Historical Earthquake Damage to Tunnels in Japan and Case Studies of Railway Tunnels in the 2004 Niigataken-Chuetsu Earthquake

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Since mountain tunnels are generally surrounded by stable ground, their displacement during seismic activity tends to be minimized, making such structures less susceptible to seismic damage. Despite this, many railway mountain tunnels have sustained damage, from the 1923 Kanto Earthquake to the 2004 Niigataken-Chuetsu Earthquake. This paper provides an outline of the historical damage to mountain tunnels in Japan and outlines the results of case studies on damage sustained in mountain tunnels. Also outlined here is a classification of the damage patterns and the conditions of damage based on the results of the case studies, and we refer to the estimated causes of damage to tunnels in the 2004 Niigataken-Chuetsu-Earthquake.

**Keywords**: mountain tunnel, earthquake, case studies

### 1. Introduction

Since mountain tunnels are generally surrounded by stable ground, their displacement during seismic activity tends to be minimized, making them less susceptible to seismic damage than other structures such as bridges and foundations (Fig. 1). However, earthquake-resistant tunnels have been highly noted since the 2004 Niigataken-Chuetsu Earthquake. Some tunnels in the disaster area were heavily damaged by the quake, and represented obstacles to the reopening of Shinkansen and conventional lines. In particular, the concrete lining of the Jyoetsu Shinkansen’s Uonuma Tunnel (located adjacent to the epicenter) was heavily damaged, requiring a two-month period for restoration.

Advances in construction technology mean that more and more railway structures are built using the tunneling method, and tunnels too need a sufficient level of earthquake resistance. In this paper, we introduce case studies on historical damage to mountain tunnels, an outline of the damage and its assumed causes resulting from the above earthquake 1).

### 2. Historical damage to mountain tunnels caused by earthquakes

#### 2.1 Outline of damage

Figure 2 summarizes the large-scale earthquakes that damaged mountain tunnels on railways in Japan. There have been four major earthquakes: the 1923 Kanto Earthquake, the 1978 Izu-Oshima-Kinkai Earthquake, the 1995 Hyogoken-Nanbu Earthquake and the 2004 Niigataken-Chuetsu Earthquake. An outline of the damage to mountain tunnels in each earthquake is given below.

<table>
<thead>
<tr>
<th>Year, Name</th>
<th>Magnitude</th>
<th>Seismic intensity</th>
<th>Tunnel performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1923 Kanto</td>
<td>7.9</td>
<td>6</td>
<td>Damage to 93 tunnels</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>25 tunnels required reinforcement</td>
</tr>
<tr>
<td>1978 Izu-Oshima-Kinkai</td>
<td>7.0</td>
<td>5</td>
<td>Damage to 9 tunnels</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2 tunnels required reinforcement</td>
</tr>
<tr>
<td>1995 Hyogoken-Nanbu</td>
<td>7.2</td>
<td>7</td>
<td>Damage to 7 tunnels</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5 tunnels required reinforcement</td>
</tr>
<tr>
<td>2004 Niigataken-Chuetsu</td>
<td>6.8</td>
<td>7</td>
<td>Damage to 24 tunnels</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5 tunnels required reinforcement</td>
</tr>
</tbody>
</table>

Fig. 1 Behavioral differences during an earthquake between bridges, foundations and mountain tunnels

Fig. 2 Historical damage to mountain tunnels caused by earthquakes in Japan
The 1923 Kanto Earthquake caused the maximum damage ever recorded in modern Japanese history, and also caused the most damage to mountain tunnels. 149 railway tunnels were located within a 120-km radius of the epicenter at the time. 93 of them sustained damage requiring reinforcement, while 25 required complete reconstruction. The earthquake resulted in many tunnels being buried underground, and linings were destroyed by ground collapses.

2.3 The 1978 Izu-Oshima-Kinkai Earthquake

Nine railway tunnels sustained damage in the 1978 Izu-Oshima-Kinkai Earthquake. The greatest damage occurred in the Inatori Tunnel, where a fault crossing the tunnel slid during the earthquake, causing a collapse of the tunnel lining and longitudinal displacement of the track. The relative displacement of the fault was 70 cm horizontally and 20 cm vertically according to survey results.

2.4 The 1995 Hyogoken-Nanbu Earthquake

The 1995 Hyogoken-Nanbu Earthquake caused the most damage of all Japanese earthquakes in recent times. In this earthquake, seven of the 43 railway mountain tunnels located within the disaster area sustained serious damage, and five tunnels required repair and reinforcement. A typical example was the Rokko Tunnel, which sustained compressive damage, shear failure at the arch of the lining and compressive failure with spalling at the joints between the arch and the sidewall, and took three months to reopen.

2.5 The 2004 Niigataken-Chuetsu Earthquake

On October 23 2004, a large earthquake of 6.8 in magnitude occurred at latitude 37°17′ N. and longitude 138°52′ E. at a depth of 13 km in Japan’s Niigata Prefecture. The earthquake caused a running Shinkansen train to derail, and some mountain tunnels sustained severe damage. 24 railway tunnels were seriously damaged, and five (the Uonuma, Myoken, Wanatsu, Tenno and Shin-Enokitoge tunnels) required lining repair and reinforcement. Table 1 shows a list of the damaged railway tunnels, Fig. 3 shows the distribution of heavily damaged railway tunnels and Fig. 4 shows the number of damaged tunnels. It is clear that the heavily dam-

<table>
<thead>
<tr>
<th>Tunnel</th>
<th>Line</th>
<th>Degree of damage</th>
<th>Damage</th>
<th>Days required for restoration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uonuma</td>
<td>Jyotetsu</td>
<td>A1</td>
<td>Detached lining, cracks, heaving</td>
<td>66</td>
</tr>
<tr>
<td>Myoken</td>
<td>Shinkansen</td>
<td>A1</td>
<td>Compressive failure, cracks, heaving</td>
<td>66</td>
</tr>
<tr>
<td>Wanatsu</td>
<td>Jyotetsu</td>
<td>A1</td>
<td>Detached lining, compressive failure, cracks</td>
<td>65</td>
</tr>
<tr>
<td>Tenno</td>
<td>conventional</td>
<td>A1</td>
<td>Cracks</td>
<td>65</td>
</tr>
<tr>
<td>Shin-Enokitoge</td>
<td>line</td>
<td>A1</td>
<td>Compressive failure, cracks</td>
<td>65</td>
</tr>
</tbody>
</table>

Note:
Degree of damage:
A1: Heavy damage requiring repair and reinforcement
A2: Damage requiring repair and reinforcement
B: Damage not requiring repair and reinforcement
C: No damage

Table 1  List of the damaged railway tunnels

Fig. 3  Distribution of railway tunnels heavily damaged in the Niigataken-Chuetsu Earthquake

Fig. 4  Number of damaged tunnels

Degree of damage:
A1: Heavy damage requiring repair and reinforcement
A2: Damage requiring repair and reinforcement
B: Damage not requiring repair and reinforcement
C: No damage
aged tunnels are concentrated in a limited area approximately within a 10-km radius from the epicenter. The most heavily damaged was the Uonuma Tunnel, which runs nearby the epicenter. The Uonuma Tunnel is an 8,625-m long railway tunnel running through Neogene mudstone. Three sections of the tunnel sustained heavy damage (Fig. 5).

Figure 6 shows the damage in the most heavily affected section. The concrete lining broke and fell onto the track. The largest concrete block was approximately $2m^3$ with a weight of five tons. Other damage observed consisted of a reduction in the tunnel diameter, heaving of the roadbed concrete and invert cracking. This was the biggest disaster of all Shinkansen tunnels since the introduction of the system. Figure 7 shows the reinforcements made to the Uonuma Tunnel. The locations were restored through rock bolting, concrete removal using breakers, shotcreting and reinforcement using precast mortar boards, but the tunnel was a critical path and took two months to reopen.

Further damage occurred in the Jyoetsu Shinkansen's Myoken Tunnel, which sustained compressive failure at the crown with a longitudinal length of approximately 50 m (Fig. 8), and an invert heaved as in the case of the Uonuma Tunnel. Figure 9 shows the reinforcements made to the Myoken Tunnel. The locations were restored through rock bolting, concrete removal using breakers, shotcreting and reinforcement using precast mortar boards, but the tunnel was a critical path and took two months to reopen.
using breakers, shotcreting and fiber-reinforced boards.

The conventional-line Wanatsu Tunnel sustained compressive failure at the crown with a longitudinal length of about 40 m, and large blocks fell off the lining exposing the steel supports of the tunnel (Fig. 10). In the Tenno and Shin-Enoki tunnels, the bedrock above the tunnel collapsed and slid, cracks occurred in the lining, and the tunnel portal was buried by earth and sand. However, this damage was caused indirectly by the collapse of the ground/slope, and the earthquake did not result in any direct damage to the tunnels.

3. Classification of damage patterns

Figure 11 shows the results of classifying the damage patterns in the 1978 Izu-Oshima-Kinkai Earthquake, the 1995 Hyogoken-Nanbu Earthquake and the 2004 Niigataken-Chuetsu Earthquake, for which a range of valuable information and data is available. The damage patterns have also been classified into three types as shown in Fig. 12.

Type 1: Damage to shallow tunnels (Fig. 13)

There are many examples of tunnel damage in the Type 1 category. In general, shallow tunnels are likely to be affected by earthquakes as they are often constructed in loose ground, where seismic activity amplifies and causes large ground deformation. Cracks in the arch of the lining are characteristic of this type. It is conceivable that tunnels deform by shearing as a result of displacement caused by the earthquake and cracks occur at the shoulder part of arches due to bending moments.

Type 2: Damage to tunnels in poor geological conditions (Fig. 14)

This type of damage is visible in tunnels in soft ground such as fractured zones, sometimes in tunnels with a large earth covering. In fractured zones, the ground is generally soft, resulting in large displacement in earthquakes. Other loads also act on the lining, such as loosening earth pressure and plastic earth pressure in the fractured zone before an earthquake. In such cases, the load acting on the lining increases, and damage caused by earthquakes tends to be severe.

Type 3: Damage to tunnels by fault slide (Fig. 15)

Type-3 damage occurs when an earthquake fault crosses a tunnel. Various stresses result from earthquake fault sliding (such as shear stress, tensile stress and compressive stress on the lining) and cause complicated cracks including shear cracks and cracks in round slices.

Many of the damaged tunnels are classified into these three types of damage pattern as shown in Fig. 11.

4. Conditions of damage

From such case studies, it is evident that even mountain tunnels sustain earthquake-related damage. The conditions under which tunnels are susceptible to dam-
damage are:
(1) Earthquakes of great magnitude
(2) Tunnel location adjacent to an epicenter or an earthquake fault

Figure 16 shows the relationship between the distance from the earthquake fault, the magnitude of the earthquake and the number of heavily damaged tunnels. From this figure, we find that the risk of earthquake damage becomes large under both conditions (1) and (2) outlined above. Roughly speaking, tunnels sustained considerable damage in areas within 10 km of an earthquake fault in the case of M7, and areas within 30 km in the case of M8. Figure 17 shows the relationship between the distance from an earthquake fault and the percentage of tunnels damaged. From this figure, we find that damage requiring reinforcement occurred within 10 km of an earthquake fault.

However, these figures do not fully consider the conditions specific to tunnels such as the ground adjacent to the tunnel and the tunnel structure. It is conceivable that tunnels tend to be vulnerable to earthquakes under certain circumstances, such as:

- a. shallow tunnels
- b. poor geological conditions
- c. sliding of an earthquake fault crossing the tunnel
- d. structural defects in the tunnel lining

Figure 18 shows the number of damaged tunnels in which these circumstances are found. Many of the heavily damaged tunnels feature some of these special conditions. It can therefore be concluded that the risk of earthquake damage becomes large under the conditions of both (1) and (2), and that the level of damage becomes large when there is at least one special condition.

5. Causes of damage to the Uonuma Tunnel

In this chapter, we introduce the causes of damage to the Uonuma Tunnel, which sustained the heaviest damage in the 2004 Niigataken-Chuetsu Earthquake.

Firstly, this tunnel was within 1 km of the epicenter, and the earthquake motion was extremely strong. Secondly, the ground in this area is Neogene mudstone and is relatively soft. We surveyed the geological characteristics and the situation behind the tunnel lining by boring in the most heavily damaged section, and two conclusions were reached. Firstly, the ground in the damaged section had a lower strength than that in neighboring sections (Fig. 19). Secondly there were voids behind the tunnel lining at the arch, and the tunnel was subject to large deformation.

It is conceivable that the Uonuma Tunnel sustained large damage due to its location adjacent to the epicen-
ter, the extremely strong earthquake motion and the presence of voids behind the tunnel lining.

6. Countermeasures against earthquakes for tunnels

We are currently planning countermeasures against earthquake damage. Figure 20 shows the methods used in existing tunnels. Backfill-grouting of voids behind linings and rock bolting to prevent spalling are among the fundamental countermeasures. For newly constructed tunnels, the countermeasures are adapted in the linings themselves. We use fiber-reinforced concrete to improve the ductility and performance of lining anti-spalling.

7. Conclusions

This paper gives an outline of the historical damage to mountain tunnels in Japan and resultant case studies of damage found in mountain tunnels. We also show a classification of damage patterns and the conditions of damage based on the case study results. However, many factors relating to the damage mechanism of tunnels in an earthquake remain unknown. It is essential to establish a method of evaluating the earthquake resistance of tunnels. We are currently planning model tests and numerical analysis to evaluate the deformation behavior of tunnels under earthquake conditions, and plan to use the results in the maintenance of railway tunnels.

References