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# Some considerations on the stability and design of underground structures during earthquakes

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ABSTRACT: In Japan, many underground structures have been constructed and are in service in spite of complex and poor geological conditions. On the other hand, Japan is famous for big earthquakes resulting a huge national loss, thus the seismic design is very important for every kind of structures. However, the seismic design of underground structures, especially mountain tunnel, has not been well discussed up to now, while mountain tunnels were also severely damaged in the recent earthquakes. Therefore, the seismic design for the underground structures should be discussed as an important and urgent problem.

Here the present situation of the seismic design for underground structures ranging from the cut-and-cover tunnels in the shallow underground to the rock tunnels in deep rock mass is briefly reviewed. Then, typical earthquake damages of rock tunnels are presented and problems to establish a proper method of seismic design for the underground structures are discussed.

## 1 CURRENT STATUS OF SEISMIC DESIGN OF UNDERGROUND STRUCTURES

Underground structures are utilized for various purposes and play 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.

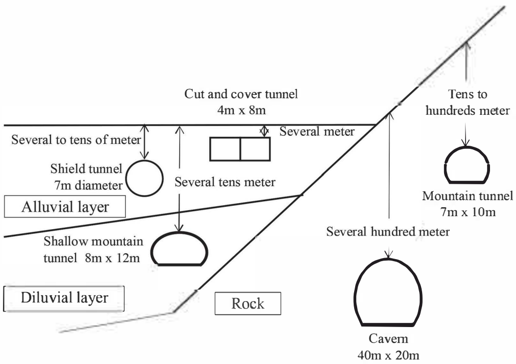


Figure 1. Various kinds of underground structures.

According to the Japanese standard for tunneling of Japanese Society of Civil Engineering, the historical change in the seismic design of underground structures can be summarized as follows.

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 seismic design and further investigation should be done."

Photo 1 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 "Seismic Design of Cut and Cover Tunnel" was published, and specific concept and method of examination were presented. Next, in the standard for shield tunneling published in 2006, the seismic design of shield tunnels in soils was discussed in detail.

For seismic design for shallow depth underground structures such as cut and cover tunnel and shield tunnel, seismic deformation method, seismic intensity method and dynamic analysis are established and seismic design of these

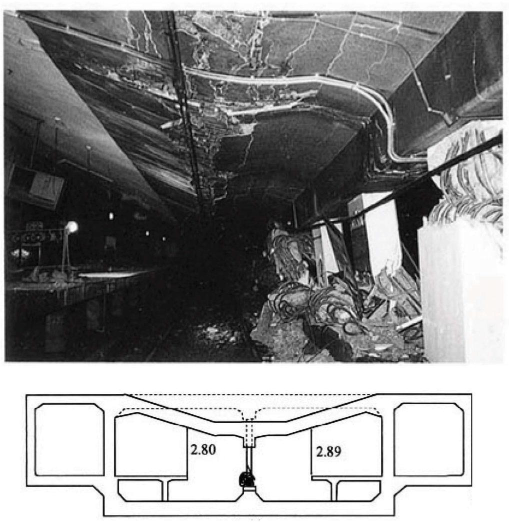


Photo 1. Damage of subway station by Great Hanshin-Awaji Earthquake in 1995 (Kobe Rapid Transit Railway Co. "Record of Disaster Recovery of Tozai Line Daikai Station". Sato Kogyo Co. 1997.1. Great Hanshin-Awaji Earthquake Disaster Materials Collection, Kobe University Library, http://www.lib.kobe-u.ac.jp/directory/eqb/book/11–276/index.html).

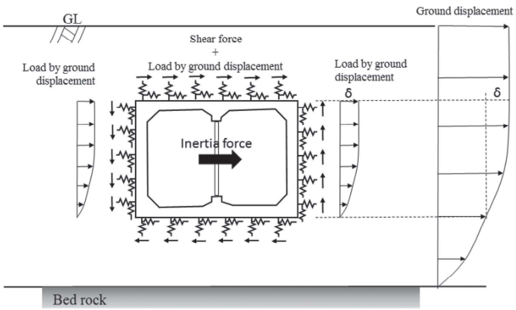


Figure 2. Analysis model of seismic deformation method for cut and cover tunnel.

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.

However regarding the tunneling in rock, the latest 2016 Standard for mountain tunneling have little touches on earthquake resistance. Although basic knowledge on earthquake 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.


Photo 2. Damage of mountain tunnel by Kanto Earthquake in 1923 (from Digital archive of Japan Society of Civil Engineers, http://library.jsce.or.jp/Image_DB/shinsai/kanto/jsce_report/jscerp_02_04.html).

## 2 SEISMIC DAMAGE OF ROCK TUNNEL

### 2.1 *Kanto earthquake in 1923 (magnitude 7.9)*

In the Kanto Earthquake, 93 tunnels out of the 149 tunnels (including under construction) of national railway was damaged and repair was done. Those tunnels was within the range of about 120 km from the epicenter. The severe damage can be seen in seven tunnels out of 11 tunnels located between Odawara and Manazuru of Atami line (present Tokaido Line). Landslides and slope failures caused collapse and burial near the portals, and cracks and cross sectional deformation occurred even in locations away from the entrance.

Photo 2 shows an example of tunnel damage, where a large scale collapse of tunnel crown occurred.

### 2.2 *Niigata-ken Chuetsu-oki earthquake in 2004 (magnitude 6.8)*

The vicinity of the epicenter of the Chuetsu-oki earthquake is a mountainous area, and many rock tunnels for various uses have been constructed. There were many earthquake damage to rock tunnels which had never been experienced by the previous earthquakes.

Photo 3 shows a damage of road tunnel, where the concrete lining was fallen down from the crown.

However as the result of the detailed survey, it was judged that large repair was not necessary and restoration with installation of steel rib and shotcrete could be carried out without closing the road. As seen in this damage picture, the rock behind tunnel lining did not collapsed and is stable state although the concrete lining collapsed.

Photo 3. Damage of rock tunnel by Chuetsu Earthquake in 2004 (provided by MLIT Hokuriku Regional Development Bureau).

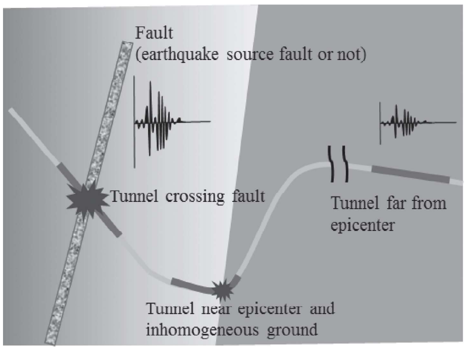


Photo 4. Damage of mountain tunnel by Kumamoto Earthquake in 2016 (Ministry of Land, Infrastructure, Transport and Tourism. Report on the seismic damages of road structures, http://www.mlit.go.jp/common/001136053.pdf.

### 2.3 *Kumamoto earthquake in 2016 (magnitude 7.0)*

Damage to rock tunnel (Tawarayama) near the earthquake source fault is shown in Photo 4. This road tunnel is located in the distance of about 0.5–1.5 km from the fault zone, and large scale lining concrete collapse from tunnel crown occurred.

### 2.4 *Cause of seismic damage*

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

Yashiro et al. 2009 investigated the structural damage caused by the earthquake to the rock tunnel and discussed the mechanism of the damage. Investigated earthquakes and the damage level of the rock tunnels in the afflicted area are given in Table 1. Yashiro also pointed out that the damage of the rock tunnels can be classified into the following three patterns.

- Damage in the area of portals (shallow overburden section),
- Damage in the area of weak rock/fracture zone and
- Damage due to fault displacement.

The major pattern of the tunnel with large level damage among the damaged tunnels shown in Table 1 is "Damage in the area of weak rock zone". Therefore, many researchers conducted numerical analysis (static and dynamic) and experimental studies using static loading devices in order to clarify the mechanism of earthquake damage in rock tunnels.

As a result, followings are 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 convergence and uplift at the bottom of tunnel.

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

Table 1. Number of damaged tunnels in major earthquake.

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

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

On the other hand, the results of a few examination by dynamic conditions indicated the effect of dynamic ground motions cannot be reproduced by the static conditions. Therefore, it seems necessary for further investigations whether dynamic effect yields a situation different from the examination result of the damaging mechanism and reinforcement effect resulted under static condition or not.

## 3 MECHANISM OF SEISMIC DAMAGE TO ROCK TUNNEL

### 3.1 *Seismic damage and tunnel condition*

Tunnel Engineering Committee of Japanese Society of Civil Engineers 2005 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 is up to 138, and the tunnels damaged by the past earthquakes were also covered.

Figure 3 shows the relationship between the construction method of these tunnels and the level of damage and the distance from the epicenter. In the tunnel by the steel-sets with timber lagging construction 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 only heavily damaged within the distance of 5 km. A big difference in earthquake resistance between tunnels of the steel-sets with timber lagging construction method and NATM tunnels is obvious.

From the three damage forms shown in 2.4 and the results in Figure 3, the relationship between the earthquake damage of the rock tunnel and the distance from the epicenter or fault can be summarized typically as shown in Figure 4 and Table 2.

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

### 3.2 *Mechanism of seismic damage*

Considering these results of examination on the mechanism of the seismic damage of the rock tunnel together with the damages shown in Section 2,

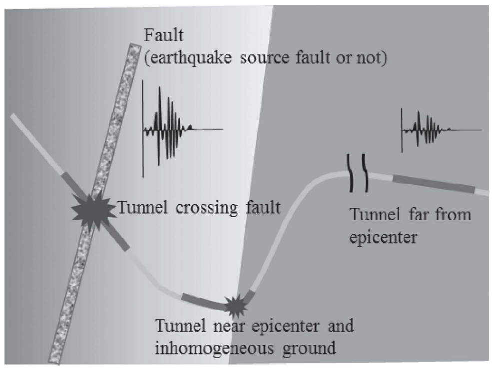


Figure 4. An illustration of the relationship among location and geological condition of a tunnel and seismic damage.

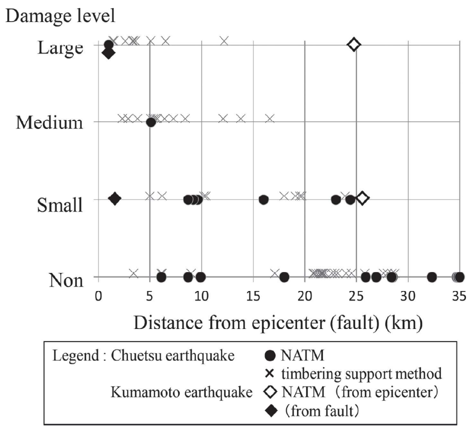


Figure 3. Relationship between damage level and distance from epicenter (fault).

Table 2. Tunnel conditions and seismic damage.

| Location and effect of earthquake | Geological condition | Structural weakness | Seismic damage |
|---|---|---|---|
| Crossing fault Fault displacement | Fault | – | Large |
| Near fault Large seismic motion | Inhomogeneous | Yes | Large |
| | | No | Large ~ medium |
| | Homogeneous | Yes | Medium ~ small |
| | | No | Small |
| Far from fault Small seismic motion | Inhomogeneous | Yes | Medium ~ small |
| | | No | Small |
| | Homogeneous | Yes | Small |
| | | No | None |

the pattern of the seismic damage of the rock tunnel is summarized as illustrated in Figure 5.

1. Pattern A
Seismic motions increase the strain of the rocks surrounding tunnel, and the lining which cannot accommodate that strain is damaged. Damages of this type have been observed as cracks in concrete lining and deformation of roadbed in many tunnels.

This strain increase is greatly affected by the rigidity of the rocks surrounding tunnel, the depth of overburden and the presence of the slope on the surface. In order to show 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 existence of the cavity just behind the lining has a big influence.

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 the tunnel lining and the surrounding rocks can reduce the strain of tunnel, or increasing the rigidity of the surrounding rocks by infilling can reduce the strain of surrounding rocks.

2. Pattern B
Strain of the rocks surrounding tunnel is increased by the seismic motion, and the rock is damaged. Increase of damaged zone of rocks causes the increase of rock pressure on the tunnel lining and lining will fracture. This type of damage are observed in some tunnels.

In case of a large damaged zone (plastic zone) is resulted around the tunnel during tunnel excavation, this damaged zone is further subjected to strain increase (stress increase) due to the earthquake as an additional external load and is further extended.

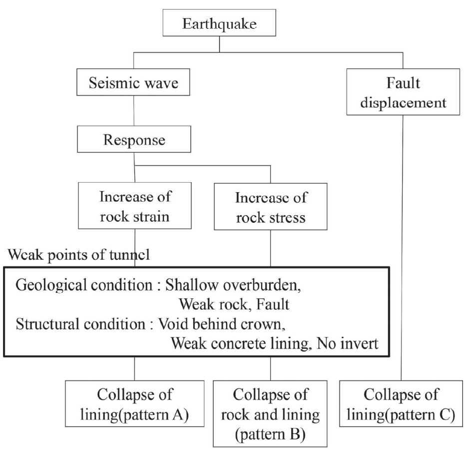


Figure 5. Effect of earthquake to seismic damage of tunnel.

Additional load due to this extended damaged zone acts on the lining and the lining falls down together with the damaged rocks. Especially when there is the cavity just behind the lining, the rocks easily yield and the lining resistibility against rock pressure decreases, so that the lining is highly likely to collapse.

For this pattern, the integration of the surrounding rocks and the tunnel lining is effective in order not to enlarge the damaged zone around tunnel. On the other hand, grouting the damaged zone improves rock strength and reduce the enlargement of loosened zone due to the earthquake.

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

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

For this pattern, an interference zone around the tunnel may reduce the direct effect of the permanent displacement of the fault due to the earthquake on the tunnel structure. However, such measures cannot be expected as long as the fault displacement due to the earthquake cannot be specifically estimated, so it seems difficult to apply this counter-measure to rock tunnels. Nevertheless, this type counter-measures for some tunnels crossing San-Andreas fault in USA and North Anatolian Fault in Turkey have been implemented.

## 4 FURTHER PROBLEMS TO BE STUDIED

### 4.1 *Problems in the evaluation of performance*

In Tables 3 and 4, existing design methods of various underground structures are summarized from the viewpoint of performance evaluation.

These clearly show that the situation of rock tunnels in the deep rock formation is different from that of tunnels in the shallow soil ground.

Many uncertainties are still remaining in the evaluation of performance of rock tunnels and caverns, and seismic design of these deep rock structures is not so common.

### 4.2 *Further studies*

In order to evaluate earthquake resistance, it is necessary to clarify the positional relationship between the target tunnel and the nearby earthquake source

Table 3. Problems in cut and cover tunnel.

| Cut and cover tunnel | |
|---|---|
| Geological condition | • can be estimated by shallow boring<br>• mechanical properties of soil can be evaluated by laboratory test |
| Underground water | • can be clarified by survey |
| Quality of structure | • reinforced concrete<br>• easy to control the quality because of open construction |
| Surrounding ground | • ground around structure is back filled so its quality can be controlled |
| Seismic design | • static and dynamic analysis are applied |

Table 4. Problems in rock tunnel and cavern.

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

faults and the structural and geological conditions of the tunnel. However it is very difficult to evaluate the earthquake resistance in practice. The reasons are as follows.

1. Seismic motion or fault displacement as external load is unknown

There is 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 be displaced by the earthquake or how much displacement would be in case of relative slip.

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

It is difficult to know the current stress condition and yield strength (namely safety factor) of the existing tunnel. Because, it has been common that the performance of the tunnel at the completion of construction is not evaluated through comparing the construction result with those requested in the design so far.

There remains a lot of uncertainty such as the existence of the void between lining concrete and rock, unevenness of excavated surface, thickness of lining concrete, location of reinforcing steel bar and so on. Of course, geological conditions different from that of assumed in the design are not discussed at the time of completion. It is almost impossible to evaluate the safety of the tunnel in use.

3. Function of concrete lining

Another important problem is that the mechanical function of plain concrete, which is the main of supporting system, is not clarified. How to evaluate and analyze the mechanical function of unreinforced concrete lining of the existing mountain tunnel in the earthquake resistance evaluation may be a problem to be solved first in discussing the earthquake resistance of the mountain tunnel.

## 5 CONCLUSIONS

As discussed above, it is necessary to solve many problems in order to evaluate the earthquake resistance of rock tunnel. On the other hand, it is necessary to take appropriate measures to prevent the damage caused by the structural or geological problems of the existing tunnel as soon as possible.

However, the effect of the possible countermeasures to prevent the seismic damage have been studied only by numerical analysis and laboratory model experiments considering limited conditions. So, the qualitative effects can be understood but there are still remaining many problems to be clarified from the viewpoint of quantitative evaluation.

It is important to start efforts to evaluate the performance of rock tunnels more than anything else. At the same time, we have to accumulate analytical and experimental studies from various perspectives on the behavior of the tunnel at the time of earthquake. Especially studies focusing on the discontinuity of rock and the rock dynamics, which has not so far been discussed, are important.

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