rock	No	no damage
34	7	No.4sany-tunnel	455	6~33	soft rock	No	no damage

3.3 The factors influence the damage of tunnels

There are many factors influence the damage of tunnels. Generally speaking, there three aspects: First, the earthquake motion, such as the earthquake intensity, the spectrum characteristics and so on; Second, the structure condition of the tunnel, as whether have lining, and its integrality, quality of the construction; Third, the tunnel environment condition, as rock condition, overburden layer depth, whether across the fault crushed zone and so on.

Sunil Sharma and William R. Judd point out in their research: Underground structure damage in earthquake is gradually increasing with the increase of the seismic motion acceleration and the decrease of the overburden depth. The damage of underground structures in soft rock is more serious than that in hard rock. As an underground structure, tunnel should have similar rule.

After the statistical analyze of the tunnel damaged in Kobe earthquake we can draw the same conclusion: Tunnel damaged mostly in intensity 10 areas, and its damage is much lightly in intensity 9 areas while little damaged in intensity 8 areas and is safe in intensity 7areas. We can learn that tunnel in soft rock is more dangerous than that in hard rock; the tunnel damage with overburden lay smaller than 10 meters are great than those with thicker overburden layers. Moreover, the tunnel damage possibility is get increase as it is longer; the damage of tunnels that cross fault is inevitable, 9 tunnels cross the fault have all received moderate or severe damage in Table 3.1.

3.4 Construction of the evaluation model based on the least square method

The construction of the evaluation model based on the least square method use the factors of the seismic intensity, overburden depth, rock classification, distance from faults and the tunnel length.

Supposed the tunnel damage index is a liner function of the damage factor. There are five factors and the number j factor has r_j categories. And their responses in the tunnel i is $\delta_i(j,k)$ (j =1 … 5). The total number of the tunnel is n. The function for the present purpose is expressed as:

$$y_i = \sum_{j=1}^{5}\sum_{k=1}^{r_j}\delta_{i(j,k)}b_{jk} + e_i \qquad i=1 \dots n \tag{3.1}$$

Where b_{jk} (k = 1, 2, ……, r_j) is a coefficient; e_i (i =1,2,……,n) is a residual of number i tunnel; $\delta_i(j,k)$ is the response of the factor j, category k in number i tunnel, it can be defined as follow: $\delta_i(j,k)$=1 when the number i tunnel has category k in factor j; $\delta_i(j,k)$=0 when the number i tunnel doesn't have category k in factor j.

The matrix express of above formula is: $y = xb + e$. Use the least square method to deduct the coefficient b to make $Q = e'e = (y-xb)'(y-xb)$ least, the necessary condition is $\frac{\delta Q}{\delta b} = -2x'(y-xb)$=0

So, we can arrive at $x'xb = x'y$. Let $A = x'x$, $P = x'y$, the formula can be $Ab = P$, solve this equations can get the coefficients b.

Use the above method can get the coefficients as showed in table 2. The correlation coefficient $R = 0.890$, the standard deviation σ =0.093. Using the constructed evaluation model to evaluate the tunnels in table 1, There are 29 tunnels accurate in this evaluation result by the deducted method, 85.3% of total, and 5 tunnels are differ one grade, 14.7% of total.

3.6 The relation of tunnel damage, construction age and fortification intensity

The formula deducted from the Kobe earthquake mainly expresses the action of earthquake and environment to the tunnel damage, and do not express the anti-seismic ability of the tunnel structure. From the tunnel damages in Chi-Chi earthquake, we can learn that the tunnel damage have a lot to do with the construction age. Among the16 tunnels constructed before 1980, 7 tunnels are moderate or severe damaged, about 44%. Wherever, only 4 tunnels in 28 tunnels constructed after 1980 in moderate or severe damaged, about 14%. So it is easy to see that the tunnel damage has relationship with the lining integrality, corrosion and firmness, and so on. For the tunnels constructed before 1980 have be used for a long time, the lining have light cracks already and the tunnel were not seismic design or constructed, so those tunnels have more serious damage.

We know that the “Specifications of Earthquake Resistant Design for Highway Engineering of China" promulgated in 1978. There is no earthquake resistant design code before 1978, tunnels that constructed before 1978 would have week anti-seismic ability. And tunnels constructed after 1978 have better anti-seismic ability. If the tunnel constructed after 1978 has considered the fortification intensity, the damage under corresponding intensity should be no damage or slight damage. So the corresponding coefficients show in table 3.2.

3.6 Relation of damage and portal stability

The discussion above doesn’t take into account of the portal stability. As it is the weak part of the tunnel, the damage is greater as the overburden layer is shallow. Especially under big earthquake motion, the phenomenon of portal landslide is usual. In Chi-Chi earthquake, as the portal is adjacent to the slopes surface, the portal damage is more serious than the mined section. There are 9 tunnels severe damaged and 6 moderate damaged for portal landslide. So the portal stability is very important.

The landslide at portal is happened at intensity 9 and 10 areas. If the landslide is not very serious, the tunnel can normally use after repairs, we can define it as moderate damage. If it needs thorough repair, we can define it as severe damage. Under the given intensity, we can defined it as good, bad or very bad portal stability if it not, little or big landslide. The corresponding coefficients can be seen in table 3.2.

To sum up, we can obtain the formula to evaluate the tunnel damage:

$$y_i = \sum_{j=1}^{7}\sum_{k=1}^{r_j} \delta_{i(j,k)} b_{jk} \qquad (3.2)$$

Where $0 \le y_i \le 1$, if $y_i > 1$, $y_i = 1$; if $y_i < 0$, $y_i = 0$, the coefficients show in the table 2.

Table 3.2 Coefficients of the formula

Factor	Category		Calculated coefficient	Suggested coefficient
Earthquake Intensity	7		-0.0908	0
	8		0.1950	0.05
	9		0.2644	0.2
	10		0.2818	0.3
overburden depth (m)	h≤10		0.1352	0.12
	10<h≤50		0.0446	0.05
	h>50		0	0.01
Rock type	Soft rock		0.0555	0.07
	Hard rock		0	0
Whether pass through the fault	Yes		0.2331	0.25
	No		0	0
length(m)	l=<1000		0	0
	l>1000		0.0796	0.08
construction age and fortification intensity	Before 1978			0.05
	After 1978	No fortification		0
		7 fortification		-0.05
		8		-0.1

		fortification		
		9 fortification		−0. 15
		10 fortification		−0. 25
portal stability	Good			0
	Bad			0. 15
	Very bad			0. 3

4. EVALUATION EXAMPLES AND CONGCLUSION

Tunnels damaged in high intensity area aren't adopted in the above deduction for lack of the description of rock and overburden depth, but we can evaluate the whole damage based on the geological condition using this formula. Most rock of tunnels in Chi-Chi earthquake are hard rock, only little tunnel passed through the fault zones or other poor geological condition areas, so the mined section damage is minor damage mostly. It accord with the above formula.

Select the tunnel evaluation results of Zigong city to check the reliability of this formula. The specific description shows in table 4.1. The results are obtained from static and dynamic analysis based on the "Specifications of Earthquake Resistant Design for railway Engineering of China" and "Specifications of Earthquake Resistant Design for Highway Engineering of China". And they are show in table 4.2. The results based on the formula suggested in this paper are show in table 4.3. Comparative analysis of table 4 and table 5 we can see that only two results are different, others are match very well. So we can know that the formula suggested in this paper is reliability.

Table 4.1 the tunnels in Zigong city

No	Tunnel	Year	Length (m)	overburden depth (m)	rock	Remarks
1	Futaishang	1990	314	10~50	Soft rock	Have good anti-seismic ability
2	Bumiwan	1981	58.4	20	Soft rock	Broad in 1987, seepage in vault
3	Jiefanroad	1977	367	20	Soft rock	seepage locally

Table 4.2 the evaluation results of static and dynamic analysis

No	Tunnel	Intensity 7	Intensity 8	Intensity 9	Intensity 10
1	Futaishang	No damage	No damage	No damage	Minor damage
2	Bumiwan	No damage	No damage	Minor damage	Moderate damage
3	Jiefanroad	No damage	No damage	Minor damage	Moderate damage

Table 4.3 the evaluation results of the suggested formula

No	Tunnel	Intensity 7	Intensity 8	Intensity 9	Intensity 10
1	Futaishang	No damage	No damage	Minor damage	Minor damage
2	Bumiwan	No damage	No damage	Minor damage	Moderate damage
3	Jiefanroad	No damage	Minor damage	Minor damage	Moderate damage

The state-of-the-art of tunnel earthquake damage and the tunnel earthquake damage mechanism are briefly introduced in this paper. A formula for tunnel seismic damage evaluation is deducted using the influence factors including earthquake intensity, overburden depth, rock type, whether pass through the fault, length, construction age and fortification intensity, portal stability, and the least square method based on the tunnels in Kobe earthquake and Chi-Chi earthquake. Then modified it based on experience.

The method is effective, reliable and feasible, can meet the need of anti-seismic and the disaster prevention programming. But some damage factors are still don't consider, so it need further research and modification.

ACKNOWLEDGEMENTS

This research was supported by the National Key Technologies Research and Development Program (Grants No. 2006BAC13B03) form the Ministry of Science and Technology of People's Republic of China, and the support is greatly appreciated.

REFERENCES

Dowding C. H., and Rozen A. (1978), Damage to rock tunnels from earthquake shaking. *Journal of the Geotechnical Engineering Division*, **2**, 175-191.

Jin-Hung Hwang, Chih-Chieh Lu (2007), Seismic capacity assessment of old Sanyi railway tunnels. *Tunneling and Underground Space Technology*, **22:7**, 433-449.

Pan Changshi (1996), the survey of the study on earthquake resistance of tunnel and underground structure, *the World Tunnel*, **5**, 7-16.

Ma Jixin (1997), The disaster and repair of mountain tunnel in north hyoxgo of Japan, *World tunnel*, **4**, 32-37.

Ministry of Communications, P. R. C. (1990), Specifications of earthquake resistant design for railway engineering of China (JTJ 004—89), Beijing, People communications publishing house.

Ministry of Communications, P. R. C. (2006), Specifications of Earthquake Resistant Design for Highway Engineering of China(GB50111-2006), Beijing, China planning publishing house.

Robert Rowe (1992), tunnel engineering in earthquake area, *Tunnels and Tunneling*, **12**, 41-44.

Shou Kejian, Fan Jietan (2006), Investigate of damage in mountain railway tunnels due to the Taiwan Chi-Chi Earthquake, 2006 Taiwan rock engineering symposium, 449-460.

Shunzo Okamoto, Choshiro Tamura (1973), Behavior of Subaqueous Tunnels during Earthquake, *Earthquake Engineering and Structural Dynamics*, **1**, 253-266.

Sunil Sharma, William R. Judd (1991), Underground opening damage from earthquake, *Engineering Geology*, **30**, 263-275.

Wang Xiuying, Liu Weining, Zhang Ming (2003), Study on the categorization and mechanism of seismic damage of underground structures, *China safety science journal*, **13:11**, 55-58.

W. L. Wang, T. T. Wang, J. J. Su, C. H. Lin, C. R, Seng, T. H. Huang (2001), Assessment of damage in mountain tunnels due to the Taiwan Chi-Chi Earthquake, *Tunneling and Underground Space Technology*, **16**, 133-150.

Yao Qunfeng, Lu Guoqiang (1996), Prediction of underground railway tunnel earthquake damage in large region, *earthquake resistance engineering*, **2**, 37-39.

Zhang Yu-er, Bai Baohong, Zhang Yaohui, Wang Zanzhi (2003), Study on subway tunnel's behavior due to seismic damage and methods of analyzing seismic response and earthquake-proof means, **22:1**, 70-74.