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Seismic response and stability of rock tunnels–its history and problems today

K. Kamemura
Fukada Geological Institute, Tokyo Japan

ABSTRACT: In Japan, a lot of underground structures has been constructed and they are in service in spite of complex and poor geological conditions. On the other hand, Japan is famous for the big earthquakes resulting a huge national loss, thus the aseismic design to prevent the severe damage of structures is very important. Though many buildings and structures are designed considering earthquakes, the aseismic design of structures constructed in deep underground has not been well discussed up to now. In this paper, the historical background of aseismic design is reviewed and typical seismic damages of rock tunnels are presented. And the present situation of static and dynamic design for underground structures ranging from the cut and cover tunnels in the shallow underground to the rock tunnels in deep rock formation is presented. Then problems to establish a practical method of aseismic design for the rock tunnels is discussed.

1 HISTORY OF ASEISMIC DESIGN OF UNDERGROUND STRUCTURES

Underground structures are utilized for various purpose and playing an important role as a social infrastructure. They are classified into the following three types according to the construction method, namely cut and cover tunnel, shield tunnel and drill and blast (rock) tunnel (including caverns). Typical shape and scale of these structures are shown in Figure 1.

As Japan is famous for big earthquakes resulting a huge national loss, thus the aseismic design is very important for every kind of structures. Today we have a strict regulation concerning to the aseismic design of buildings and a various kind of civil structures. It has to have a long way to result in this situation and even now we are repeating "Lesson and Learn".

According to the Japanese standard for tunneling of Japanese Society of Civil Engineering (JSCE), and other aseismic design related documents, the history of aseismic design for buildings and underground structures can be summarized as follows.

Aseismic design in Japan started in 1923 taking the opportunity of the Great Kanto Earthquake. It was the very first huge earthquake that had hit the modernized metropolitan area with magnitude of 7.9. Up to 100,000 people died and about 300,000 houses were collapsed or burnt out. The enormous damage occurred in the lifeline and the life of the citizens was seriously.

As a result of serious damages by Kanto Earthquake, aseismic design regulation for buildings with a horizontal seismic intensity of 0.1 was set in 1924. This is the world's first aseismic design standard. Table 1 shows the major earthquakes following to the Kanto Earthquake and corresponding situation in the area of design for buildings and tunnels. As shown in Table 1, aseismic design of buildings have been improved in each time of the serious seismic damage occurred. However, nothing had been done on the tunnels until 1995 Hyogo-ken Nanbu Earthquake, in spite of the serious damages on the tunnels.

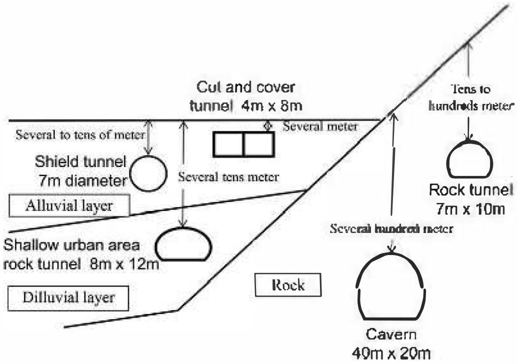

Figure 1. Various kinds of underground structures

1.1 *Kanto Earthquake And Damage Of Tunnels*

In the Kanto Earthquake, 93 tunnels out of the 149 tunnels (including under construction) of national railway were damaged and repaired. Those tunnels were within the range of about 120 km from the epicenter.

The most severe damage can be seen in seven tunnels out of 11 tunnels located between Odawara and Manazuru of Atami line (present Tokaido Line). They were locating near to epicenter with the distance of 20-25km.

Table 1. Major earthquakes and aseismic design

Earthquakes and aseismic design		
1923.9.1		**Great Kanto M=7.9**
	[Buildings] In 1924, Urban Building Law to be the world's first earth-quake resistance regulation (**seismic intensity 0.1**) was enact. [Tunnels] non	
1930.11.26		Kitaizu M=7.3
1943.9.10		Tottori M=7.2
1944.12.7		Toh-nankai M=7.9
1945.1.13		Mikawa M=6.8
1946.12.21		Nankai M=8.0
	Because of World War II, damages were not made public and nothing was feedback to aseismic design	
1948.6.28		**Fukui M=7.1**
	[Buildings] The seismic intensity method was examined and the necessity of dynamic analysis were discussed, and in **1950** the Building Standard Law (**seismic intensity 0.2**, idea of long-term and short-term stability) was enacted.[Tunnels] non	
1964.6.16 Niigata M=7.5		
1968.7.9 Tokachi-oki M=7.9		
1978.6.12 Miyagiken-oki M=7.4		
	[Buildings] In **1981**, the Building Standards Law was revised. In new aseismic design method reflecting the concept of **dynamic design method**, seismic force is set according to the vibration characteristics of buildings, and earthquake resistance is calcu-lated.[Tunnels] non	
1983.5.26 Nihonkai-chuubu M=7.7		
1993.7.12 Hokkaido-nanseioki M=7.8		
1995.1.17 Hyougo-ken Nanbu(Great Hanshin Awaji) M=7.3		
	[Tunnels] In **1996,** Tunnel Standards states that further investigation is in need after clarifying the importance of aseismic design due to the damage of the tunnel structure by the Hyogo ken Nanbu Earthquake. [Tunnels] In **1998**, Aseismic design of **cut & cover tunnel** was pub-lished. [Buildings] In **2000**, the Building Standards Law was revised again and the **performance design method** was introduced. [Tunnels] In **2006, t**he tunnel stand-ard specified aseismic design for **shield tunnels** as well as cut & cover tunnels, and aseismic design has been in practice.	
2011.3.11 Great East Japan M=9.0		
The largest earthquake observed around Japan		
2016.4.14/16 Kumamoto M=6.5 and 7.3		
In the latest 2016 tunnel standard for rock tunnel, only a basic idea of earthquake resistance is stated and detailed discussions are not described.		

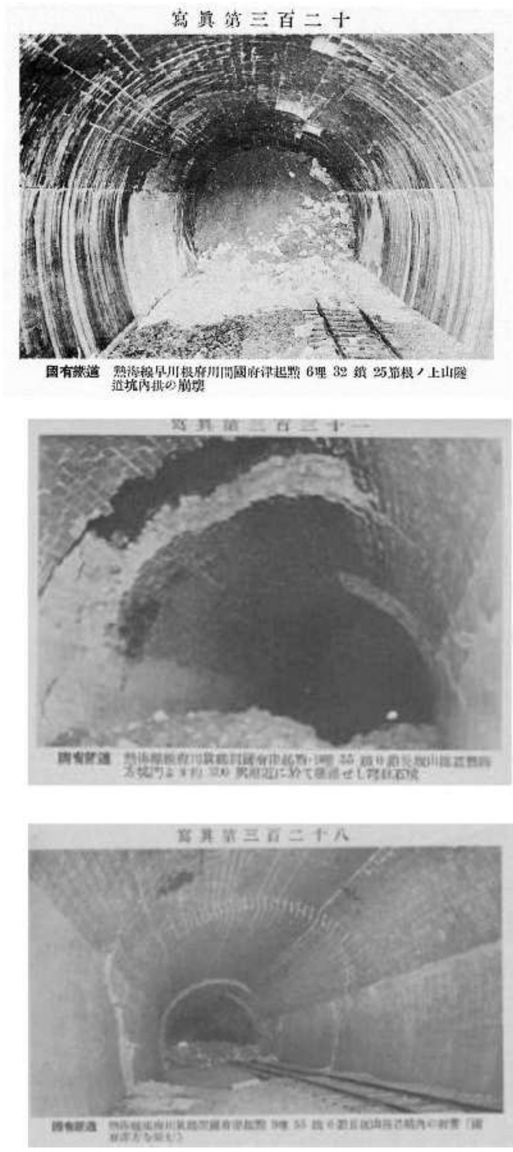

Photo 1. Damage of rock tunnel by Kanto Earthquake in 1923 (from National Diet Library Digital Collections, http://dl.ndl.go.jp/info:ndljp/pid/1175815)

Landslides and slope failures caused collapse and burying near the portals, and cracks and cross sectional deformation occurred even in locations away from the entrance. Photo 1 shows examples of tunnel damage.

In 1927, the Ministry of National Railway published a report on the survey results of every kind of facilities related to the railway, and that concluded about the seismic damage of tunnel as follows;

The most of damage of railway tunnels is;

- crack of arch
- crack of side wall
- break of arch
- break of entrance

Most of them can be seen near the entrance and not so many in the central part of tunnel. However, if the central part is in the condition of;

- soft soil/rock
- thin overburden
- fault part or changing hard to/from soft part

there are some serious damages such as crack or collapse.

In addition, those with significant damage near the entrance are necessarily causing slope failure of upper part of the entrance.

1.2 *Hyogo-Ken Nanbu Earthquake and aseismic design of underground structures*

The Hyogo-ken Nanbu Earthquake in 1995, with magnitude of 7.3, was the earthquake causing a largest national loss after World War II until The Great East Japan Earthquake in 2011. More than 6,000 lives were lost, more than 110,000 houses were collapsed or burnt out, and enormous damage also occurred in the lifeline.

Taking these seismic damages seriously, discussions concerning to the seismic resistance of underground structures finally started. The first description on the earthquake resistance of underground structures can be found in the standard of 1996 year edition. It says"Based on experience of the damage of the underground structures by the 1995 Hyogo-ken Nanbu (or Great Hanshin-Awaji) Earthquake, it is necessary to clarify the importance of aseismic design and further investigation should be done."

Photo 2 shows a typical damage of subway station, which was constructed by cut and cover tunneling method in Kobe city. Center pillars were buckled and ceiling subsided. This subsidence was reached to the ground surface.

In 1998, "Aseismic design of Cut and Cover Tunnel" was published by JSCE, and specific concept and method for the examination of aseismic design were presented. Next, in the standard for shield tunneling published in 2006, the aseismic design of shield tunnels in soils was discussed in detail.

For aseismic design for shallow depth underground structures such as cut and cover tunnel and shield tunnel, seismic deformation method, seismic

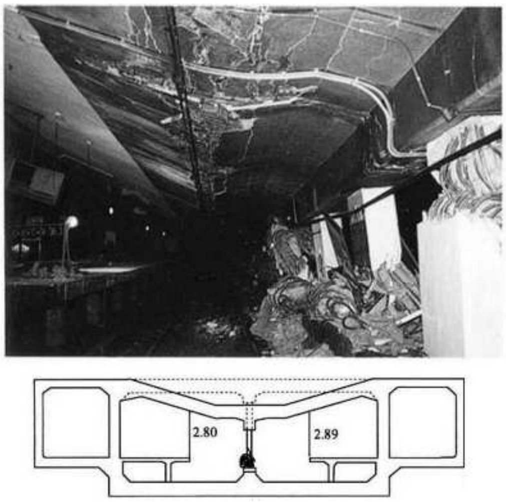

Photo 2. Damage of subway station by Great Hanshin-Awaji Earthquake in 1995 (Kobe Rapid Transit Railway Co. "Record of Disaster Recovery of Tozai Line Daikai Station". Sato Kogyo Co. 1997.1. Great Hanshin-Awaji Earthquake Disaster Materials Collection, Kobe University Library,http://www.lib.kobe-u.ac.jp/directory/eqb/book/11-276/index.html)

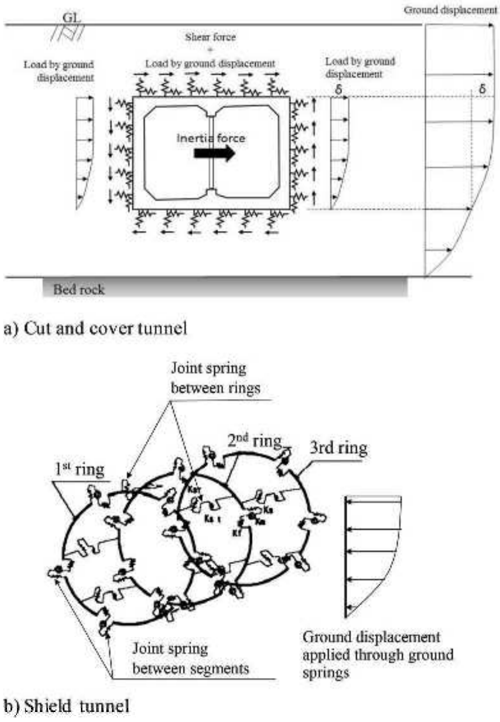

Figure 2. Analysis model of seismic deformation method

intensity method and dynamic analysis are established and aseismic design of these structures has become common in practical design. Example of seismic deformation method for cut and cover tunnel and shield tunnel are illustrated in Figure 2.

Photo 3. Damage of pilot tunnel of Tanna tunnel by Kitaizu Earthquake in 1930 (Kobe University Library, News Paper Archive: http://www.lib.kobe-u.ac.jp/das/jsp/ja/ContentViewM.jsp?METAID=00102374&TYPE=PRINT_FILE&POS=8)

However regarding the tunneling in rock, the latest 2016 Standard for mountain tunneling have little touches on earthquake resistance. Although basic knowledge on seismic damage of rock tunnels has been stated, it does not mention specific concept and how to design.

This is probably because the knowledge needed to examine the earthquake resistance of the rock tunnel is not sufficient yet.

2 SEISMIC DAMAGE OF ROCK TUNNEL

In this section, a typical seismic damage of rock tunnel is reviewed and study result concerning to the damage of rock tunnel is shown.

2.1 *Kitaizu Earthquake In 1930(Magnitude 7.3)*

The Kitaizu Earthquake occurred due to the activity of Kitaizu fault system, and was a near-field earthquake. Survey after the earthquake revealed many faults and the largest Tanna fault among them was reported to be about 35 km in length and moved 2.4 m in vertical and 2.7 m to the north. This fault intersects the Tanna tunnel under construction for the new line of the Tokaido Line (current Gotemba Line), and as Photo 3 shows, the cross section of pilot tunnel is completely blocked due to a large shear displacement. This is a typical tunnel damage due to fault displacement

2.2 *Notohanto-oki Earthquake in 1993 (Magnitude 6.6)*

In the Notohanto-oki Earthquake, Kinoura tunnel was heavily damaged as shown in Photo 4. Tunnel crown fell down together with the upper loosened rock and its repair required several months. This tunnels was within the range of about 120 km from the epicenter.

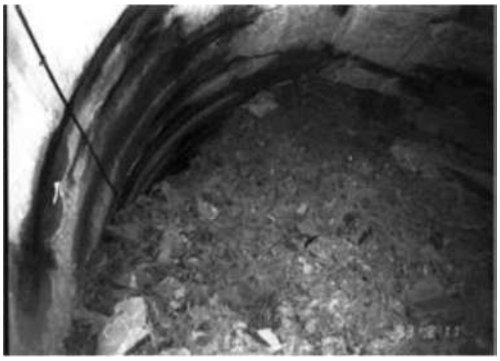

Photo 4. Damage of Kinoura tunnel by Notohanto-oki Earthquake in 1993 (provided by MLIT Hokuriku Regional Development Bureau)

2.3 *Niigata-ken Chuetsu-oki Earthquake in 2004 (Magnitude 6.8)*

The vicinity of epicenter of the Chuetsu-oki Earthquake is a mountainous area, and many rock tunnels have been constructed for various uses. As the result, many rock tunnels were damaged which had never been experienced after the Kanto Earthquake. Photo 5 shows a damage of road tunnel, where the concrete lining of tunnel crown was fallen down.

In this case, as the result of detailed investigation of tunnel damage, it was concluded that a large repairs was not necessary and restoration with installation of steel rib and shotcrete could be carried out without closing the road. As seen in this photo, the rock behind tunnel lining did not collapsed and was in a stable state although the concrete lining collapsed.

2.4 *Kumamoto Earthquake in 2016(Magnitude 7.0)*

The damage of Tawarayama tunnel near the earthquake source fault is shown in Photo 6. This road tunnel is located in the distance of about 0.5 - 1.5 km from the fault, and a large scale of lining concrete collapsed from tunnel crown.

Photo 5. Damage of Wanatsu tunnel by Chuetsu Earthquake in 2004 (provided by MLIT Hokuriku Regional Development Bureau)

Photo 6. Damage of Tawarayama tunnel by Kumamoto Earthquake in 2016 (Ministry of Land, Infrastructure, Transport and Tourism. Report on the seismic damages of road structures, http://www.mlit.go.jp/common/001136053.pdf

2.5 *Cause of Seismic Damage*

Through these tunnel damages due to recent large earthquakes, especially many tunnel damages of railroads, roads and waterways in the Chuetsu Earthquake in 2004, tunnel engineers have realized that the vaguely belief "rock tunnels have sufficient earthquake resistant" is not right anymore. And many researches related to the mechanism of seismic damage in rock tunnels have started after the Chuetsu Earthquake.

Yashiro et al. 2009 examined the structural damage of rock tunnel caused by the earthquake and discussed the mechanism of the damage. Number of damaged tunnel in the afflicted area of investigated earthquake is listed in Table 2, where the damage of rock tunnels is classified into 4 levels. Yashiro also pointed out that the damage of the rock tunnels can be classified into the following three types.

① Damage in the area of portal or shallow overburden section
② Damage in the area of weak rock/fracture zone
③ Damage due to fault displacement

Table 2. Number of damaged tunnels in major earthquakes

Earthquake(Max. Intensity)	Level of tunnel damage* L	M	S	None	Total
Kanto, 1923	25	12	56	55	148
M 7.9 (7)	(17)	(8)	(38)	(37)	(100)
Izu, 1978	2	4	3	22	31
M 7.0 (5)	(6)	(13)	(10)	(71)	(100)
Hyogo, 1995	12	0	18	80	110
M 7.3 (7)	(11)	(0)	(16)	(73)	(100)
Chuetsu, 2004	11	14	24	89	138
M 6.8 (7)	(8)	(10)	(17)	(65)	(100)
Chuetsu-oki, 2007	4	1	1	14	20
M 6.8 (6S)	(20)	(5)	(5)	(70)	(100)

* Level of damage
L: Large=Large scale repair is required.
M: Medium=Repair is required.
S: Small=Repair is not required

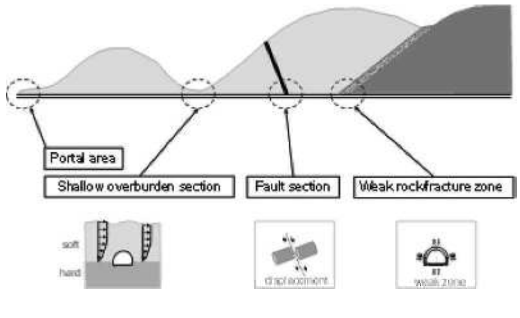

Figure 3. Patterns of seismic damage of rock tunnel (based on Yashiro et al. 2009)

Images of these damage pattern is shown in Figure 3.

It should be noted that the damage types shown here is almost same as the damage patterns concluded in the damage survey report of the Kanto Earthquake in the previous section 1.1.

Investigated result showed the major pattern of "Large" level damaged tunnel shown in Table 2 is "Damage in the area of weak rock zone". Therefore, many researchers had conducted numerical analysis (static and dynamic) and experimental studies using static loading devices in order to clarify the mechanism of seismic damage in rock tunnels.

As a result, followings were pointed out. Damage is likely if a void between lining concrete and rock exists near the tunnel crown. Installation of invert section can improve the rigidity of the entire tunnel structure, and also makes it possible to suppress the deformation of lining and uplift of the bottom.

However, it was very difficult to explain the destructive concentration of stress near the tunnel crown by numerical analysis and experimental studies under the static loading condition of forced displacement.

On the other hand, the results of a few examination in the dynamic conditions indicated the effect of dynamic ground motions could not be explained by the static conditions. Therefore, it seems necessary for further investigations, whether examination result considering dynamic effect shows same result by the static examination related to the damage mechanism and reinforcement effect, or not.

3 SEISMIC DAMAGE MECHANISM OF ROCK TUNNEL

3.1 *Seismic damage and tunnel condition*

In 2005, Tunnel Engineering Committee of JSCE, started up "Niigata-ken Chuetsu Earthquake Special Subcommittee" and compiled the whole situation of the damaged tunnels, such as roadway tunnels, railway tunnels, and conduits. Number of surveyed tunnel was up to 138, and the damage level of each tunnel was classified into 4 levels as shown in Table 2.

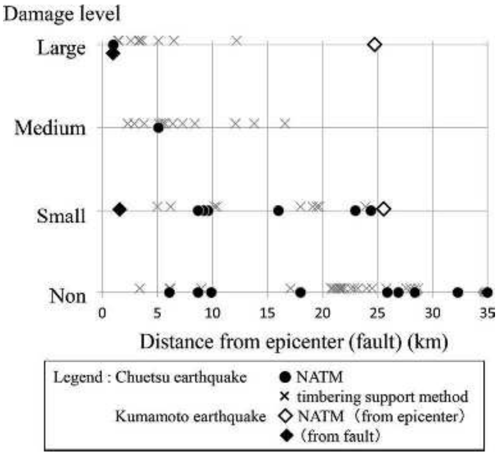

Figure 4 Relationship between damage level and distance from epicenter (fault)

Figure 4 shows the relationship between the distance from the epicenter and the damage level of each tunnel, where tunnel construction method is also shown. In the tunnel by timbering support method (conventional tunneling method), large and medium damage has occurred even if it is 10 km or more away from the epicenter. On the other hand, tunnels by NATM are heavily damaged only within the distance of 5 km. A big difference in earthquake resistance between tunnels by the conventional method and that by NATM tunnels is obvious.

From the three damage types shown in 2.5 and the results of Figure 4, the relationship between the seismic damage of the rock tunnel and the distance from the epicenter or fault can be conceptually summarized as shown in Figure 5 and Table 3.

If the tunnel is located close to or crossing an earthquake fault, or there are geological structures such as faults, fracture zones and inhomogeneity, the potential of large seismic damage increases. Especially with a structural weakness such as a void between lining and surrounding rock, the possibility of damage becomes higher.

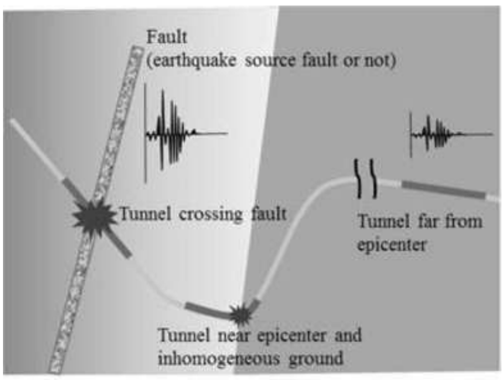

Figure 5. An illustration of the relationship among location and geological condition of a tunnel and seismic damage.

Table 3. Tunnel conditions and seismic damage

Location and effect of carthquakc	Geological condition	Structural wcakncss	Seismic damagc
Crossing fault Fault displacement	Fault	-	Largc
Near fault Large seismic motion	Inhomoge-neous	Yes	Large
		No	Large ~medium
	Homogene-ous	Yes	Medium ~ small
		No	Small
Far from fault Small seismic motion	Inhomoge-neous	Yes	Medium ~ small
		No	Small
	Homogene-ous	Yes	Small
		No	None

3.2 *Mechanism of seismic damage*

Considering these results of examination together with the damage examples shown in Section 2, the mechanism of the seismic damage of rock tunnel can be summarized as illustrated in Figure 5

Pattern A: Seismic motions increase the strain of the rock surrounding tunnel and tunnel, and the lining which cannot withstand that strain increase is damaged. Damages of this pattern have been observed as crack in concrete lining and deformation of roadbed in many tunnels. In some cases, large collapse of concrete lining has occurred (Photo 5, 6).

This strain increase is greatly affected by the rigidity of rock around tunnel, the depth of overburden and the presence of the slope on the ground surface. In order to perform the original function of tunnel lining against this strain increase, it is necessary for the tunnel to be integrated with the surrounding rocks. In this point of view, the void existing between the lining and rock has a large influence. It is very important to investigate voids and fill by grouting.

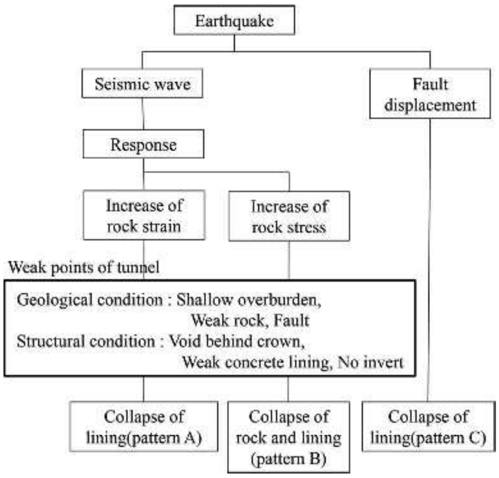

Figure 6. Effect of earthquake and patterns of seismic damage of tunnel

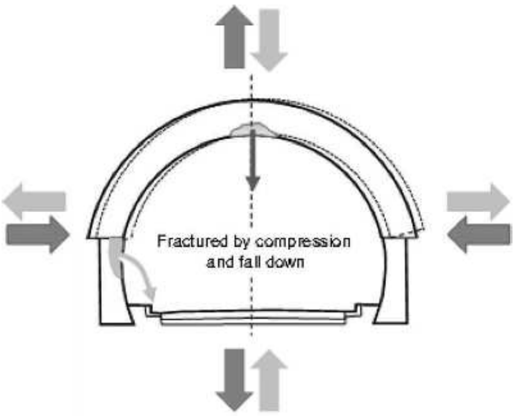

Figure 7. Seismic damage of tunnel: Pattern A

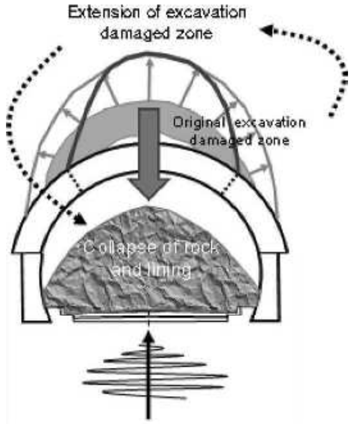

Figure 8. Seismic damage of tunnel: Pattern B

For this pattern, lining with high yield strength that can accommodate the seismic motion of the surrounding rock will be effective. Also a cushioning material between tunnel lining and surrounding rock may be able to reduce the strain increase of tunnel. Grouting to surrounding rock may increase the rigidity of surrounding rock and can reduce the strain increase of surrounding rock and tunnel.

Pattern B: Strain of the rock surrounding tunnel is increased by the seismic motion, and the rock is damaged. Increase of damaged zone of rock causes the increase of rock pressure acting on the tunnel lining, and lining will break. This type of damage has been observed in some tunnels (Photo 4).

In case of a large damaged zone (plastic zone) is already resulted around the tunnel during tunnel excavation, this damaged zone is subjected to strain increase (stress increase) due to the earthquake as an additional external load and is further extended. Additional load due to this enlargement of damaged zone acts on the lining and in case of the lining cannot bear, the lining breaks and then falls down together with the damaged rocks. Especially when there is the void between lining and surrounding rock, the rock easily yields and the lining resistibility against rock pressure decreases, so that the lining is highly likely to collapse.

For this pattern, the integration of surrounding rock and tunnel lining is effective in order not to enlarge the damaged zone around tunnel. This may be possible by means of grouting to the void between lining and surrounding rock and by the placement of rock-bolts. On the other hand, grouting to the damaged zone may improve rock strength and reduce the enlargement of loosened zone due to the earthquake.

Pattern C: Permanent displacement will occur in the fault zone crossing the tunnel due to seismic motion and will fracture the lining. This type of damage was seen in the Tanna tunnel by Kitaizu Earthquake in 1930 (Photo 3).

Many faults in various scales can be usually seen during tunnel excavation. If such faults cause permanent shear displacement due to the earthquake, they act as forced displacement against the tunnel, so that the structural damage of the tunnel is inevitable. However, it is very difficult to know which fault will move and how much displacement will occur, beforehand.

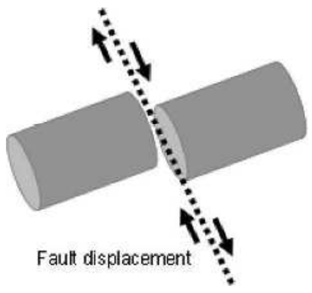

Figure 9. Seismic damage of tunnel: Pattern C

For this pattern, a buffer zone using deformable material around the tunnel is proposed. It is expected that this kind buffer zone can reduce the direct effect of permanent displacement of the fault due to the earthquake on the tunnel structure. However, such measures are not effective as long as the fault displacement due to the earthquake cannot be specifically estimated, so it seems difficult to apply this countermeasure to rock tunnels.

4 FURTHER PROBLEMS TO BE STUDIED

From the survey and relating study on tunnel damage caused by the recent earthquakes, as shown in Section 3, rough image on the mechanism of seismic damage has been clarified. Namely, if it is possible to know the positional relationship between the tunnel to be examined and the earthquake fault in the vicinity, and the geological condition around the tunnel, necessary and effective countermeasures may be decided.

However, it is not so easy to design the practical countermeasure for existing tunnel and newly

Table 4. Features in the design of cut and cover tunnel

cut and cover tunnel		
geological condition	–	can be estimated by shallow boring
	–	mechanical properties of soil can be evaluated by laboratory test
underground water	–	can be clarified by survey
quality of structure	–	reinforced concrete
	–	easy to control the quality because of open air construction
surrounding ground	–	ground around structure is back filled so its quality can be controlled
seismic design	–	static and dynamic analysis are applied

Table 5. Features in the design of shield tunnel

shield tunnel		
geological condition	Same as cut & cover tunnel	
underground water	Same as cut & cover tunnel	
quality of structure	–	reinforced concrete
	–	quality is clear because of plant product
surrounding ground	–	ground around structure is little affected by excavation
seismic design	Same as cut & cover tunnel	

Table 6. Difficulties in the design of rock tunnel and cavern

Rock tunnel and cavern		
geological condition	–	only rough condition can be estimated by limited information in advance
	–	can be clarified through the data obtained during excavation
	–	mechanical properties of rock mass is difficult to evaluate because of discontinuities
underground water	–	difficult to clarify by survey
	–	unexpected water inflow will cause difficulties
quality of structure	–	plain concrete
	–	difficult to control the quality because of in-situ condition
surrounding ground	–	EDZ(excavation disturbed zone) is created
	–	character of EDZ is hard to evaluate
	–	ground water condition may change and affect the construction
seismic design	–	usually not carried out

constructed tunnel. Because, we still have many problems to be solved as follows.

In Tables 4, 5 and 6, existing design methods of underground structures are summarized from the viewpoint of performance evaluation. Comparing these tables, it is clear that the situation of rock tunnel in the deep underground is very different from that of tunnels in the shallow soil ground. Many uncertainties and unknowns are still remaining in the evaluation of performance of rock tunnels and caverns, so the aseismic design of these deep rock structures is not easy to generalize.

For the structures constructed in the soft ground such as cut & cover tunnel and shield tunnel, ground conditions can be clarified by shallow boring and laboratory tests, and of course many of laboratory test are prescribed by standard. The groundwater condition also can be clarified by survey. And these structures are made by reinforced concrete, which is constructed in open air condition or is manufactured in plant, so the quality of structure is easy to control. Also, there is no need to worry about the existence of excavation damaged zone which may affect the seismic behavior of structure and surrounding ground. That is, it is easy to clearly define the static stress condition which is the initial condition of the aseismic analysis, and seismic design condition such as boundary condition and material parameter of ground.

On the other hand, as shown in Table 6, many uncertainties and unknowns are still remaining in the evaluation of performance of rock tunnels and caverns. First of all, detailed geological condition around tunnel is not so clear in the design stage because the survey in rock tunnel are usually limited to few borings and field investigation. And even in the completion of construction, we only know the geological condition around the tunnel through the tunnel face observation. So in order to make the aseismic design of deep rock structures practical, following problems should be examined, besides discussing about the method to know more detailed geological condition.

Seismic motion or fault displacement as external load is unknown:

In order to carry out the aseismic analysis, seismic motion or fault displacement should be set up as a loading condition. However there has been no well-established method to evaluate the seismic motion that may possibly occur in tunnel and its surrounding rocks under the deep rock condition. Moreover, it is impossible to judge whether the fault that crosses the tunnel would move or not by the earthquake and how much displacement would occur in case of relative slip.

Stress condition (or safety factor) of tunnel in use is unknown:

As the initial condition of aseismic analysis, the current stress and strength condition (namely safety factor) are important. However it is difficult to have a detailed information about those conditions of the existing tunnel and surrounding rock. Because, it has been common that the performance of the tunnel at the completion of construction has not been evaluated by means of comparing the construction result with that of requested in the design, so far.

There are remaining a lot of uncertainties and unknowns such as the existence of the void between lining concrete and rock, unevenness of excavated surface, actual thickness of lining concrete, location of reinforcing steel bar and so on. Moreover, it is very rare to discuss the difference of geological condition between that of assumed in the design stage and that of clarified in the excavation, and its influence on the tunnel stability at the time of completion. So it is almost impossible to evaluate the safety of the tunnel in use.

Function of concrete lining:

Another important and difficult problem is that the mechanical function of tunnel lining is not clear. Usually tunnel lining is constructed using plain concrete, and there is no design method for the plane concrete lining.

How to evaluate and analyze the mechanical function and the performance of plain (not reinforced) concrete lining of the existing rock tunnel in the aseismic design, may be a problem to be solved first in the discussion on the aseismic design of rock tunnel.

5 CONCLUSIONS

As mentioned in Section 1, since the Hyogo-ken Nanbu Earthquake, research on the seismic resistance of rock tunnels has been undertaken by many research institutions and companies, and the obtained results have been presented at related societies. However, standard as the final target of these researches has not been established up to now.

So what is important to establish the standard? Here, I would like to show a former research result which is describing how to proceed the study on earthquake resistance evaluation of tunnels.

Okamoto, one of the most famous earthquake engineers, et al. 1963 said in their paper titled "On the seismic force acting on structures under the ground" about seismic damage of tunnels as follows;

"Although the tunnel lining is often damaged by the earthquake, there is no empirical formula or theoretical expression to evaluate the behavior at the time of the earthquake. It is a fact that the aseismic design is made only by experiences.

Therefore, establishment of the theory of seismic stress calculation is desired, but there is no other way than to establish a method of analysis step by step considering various environmental conditions. And the accumulation of such theories and analysis, related to the surveyed seismic damage, will eventually give a sufficient engineering solution to this difficult problem."

These are exactly right pointing out, and the fact that this was already made in 1963 is surprising. The first thing to do may be to reflect on that practical actions have not been taken for a long time.

As discussed in 4.2, it is necessary to solve many problems in order to evaluate the earthquake resistance of rock tunnel and this will have a long time. On the other hand, it is also necessary to take appropriate measures as soon as possible to prevent the damage caused by the structural or geological weak-points of the newly planned tunnel.

On this point of view, although it is not the standard yet, guidelines concerning to the countermeasures has been prepared based on the accumulated discussion on the seismic resistance of rock tunnels up to now. For example, in March 2017, Road Bureau of Ministry of Land, Infrastructure, Transport and Tourism issued the following notice. It is titled as "Points to be noted about aseismic countermeasures for road tunnels on the basis of the Kumamoto earthquake in 2016" and is stating about seismic countermeasures in road tunnel as follows;

1) Special condition of the tunnel considered to be possibly damaged by the earthquake

1-1: Sections where long-term interruption of construction is enforced due to sudden massive groundwater inflow or equivalent thereto

1-2: Sections where construction has been suspended for a long time due to the large scale collapse of the face

1-3: Sections using large-scale countermeasures against for the instability of the rock

1-4: Sections where the geological condition has suddenly changed and two or more ranks of support patterns have been changed (Excluding the connected section with the entrance section)

1-5: Sections where the mechanical property of the rock dynamically changes in longitudinal and/or cross sectional direction

1-6: Sections subjected to unsymmetrical large earth pressure

1-7: Sections where the earth covering is extremely small

1-8: Sections where rock classification is evaluated as D2 or worse (including faults and fracture zones)

2) Supporting in the section with special condition

2-1: Make the tunnel into a ring structure with an invert and make the structure more mechanically stable

2-2: Apply sufficient amount of supporting such as shotcrete, steel rib and rock bolts

2-3: Even if the arch concrete is damaged due to the earthquake, to avoid the fall of large scale concrete blocks, reinforcing with the single steel bar and other is applied

We are still on the way to establish the effective seismic design method for existing and planned tunnels. Many numerical analysis and laboratory model experiments are carried out to search the effective and possible measures to prevent the seismic damage.

However, we must pay careful attention on the evaluation of the results of such studies, because in the numerical analysis and model test, a limited number of analysis and testing conditions is assumed. From those results, we can understand the qualitative effects of aseismic measures, however many problems that should be clarified from the viewpoint of quantitative evaluation are still remaining. In fact, some results of previous research show the inconsistent results between static analysis and dynamic analysis. And some other case show the difference of seismic behavior between model experiment and numerical analysis. Namely, more and more studies and discussions are needed to establish a practical methodology both in the aseismic retrofitting of existing tunnels and in the aseismic design of new tunnels.

In order to evaluate the performance of rock tunnel and to take appropriate aseismic measures, it is most important that stakeholders join together and start discussions. At the same time, we must accumulate analytical and experimental studies from various perspectives on the behavior of tunnels during earthquake. Of course, in those studies, it is very important to focus on the discontinuity of rock and the rock dynamics which have not been well discussed so far.

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