Damage Assessment of Tunnels in Seismic Prone Zone During Earthquakes: A Part of Hazard Evaluation

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Abstract Tunnels are generally constructed in urban areas and metro cities to fulfill the rising need of space and passage due to urbanization. These infrastructure may get damaged because of earthquakes occurring in that particular area where tunnels are constructed. While designing tunnels in seismic prone zones, it is ensured that tunnels must withstand under both seismic and static loading. Recently occurred large magnitude earthquakes caused significant damages of the tunnels including the 1995 Kobe earthquake in Japan, the 1999 Chi-Chi earthquake in Taiwan and the 2008 Wenchuan earthquake in China. During damage evaluation, tunnel damages are broadly categorized into five classes based on damage index including no damage, minor damage, moderate damage, major damage and collapse. This paper gathers the materials of tunnels affected by the 1995 Kobe earthquake in Japan and the 1999 Chi-Chi earthquake in Taiwan, and the grades of damage are calculated based on seismic performance. Earthquake intensity, distance from fault, rock classification, tunnel length and overburden depth are considered as the tunnel damage factors while doing analysis. Considering these parameters, the formula for seismic damage evaluation for tunnel is deducted using the least square method. Further, this formula is modified after taking into account additional factors like construction time, seismic fortification strength and portal stability.

Keywords Tunnel damage · Damage assessment · Earthquake · Regression analysis

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1 Introduction

The large magnitude earthquakes may cause the damage of surface as well as underground structures [1, 3]. Tunnels are generally constructed in urban areas and metro cities to fulfill the rising need of space and passage due to urbanization. They may be subjected to different types of dynamic loading conditions like impact load, blast load and seismic load. Construction of tunnels in seismically active region involves a unique challenge for geotechnical as well as structural engineers to make earthquake-proof underground structures. These structures are subjected to strong damage in case of earthquakes if designed without considering seismic effects [2]. Seismically induced tunnel damage with surface peak ground acceleration correlated using data from 70 case histories and employing relevant attenuation relationships [7]. The rock tunnels are subjected to damage for Peak Ground Acceleration (PGA) below 0.4 g [13]. Tunnels constructed at greater depth are safer while damage will be more extensive with increasing magnitude of an earthquake and decreasing epicentral distance [16].

Minor damage on tunnels for Peak Ground Acceleration (PGA) values lower than 0.2 g and slight to heavy damage for Peak Ground Acceleration (PGA) greater than 0.2 g observed during the 1995 Hyogoken-Nambu earthquake in Kobe, Japan [14]. It is worth noticing that the 1995 Hyogoken-Nambu earthquake was a rather destructive event for tunnels, as more than 12% of the tunnels in the epicentral area were heavily damaged [4, 19]. The damage mechanisms were extensively studied by several researchers. They all highlighted that most of the damaged tunnels were designed and built neglecting an appropriate seismic assessment [8]. The collapse of the twin Bolu tunnel (Turkey) during the 1999 Kocaeli earthquake caused by the combined effects of ground shaking and ground permanent deformation [8, 10]. The collapse took place during construction in the unfinished section of the tunnel, which was deformed in an oval shape, causing crushing of the shotcrete and buckling of the steel ribs at the shoulder and at the knees. A large number of mountain tunnels suffered significant damage during the 1999 Chi-Chi earthquake in Taiwan [11, 12]. In this event, 26% of the 50 tunnels located within 25 km of the earthquake fault were severely damaged, while over 20% of the tunnels were moderately damaged. Various types of damage were observed like lining cracks, portal failures, displaced lining, spalling of the concrete lining, groundwater inrush, rockfalls in unlined sections ad lining collapses.

Similar to Chi-Chi earthquake, devastating damages were observed in mountain tunnels during the 2004 Mid Niigata Prefecture earthquake in Japan, the 2007 Niigata Prefecture Chuetsu Offshore Earthquake and the 2008 Wenchuan earthquake in China [9, 15, 18, 20]. Earthquake magnitude, depth and epicentral distance of the seismic source, geometrical properties of the lining, burial depth and sudden changes of tunnel dimensions are the most critical parameters affecting mountain tunnel damages during the seismic activity. A damage classification for tunnels was proposed based on 254 damage reports from the 1999 Chi-Chi earthquake, the 2004 Mid Niigata Prefecture earthquake and the 2008 Wenchuan earthquake [18]. The ring

Table 1 Major tunnel damages due to historical earthquakes

Tunnel name	Usage	Location	Earthquake magnitude (M_w)	Date
Wrights	Railway	San Francisco, USA	7.9	18 Apr 1906
Tanna	Railway	North Izu, Japan	7.2	26 Nov 1930
Kern County	Railway	Kern Co., CA, USA	7.5	21 Jul 1952
Inatori	Railway	Izu Oshima, Japan	7.0	14 Jan 1978
Pavoncelli	Water supply	Irpinia, Italy	6.8	23 Nov 1980
Rokko	Railway	Kobe, Japan	7.2	17 Jan 1995
Shioya-Danigawa	Railway	Kobe, Japan	7.2	17 Jan 1995
outlet tunnel of Kakkonda 2 hydropower station	Diversion tunnel of dam	Iwate, Japan	6.1	3 Sep 1998
Bolu	Istanbul-Ankara highway	Izmit, Turkey	7.4	17 Aug 1999
Intake tunnel of Shih-Kang dam	Intake	Chi-Chi, Taiwan	7.6	23 Sep 1999
Intake tunnel of Omiya dam	Intake	Tottori, Japan	7.3	6 Oct 2000
Tottori	Hydropower plant	Tottori, Japan	7.3	6 Oct 2000
Uonuma	Railway	Chuetsu, Japan	6.8	23 Oct 2004
Longxi	Road	Wenchuan, China	8.0	12 May 2008

cracks were found on the Tawarayama tunnel with a spacing of 10 m in around 20% of the spans of the tunnel during 2016 Kumamoto Earthquake [21]. A back analysis of damages suffered by Benedetto tunnel during the 2016 Norcia earthquake (Italy) carried out to evaluate the ability of available methods for analysis to predict seismic performance of tunnels [5]. Damage of tunnels due to earthquakes will lead to failure of transportation network and economical loss. Hence, it is very important to understand the damage pattern of tunnel in seismically prone zones so as to mitigate the damages of these infrastructure postured by such catastrophism (Table 1).

2 Damage Assessment of Tunnels

The relationship of tunnel damage level with the magnitude and intensity of earthquake as well as epicenter developed considering 71 rock tunnel response to earthquake motions [7]. Ground moment acceleration ≤0.19 g and ground moment velocity $\leq$20 cm/s will lead to no tunnel damage. Ground moment acceleration ranging between 0.19 g and 0.5 g and ground moment velocity ranging between 20 cm/s and 80 cm/s will cause minor tunnel damage. In case, if ground moment acceleration and ground moment velocity become greater than 0.5 g and 80 cm/s respectively, then tunnel will be subjected to severe damage. Increasing in tunnel lining thickness will result into more damage. The 40 cm and 30 cm thickness of tunnel lining contribute around 85% and 35% damage, respectively. The percentage of damages are 16%, 40% and 60% for hard rock, soft rock and earth, respectively.

The correlation between Peak Ground Acceleration (PGA) at surface, overburden depth and damage was developed to study the stability of underground structures by considering the 85 historical earthquakes that occurred across the world [16]. Tunnels constructed in soft soil can be damaged easily. Safety index for tunnel damages due to fault and liquefaction analyzed which proved that damage level can be decided based on fault displacement and tunnel lining materials [6]. Tunnels passing through the fault zone will be subjected to serious damage in case if portals located nearby fault line. In case of severe damage, there is strong probability of portal landslide.

2.1 Earthquake Induced Tunnel Damages

Earthquake induced tunnel damages can be broadly categorized as follows:

(a) Damages due to rock failure including landslides and liquefaction
(b) Damages due to fault displacement
(c) Damages due to vibration and ground shaking.

The damages of tunnels due to ground failure can be controlled by means of doing proper geological investigation as well as geotechnical analysis. Damage due to fault displacement may cause serious destruction of tunnel lining and tunnel portals. There would be chances of minor damage in cases of any ground shaking compared to fault displacement. For the case of firm type of surrounding geology, tunnel structures would not be able to resist the deformation due to propagation of seismic waves during any earthquake activity.

2.2 Types of Damage Grade and Damage Index

The tunnel damages are broadly categorized into five grades. There are (a) no damage, (b) minor damage, (c) moderate damage, (d) severe damage and (e) collapse.

(a) No Damage: In case of no damage case, small cracks are developed with no rock fall.
(b) Minor Damage: Tunnel linings start showing cracks in case of minor damage with rock fall.

(c) Moderate Damage: Lots of destructive cracks are developed while having moderate case of damage.
(d) Severe Damage: In this case, big cracks developed in tunnel lining, falls of big rocks and sinking of road surfaces. Tunnels get heavy damages and remain useless without repair.
(e) Collapse: This is the extreme destructive case of tunnel damage during earthquakes, where serious cracks and clear deformation can be observed in the tunnel lining. Tunnel structure gets collapsed and there occurs need of reconstruction as traffic gets blocked completely and traffic network is interrupted.

For above mention five types of damage classes, there 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.

3 Development of Damage Assessment Model

Recently occurred 1995 Kobe earthquake in Japan and 1999 Chi-Chi earthquake in Taiwan caused significant damages of the tunnels. In this study, the materials of tunnels affected by the 1995 Kobe earthquake in Japan and the 1999 Chi-Chi earthquake in Taiwan, and the grades of damage are calculated based on seismic performance [4, 11, 12, 17].

A large number of mountain tunnels suffered significant damage during the 1995 Kobe earthquake in Japan and the 1999 Chi-Chi earthquake in Taiwan whose damage grade as well as damage index are decided based on their damage level as described in the previous Sect. 2.1. Earthquake intensity, distance from fault, rock classification, tunnel length and overburden depth are considered as the earthquake damage factors while developing damage assessment model as mentioned in Table 2.

For analysis, least square method was used assuming damage index as a linear function. Total five governing parameters and "n" number of tunnels considered where number j factor has r_j categories when ith tunnel response is $\delta_{i(j.k)}$ ($j = 1 \ldots 5$). The damage function is represented as follows:

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

In the above mentioned mathematical equation, $b_{jk} (k = 1, 2, \ldots, r_j)$ is a coefficient; $e_i (i = 1, 2, \ldots, n)$ is a residual number for ith tunnel; $\delta_{i(j,k)}$ is the response of the factor j. The value of $\delta_{i(j,k)}$ will be equal to 0 if ith tunnel does not have category k for the factor j. The y_i mentioned in the above equation can be represented as $y = xb + e$ where coefficient "b" can be calculated using regression analysis based on the least square method which is represented in the following Table 3. Here, the correlation coefficient and stand deviation are 0.834 and 0.094, respectively.

Table 2 Tunnels damaged during 1995 Kobe and 199 Chi-Chi earthquake

Tunnel name	Earthquake intensity	Rock classification	Tunnel length (km)	Overburden depth (m)	Through the fault	Damage grade
Rokko	10	Hard rock	16.25	460	Yes	Severe
Kitakshi	10	Hard rock	6.91	350	Yes	Severe
Keihaku	10	Hard rock	1.8	20.25	Yes	Severe
Shinkobe	10	Hard rock	6.85	330	Yes	Moderate
Kobe	10	Hard rock	7.95	272	Yes	Moderate
Nishitakura	10	Hard rock	0.25	42	No	Minor
Nagasaka	9	Soft rock	0.63	20	No	Minor
Seikotsudaini	9	Hard rock	0.20	40	No	Minor
Getsnmi	9	Soft rock	0.31	45	Yes	Severe
Rokoyama	9	Hard rock	2.85	280	No	Minor
Takakura	9	Hard rock	0.58	87	No	Minor
Yekana	8	Soft rock	1.25	145	No	Minor
Gosha	8	Hard rock	0.12	40	No	Minor
Arima	8	Hard rock	0.45	6.5	No	Minor
Tonglu	7	Soft rock	0.33	6.3	No	No damage
Sanyi - 1	7	Soft rock	7.5	24.1	Yes	Severe
Sanyi - 2	7	Soft rock	0.52	3.5	No	No damage
Miaoli	7	Soft rock	0.98	4.5	No	No damage
Doufu	7	Soft rock	0.65	6.5	No	No damage

Modification of Damage Assessment Model

The damage assessment model was developed based on five important factors including earthquake intensity, distance from fault, rock classification, tunnel length and overburden depth. But from the historical earthquakes, it is clear that construction time also plays a role for tunnel damage as tunnels constructed after 1990 showed better performance when subjected to earthquakes in 1995 and 1999.

Tunnels construed before 1990 had small cracks in tunnel lining and not designed properly considering seismic loading conditions. In case of any major earthquake having intensity 9 or 10, the tunnel portals are affected a lot resulting into portal landslides. Hence, few more factors, construction time and seismic fortification strength as well as portal stability considered to modify the already developed damage assessment model. Following formula evaluated after doing regression using least square method.

Table 3 Factors considered and resulting coefficient for damage assessment model

Factor	Category	Coefficient	
		Calculated	Suggested
Earthquake intensity	7	−0.0911	0
	8	0.1840	0.03
	9	0.3144	0.3
	10	0.3712	0.4
Rock classification	Soft rock	0.0565	0.06
	Hard rock	0	0
Tunnel length (km)	<1 km	0	0
	>1 km	0.0696	0.07
Overburden depth (m)	<30	0.1565	0.15
	30–100	0.346	0.03
	>100	0	0.01
Through the fault	Yes	0.2891	0.22
	No	0	0
Construction time and seismic fortification strength	No fortification		0
	7 fortification		−0.03
	8 fortification		−0.12
	9 fortification		−0.18
	10 fortification		−0.22
Portal stability	Very bad		025
	Bad		0.17
	Good		0.1
	Very good		0

$$y_{i(modified)} = \sum_{j=1}^{7} \sum_{k=1}^{r_j} \delta_{i(j,k)} b_{jk} i = 1 \ldots n \tag{2}$$

In the above equation, the suggested coefficient "b" can be calculated using least square method represented in the following Table 3.

4 Conclusion

In a way to fulfill the needs of space and passage due to rapid growth in population and industrialization, sometime it becomes impossible to construct the tunnels in a seismically prone zones. From the historical earthquakes, we get a lesson that tunnels are subjected to damages ranging from no damage to collapse depending on earthquake intensity and other geological parameters. In this study, types of earthquake-induced tunnel damage as well as their damage mechanics discussed. Using the technique of regression analysis based on least square method, damage assessment model was developed considering tunnel materials affected during the 1995 Kobe earthquake and 1999 Chi-Chi earthquake. For this purpose, earthquake intensity, distance from fault, rock classification, tunnel length and overburden depth, construction time and seismic fortification strength as well as portal stability like factors considered which influence the tunnel damage. This technique is effective and feasible and helps to design the future tunnels considering seismic loading conditions. There are some other damage factors which are not considered in this study, but can be used for further research in a way to modify the existing damage formula. This study will be helpful to formulate and design the mitigation measures with the early warning systems as a part of hazard evaluation, which may eventually lead to less damage of the tunnel structures.

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