15th ISRM Congress 2023 & 72nd Geomechanics Colloquium. Schubert & Kluckner (eds.) © ÖGG

Seismic resistance evaluation based on earthquake damage survey data of mountain tunnels

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ABSTRACT: Tunnels constructed in the rock formation have been considered safe against earthquakes. However, the 1995 Hyogo-ken Nanbu Earthquake (M7.3) caused large damages to mountain tunnels as many as to other structures. Tunnels are one of the important infrastructures, so the evaluation of seismic resistance is a very important issue. Here damage reports on the 1923 Kanto Earthquake, the 1995 Hyogo-ken Nanbu Earthquake, the 2004 Niigata-ken Chuetsu Earthquake and others in total seven earthquakes are studied and the seismic resistance is evaluated as in the relationship between the seismic intensity and the damage rate. Using this relationship and the earthquake probability provided by official organization, the seismic risk that is very useful tool to plan appropriate earthquake countermeasures can be evaluated.

Keywords: Mountain tunnel, Seismic damage, Seismic resistance evaluation, Seismic risk.

1 INTRODUCTION

In Japan, which is well known for its frequent occurrence of earthquakes, the seismic resistance of various structures and facilities is important. So, researches and developments on seismic resistance based on many earthquake damage data have been carried out, and evaluation methods have been developed. Then specific seismic resistance standards have been established. However, mountain tunnels constructed in the rock have been considered to be resistant to earthquakes and specific seismic resistance has not been discussed till now.

However, recent major earthquakes have caused significant damage to mountain tunnels as same as various other structures (Kamemura, 2019). The seismic damage of infrastructural facilities such as tunnels is immeasurable social losses, not only due to the damage to the facilities themselves, but also to the impact on disaster response immediately after the earthquake and post-earthquake restoration activities by the loss of their function. Therefore, it is required to clarify the specific seismic resistance of tunnels in the rock.

In this paper, the relationship between the magnitude of seismic motion (seismic intensity) and the probability of damage is evaluated based on the results of surveys of major earthquakes that have caused damages to many mountain tunnels in order to evaluate the seismic resistance of tunnels. By using this relationship and the probability of earthquake occurrence at the tunnel location, the seismic risk that is a useful tool in the evaluation of the seismic resistance of specific mountain tunnels can be calculated.

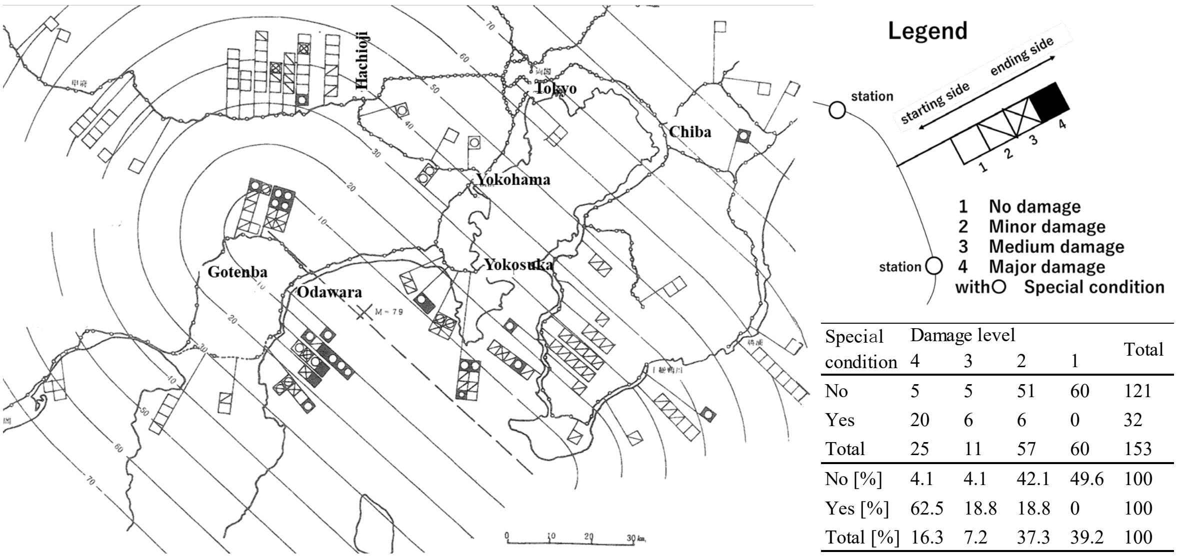
2 EARTHQUAKE DAMAGE OF TUNNELS AND SEISMIC INTENSITY

In Japan, many mountain tunnels have been damaged by large-scale earthquakes. Here, the survey results of tunnels damaged by seven earthquakes, including the Kanto Earthquake, are compared with an estimated seismic intensity distribution map to obtain the relationship between seismic intensity and damage rate.

2.1 Earthquake damage and seismic intensity in the 1923 Kanto Earthquake

First, the relationship between damaged tunnels and seismic intensity is studied for the 1923 Kanto Earthquake. This earthquake occurred on September 1, 1923 with M7.9 and caused extensive damage in a wide area including Tokyo and Yokohama. Yoshikawa (1979) examined the damage of tunnels based on the earthquake damage report published in 1927 and showed the result as in Figure 1.

The special condition of damaged tunnel in Figure 1 is the structural weakness of tunnel, such as (1) unstable topography and geology, (2) accident during construction, (3) deformation before the earthquake, and (4) under construction. Each damage level is then defined as shown in Table 1.



Special condition	Damage level 4	3	2	1	Total
No	5	5	51	60	121
Yes	20	6	6	0	32
Total	25	11	57	60	153
No [%]	4.1	4.1	42.1	49.6	100
Yes [%]	62.5	18.8	18.8	0	100
Total [%]	16.3	7.2	37.3	39.2	100

Figure 1. Damage to Tunnels by the Kanto Earthquake (Yoshikawa, 1979).

Table 1. Definition of seismic damage level.

Damage level	Minor damage	Medium damage	Major damage
Definition	Can be operated without countermeasures	Can be operated with protection works and emergency measures	Can be operated after improvement and emergency restoration
Image of damage (Digital Archives)	Crack initiation, opening and extension of existing cracks		

Until now, the relationship between seismic damage and seismic motion in such mountain tunnels has been discussed in terms of earthquake magnitude and distance from the epicenter. However, in order to evaluate the seismic resistance of individual tunnels, it is necessary to show the relationship between the magnitude of seismic motion acting on the structure and its seismic resistance, as is the case with buildings and other structures.

At the time of the Kanto earthquake, there was no scientific evaluation of seismic motions, and the distribution of seismic intensity that is currently provided by the Japan Meteorology Agency. Therefore, the result of the seismic intensity evaluated based on the earthquake damage data of buildings will be adopted. Figure 2 is the seismic intensity distribution map estimated by Moroi & Takemura (2002). Superposing this with Figure 1, the relationship between seismic intensity and damage rate can be obtained as shown in Table 2.

The results show that the damage rate of "medium" and "major" increase when the seismic intensity is 6+ or higher, and also that the presence of special conditions has a significant impact on the seismic resistance of tunnels.

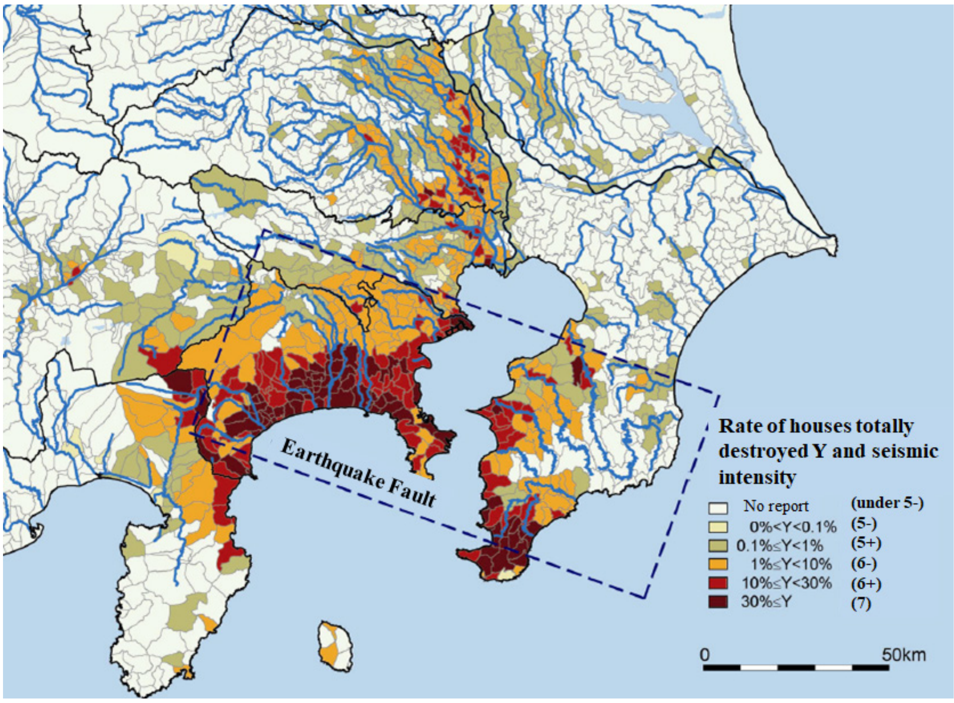


Figure 2. Estimated seismic intensity distribution for the Kanto earthquake (Moroi & Takemura, 2002).

Table 2. Tunnel damage and seismic intensity by 1923 Kanto Earthquake.

Special condition	Seismic intensity	Major damage	Medium damage	Minor damage	No damage	Total
No	7	3	3	13	4	23
	6+	1	2	15	2	20
	6-	0	0	9	10	19
	5+	1	0	14	18	33
	5-	0	0	0	26	26
	Total	5	5	51	60	121
Yes	7	14	3	4	0	21
	6+	4	0	1	0	5
	6-	1	1	0	0	2
	5+	0	2	1	0	3
	5-	1	0	0	0	1
	Total	20	6	6	0	32

2.2 Evaluation of relationship between damage rate and seismic intensity

Same process as the case of Kanto Earthquake is applied to examine the relationship between seismic damage and seismic intensity for a total of seven earthquakes shown in Table 3. By integrating the relationships for all seven earthquakes, the relationship between the probability of damage to mountain tunnels and seismic intensity is evaluated.

The presence of special conditions is particularly important because they affect the seismic resistance of the tunnel. For many damaged tunnels, information at the time of construction was investigated to explore the causes of the damage, and the presence of special conditions was evaluated. However, for tunnels evaluated as no damage, the presence of special conditions has not been investigated. In order to integrate the data, it is necessary to estimate how many tunnels with special conditions are included among the tunnels that have not been evaluated for the presence or absence of special conditions. Here, referring to the survey report concerning to the tunnels that encountered problems during construction, it is assumed that 20% of tunnels that were "no damaged" had special conditions, and all data was corrected. Table 4 and 5 show the results of integrating all data after unifying the classification of the surveyed tunnels for all earthquakes.

Table 3. Seven earthquakes examined for seismic damage of tunnels.

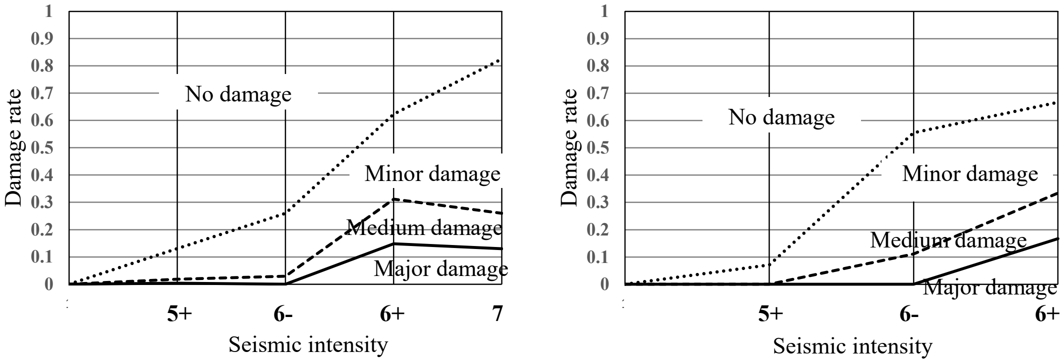
	Earthquake	Date	Magnitude	Surveyed Tunnel
1	Kanto	1923.9.1	7.9	153
2	Niigata	1964.6.16	7.5	103
3	Izu – Oshima	1978.1.14	7.0	36
4	Hyogo-ken Nanbu	1995.1.17	7.3	110
5	Niigata-ken Chuetsu	2004.10.23	6.8	137
6	Niigata-ken Chuetsu-oki	2007.7.16	6.8	20
7	Off the Pacific coast of Tohoku	2011.3.11	9.0	160

Table 4. Tunnel Damage and Seismic Intensity by 7 Earthquakes (Tunnels without Special Condition).

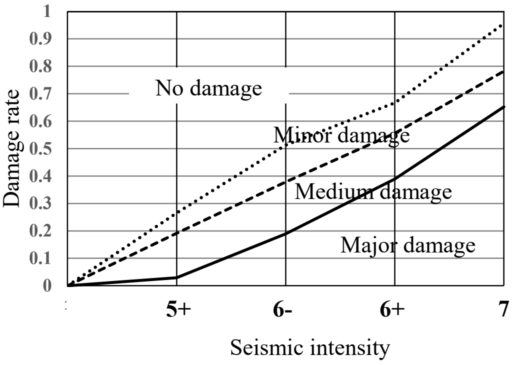
Seismic Intensity	Traditional Method (472 tunnels)				
	Major Damage	Medium Damage	Minor Damage	No Damage	Total
~ 5+	1	4	32	247	284
6-	0	3	24	77	104
6+	9	10	19	23	61
7	3	3	13	4	23
Total	13	20	88	351	472
	NATM (85 tunnels)				
~ 5+	0	0	5	65	70
6-	0	1	4	4	9
6+	1	1	2	2	6
Total	1	2	11	71	85

Table 5. Tunnel Damage and Seismic Intensity by 7 Earthquakes (Tunnels with Special Condition).

Seismic Intensity	Traditional Method (146 tunnels)				
	Major Damage	Medium Damage	Minor Damage	No Damage	Total
~ 5+	2	11	5	50	68
6-	7	7	5	18	37
6+	7	3	2	6	18
7	15	3	4	1	23
Total	31	24	16	75	146



a) Conventional method tunnel without special condition b) NATM tunnel without special condition



c) Conventional method tunnel with special condition

Figure 3. Fragility Curve (relationship between damage rate and seismic intensity).

Finally, fragility curves showing the relationship between damage rate and seismic intensity can be obtained as shown in Figure 3. The NATM tunnels with special conditions are omitted here because they are unreliable due to the small number of damage cases.

Figure 3a) shows the relationship between the damage rate and the seismic intensity for 472 conventional method tunnels without special conditions. Minor damage occurs at around intensity 5+ or higher, and "Medium" and "Major" damage requiring repair or reinforcement occurs at intensity 6+ or higher. The percentage of "Medium" and "Major" damages is about 15%, and does not increase even in the intensity 7. The same trend is observed for the NATM tunnels shown in Figure 3b), suggesting that the difference in the damage rate in tunnels without special conditions depending on the construction method is not so large.

On the other hand, in the conventional method tunnels with special conditions shown in Figure3c), "Medium" damage occurs at an intensity of 5+ or higher. And at an intensity of 6-, together with "Major" damage, significant damage occurs in approximately 40% of the tunnels.

The "Major" damage rate increases as the seismic intensity increased, and at seismic intensity 7, approximately 60% of the tunnels are damaged. It is clear that the special conditions have a significant impact on the seismic resistance of mountain tunnels, and how to deal with these special conditions is a next important problem.

3 SEISMIC RESISTANT EVALUATION USING SEISMIC RISK

It is difficult to appropriately determine the extent to which countermeasures should be taken for the major earthquake, which occurs rarely. Herein lies the importance how to evaluate quantitative indicators for highly uncertain earthquake damage in order to plan effective countermeasures.

Here, the seismic risk of mountain tunnels is quantified as the product of the probability of damage (P) and the loss (C) by using the probabilistic method used to evaluate various types of seismic damage. Since the 1995 Hyogo-ken Nanbu Earthquake, seismic risk assessment has been widely applied to buildings, houses, and other structures, as well as facilities and systems, and has been used to plan various seismic risk reduction measures.

Seismic risk assessment is performed according to the flow shown in Figure 4. First, a seismic hazard curve, which shows the relationship between the magnitude of seismic motion that may occur at a certain point and its probability of occurrence, is obtained based on the source characteristics of the assumed earthquake and the ground information at the tunnel location. As this hazard curve, one published by a public institution can be used, or an earthquake fault can be specified and determined by a probabilistic method.

On the other hand, for the tunnel to be considered, the seismic damage probability P from fragility curve and the loss cost C in the event of damage are evaluated, and a seismic loss curve is obtained from these two factors. A seismic risk curve is then obtained by eliminating the magnitude of earthquake motion common to the hazard and loss curves. Using this seismic risk curve, the effectiveness of various risk countermeasures to be evaluated and specific measures can be determined.

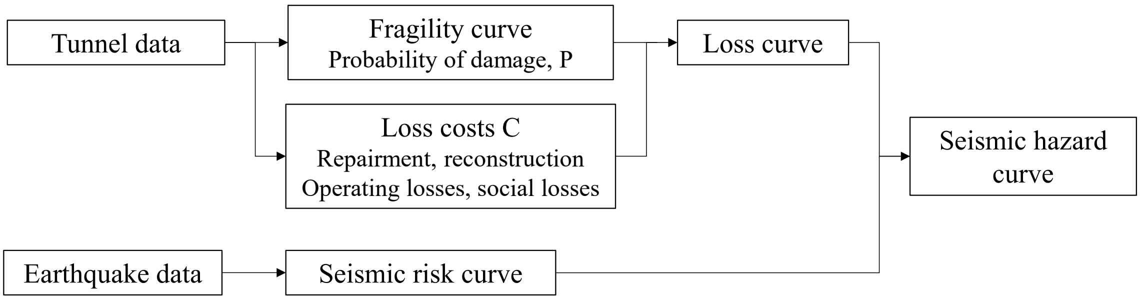


Figure 4. Flow for evaluation of seismic risk.

4 CONCLUSION

Damage survey data of mountain tunnels caused by 7 earthquakes was reviewed and seismic resistance was evaluated as the relationship between probability of damage and seismic intensity. Result shows that the seismic resistance of tunnels with special conditions which cause the structural weakness is very poor. And it is shown that seismic risk can be evaluated by using this relationship and the probability of earthquake occurrence at each tunnel location. Seismic risk is very useful to plan the appropriate seismic reinforcement.

From now on, the need for seismic reinforcement of tunnels should be examined according to the evaluation result of seismic risk. At the same time, seismic reinforcement methods should be established after clarifying the mechanical effects of special conditions on the seismic resistance of tunnels.

REFERENCES

Digital Archives, JSCE Library, Photos from the Great Kanto Earthquake, Earthquake Damage Survey Report 1926, from http://library.jsce.or.jp/Image_DB/shinsai/kanto/jsce_report/jscerp_02_04.html

Kamemura, K.2019. Seismic response and stability of rock tunnels - its history and problems today. In: *Proceedings of the 2019 Rock Dynamics Summit (RDS 2019),* Okinawa, Japan, 7-11 May, 2019, pp. 53-62.

Moroi, T. & Takemura, M. 2002. Re-evaluation on the Damage Statistics of Wooden Houses for the 1923 Kanto Earthquake and Its Seismic Intensity Distribution in and around Southern Kanto District. In: *Journal of JAEE, Vol.2, No.3*, 2002, pp. 35-71. (in Japanese)

Yoshikawa, K. 1979. Investigations about Past Earthquake Disasters of Railway Tunnels. *Railway Technical Research Report 1123*, The Railway Technical Research Institute, Japanese National Railways, Japan (in Japanese)