Damage assessment of tunnels caused by the 2004 Mid Niigata Prefecture Earthquake using Hayashi's quantification theory type II

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Abstract:

Mountain tunnels, being underground structures and situated deep within rock layers, are generally considered to suffer appreciably less damage from earthquakes than surface structures. However, it has been reported that many tunnels were damaged by the 1923 Great Kantou earthquake, the 1995 Great Hanshin Earthquake, the 1999 Taiwan Chi-chi Earthquake, the 2004 Mid Niigata Prefecture Earthquake and the May 2008 Great Wenchuan Earthquake in China. In this study, the damaged tunnels in the 2004 Mid Niigata Prefecture Earthquake are the study objects. The damage patterns are analyzed and the information which is considered to be of influence, such as the distance to epicenter, the completion time, the geological conditions, etc., are collected. A database of the damaged tunnels has been created using a Geographic Information System (GIS). The influence ranking for these factors has been analyzed using Hayashi's quantification theory II. The degree of the tunnel damage has also been assessed using GIS and Hayashi's quantification theory II. The field investigation is in close agreement with the assessment results following Hayashi's quantification theory II.

Keyword: *Tunnel; Earthquake; Damage; Geographic information system (GIS); Hayashi's quantification theory type II*

1. Introduction

In Japan, about 70% of the total national territory is composed of mountainous terrain. Due to the limitation of the mountainous topography, tunnels are used extensively both in the railway and highway systems. The Japanese islands are squeezed between the Pacific, Philippine, Eurasian and the North American plates. The plate motions and active volcanism cause frequent earthquakes. Mountain tunnels, being underground structures and situated deep within rock layers, are generally considered to suffer appreciably less damage from earthquakes than surface structures (Okamoto 1973; Sharam and Judd 1991; Hashash et al. 2001), however when a tunnel experiences extremely strong earthquake shaking, it may still possibly be damaged. It is reported that many tunnels have been damaged by the 1923 Great Kantou earthquake (Yoshikawa 1981; Yashiro and Kojima 2007), the 1995 Great Hanshin Earthquake (Asakura and Sato 1998), the 2004 Mid Niigata Prefecture Earthquake (Shimizu et al. 2007; Yashiro and Kojima 2007; Tunnel Engineering Committee, JSCE 2005), the 2007 Niigata Prefecture Chuetsu Offshore Earthquake in Japan (Tunnel Engineering Committee, JSCE 2008) and the May 2008 Great Wenchuan Earthquake in China (Lin and Chai 2008). Hence, the safety of mountain tunnels in seismically active areas should be an important issue to tunnel engineers.

Dowding and Rozen (1978) gave a preliminary study of damage mechanisms in tunnels resulting from earthquakes. Wang et al. (2001) summarized the damage patterns and described the findings of a systematic assessment of damage in the mountain tunnels due to the 1999 Taiwan Chi-Chi Earthquake. More detailed field investigation and analysis of tunnel damage have been carried out by many researchers in Japan for the 1978 Izu-Oshima-Kinkai earthquake (Kawakami, 1984), the 1995 Great Hanshin Earthquake (Asakura and Sato 1998), the 2004 Mid Niigata Prefecture Earthquake (Tunnel Engineering committee, JSCE 2005; Shimizu et al. 2005; Shimizu et al. 2007; Konagai et al. 2008) and the 2007 Niigata Prefecture Chuetsu Offshore Earthquake (Saito et al. 2007; Tunnel Engineering committee, JSCE 2008; Jiang et al. 2008a and 2008b). The epicenter is located inland in the 2004 Mid Niigata Prefecture Earthquake. 49 tunnels suffered significant damage to various extents. In this study, using a Geographical Information System (GIS) and Hayashi’s quantification theory type II (Hayashi

1954, 1974), the damage to tunnels structures caused by the 2004 Mid Niigata Prefecture Earthquake are analyzed and assessed.

2. Description of the 2004 Mid Niigata Prefecture Earthquake

On 23 October 2004, at 17:56 local time, a strong earthquake with a magnitude of 6.8 according the Japan Meteorological Agency (JMA) Magnitude scale occurred at latitude 37º17'N and longitude 138º52' E on the inland of Mid Niigata Prefecture, at a depth of approximately 13 km. Figure 1 shows the epicenter location and the distribution of the seismic intensity following the Japan Meteorological Agency seismic intensity scale in Niigata Prefecture. The earthquake was caused by a blind-thrust fault, which was not indicated on the active fault map of Japan. It had an unusual after-shock activity and at least 4 large after-shocks having a magnitude greater than 6.0 took place. The epicenter fault was presumed to be running in a N35E direction for a total length of 22km. The presumed epicenter fault, the crustal horizontal movement vector are shown in Figure 2. The Mid Niigata area suffered catastrophic damage during the earthquake, with 67 deaths, over 4790 people being injured, more than 120700 houses either collapsed or destroyed and 49 tunnels damaged. The most heavily damaged towns were Kawaguchi with an intensity of 7 on the intensity scale of the Japan Meteorological Agency (JMA). The earthquake inflicted heavy damage to Kanetsu Expressway and Hokuriku Shinkansen Line and Joetsu railway line. In particular, it caused a Shinkansen train (bullet train) traveling at a speed of 200km/h to derail for the first time in the forty-year history of high-speed trains in Japan.

3. Damage analysis to tunnels

3.1 The damaged tunnels database

After the October 2004 Mid Niigata Prefecture Earthquake, a systematic investigation was conducted on 138 tunnels including railway tunnels, road tunnels, Shinkansen tunnels and water conveyance tunnels for hydroelectric power projects (Tunnel Engineering Committee, JSCE 2005). The total length of the investigated tunnels is about 246 km. In order to store the information of the investigated tunnels, such as the location, length, width, height, geology, and the photos taken to show the damaged conditions, a tunnel database has been created within a Geographic Information System (GIS). Among the 138 tunnels investigated, 49 tunnels suffered various degrees of damage. Table 1 is the attributes of the GIS database and lists the basic information and damage conditions of the 49 damaged tunnels and Figure 3 shows their distribution within about 20km from the presumed epicenter.

In order to efficiently implement the functions of querying, managing data and displaying the photographs of the damaged tunnels, a GIS-based querying tool has been developed by using ArcObjects (ESRI 2001) which are the building blocks of COM-based ArcGIS software. Figure 4 illustrates the application of the querying tool for searching and showing the damaged conditions of Myoken tunnel, No. 24 in Table 1 within ArcGIS environment.

3.2 Damage patterns due to the 2004 Mid Niigata Prefecture Earthquake

3.2.1 Cracking of lining

From Table 1, we can see that almost all of the damaged tunnels suffered cracking of the concrete lining. The types of the lining cracks are longitudinal cracks, transverse cracks and inclined cracks in the arch, sidewall and roadbed. The extent of cracks is various. Slight cracks have little influence on the function of the concrete lining. But opening of cracks and buckling of the lining, inflicted spalling or collapse of the lining and consequently water leakage happened.

3.2.2 Spalling of lining

Spalling of concrete lining is the severe damage pattern in this disaster. There are three causes for spalling: space over the arch crown; imperfection of the contact between the concrete material and the rock surrounding of the tunnel; and the aged concrete lining. The seismic shaking force is the initiation factor. Figures 5 (a) and (b) show typical examples of spalling of the concrete lining at the most heavily damaged sections in Uonuma tunnel and Kizawa tunnel respectively. Uonuma tunnel, which is located nearby the epicenter, is an 8625 m long

Shinkansen railway tunnel running through Neogene mudstone and alternating beds of sandstone and mudstone. The concrete lining broke and fell into the track and the largest concrete block was approximately 2m^3 with a weight of five tons. Kizawa tunnel, a 305m road tunnel, runs through Pliocene sandstone and mudstone. The cracks on the east side wall extend over 45-83m from the north tunnel mouth, while the cracks appeared over 38-88m distance on the west side wall. Some parts of the concrete lining inflicted spalling. Kongai et al. (2008) gave a detailed analysis of the causes of the damage in Kizawa tunnel.

3.2.3 Other damage patterns in this disaster

A large number of slope failures and debris-flows were also induced by the 2004 Mid Niigata Prefecture Earthquake. Fortunately, slope failures have not inflicted tunnel collapse in this earthquake. However the gravels from slope failures and debris-flows obstructed the portal entrances of the Siotani tunnel and Enoki tunnel (Fig. 6).

3.3 Influence factors of the degree of tunnel damage

The degree of tunnel damage is associated with many combined influence factors. The distance to epicenter, the geological conditions, the overburden and the completion time (or the aged time of concrete lining) are the factors considered in this study. How these factors affect the degree of tunnel damage will be evaluated by using Hayashi’s quantification theory type II and GIS technique.

4. Analysis using Hayashi’s quantification theory type II

4.1 Hayashi’s quantification theory type II

Hayashi’s quantification theory, which is developed by Chikio Hayashi, includes a set of statistical methods, namely, Hayashi's quantification type I, II, III, and IV. In Japan, Hayashi’s methods of quantification are well known and widely used in various fields, such as social and marketing surveys, psychological and medical research, etc., where information is obtained mainly in the form of qualitative categories. Hayashi’s quantitative theory type II is a method of multivariate discrimination analysis to manipulate attribute data as predictor variables. In this study, the outside variable is the degree of tunnel damage, A (A1 and A2) and B (Table 2). The predictor variables, that is, the items, are the influence factors. Table 3 shows the items, the categories and the statistical information of the 49 damaged tunnels.

4.2 Computing procedure

In order to express the response of item and category for each sample, the dummy variable $\delta_{i\alpha}(j,k)$ is introduced to the model when samples α represent the factor in category k of item j:

$$\delta_{i\alpha}(j,k) = \begin{cases} 1 & \text{if response of } \alpha\text{th sample in the category } k \text{ of item } j \text{ to} \\ & \text{the corresponding external criterion, in } i\text{th group} \\ 0 & \text{otherwise,} \end{cases} \tag{1}$$

In order to estimate the overall score response to the category for each sample, the linear regression method shown in the following equation (2) is used.

$$Y_{i\alpha} = \sum_{j=1}^{R}\sum_{k=1}^{C_i} a_{jk}\delta_{i\alpha}(j,k),\ i = 1,2,\ldots,N \tag{2}$$

where N represents the total number of samples, $Y_{i\alpha}$ is the overall score of αth sample in ith group, and a_{jk} is a category weight. When $\delta_{\alpha i}(j,k) = 1$, which respond αth sample in the category k of item j to the corresponding external criterion in ith group the value a_{jk} can be obtained. Then the overall score $Y_{i\alpha}$ of the external criterion, which response category in total item can then be calculated. To explain this in more detail, among L number of groups of values, if one lets the ratio of the difference among the groups (Sb) to the net difference (St) approach its maximum value, then a_{jk} can be obtained. The net difference of $Y_{i\alpha}$, St, can be represented using Eq. (3), as a sum of the difference between groups and the difference within groups:

$$\sum_{i=1}^{L}\sum_{\alpha=1}^{n_i}(Y_{i\alpha} - \overline{Y}_{..})^2 = \sum_{i=1}^{L} n_i(\overline{Y}_{i.} - \overline{Y}_{..})^2 + \sum_{i=1}^{L}\sum_{\alpha=1}^{n_i}(Y_{i\alpha} - \overline{Y}_{i.})^2 \tag{3}$$

where the item on the left of the equation is the net difference (St) of $Y_{i\alpha}$. On the right-hand side of the equation, the first item is the difference between groups (Sb), and the second item is the difference within groups (Sw).

As shown in Eq. (4), *f(jk,uv)* represents the responded sample number in both *k*th category of item j and *v*th category of item *u*. $g^t(j,k)$ represents the responded sample number in *k*th category of item *j* of *i*th group. n_{jk} represents response sample number in *k*th category of item *j*:

$$t(jk,uv) = f(jk,uv) - \frac{n_{jk}n_{uv}}{n}, \quad b(jk,uv) = \sum_{i=1}^{L} \frac{g^i(j,k)g^i(u,v)}{n_i} - \frac{n_{jk}n_{uv}}{n} \tag{4}$$

If the ratio of correlation η^2 is defined as a ratio of the difference between groups (Sb) to net difference (St) shown in Eq. (5), $0 \leq \eta^2 \leq 1$, the category weight a_{jk} could be calculated by the solution of matrix equation (6):

$$\eta^2 = \frac{\sum_{j=1}^{R}\sum_{k=2}^{C_j}\sum_{u=1}^{R}\sum_{v=2}^{C_u} b(jk,uv)a_{jk}a_{uv}}{\sum_{j=1}^{R}\sum_{k=2}^{C_j}\sum_{u=1}^{R}\sum_{v=2}^{C_u} t(jk,uv)a_{jk}a_{uv}} \to Max \tag{5}$$

$$(\mathbf{B} - n^2\mathbf{T})\mathbf{a} = 0 \tag{6}$$

According to the outcome of the discriminatory analysis, a calculation numerical value, which is called a “category score”, is given to each category of the nonquantitative traits and a range is calculated for each item as follows,

range = maximum of category scores – minimum of category scores. (7)

A wider range of category scores for each item also indicates a greater contribution of the outside variable, that is, the degree of the tunnel damage. The larger the item range, the more contribution percentage to the degree of tunnel damage. A partial correlation coefficient which represents the weight for discrimination is calculated for each item. Herein, a contributing weight for each item to the degree of tunnel damage is also given as follows,

$$\alpha_i = \frac{r_i}{\sum_{j=1}^{n} r_j} \tag{8}$$

Where, α_i is the contributing weight, r_i is the range for each item, n is 4.

4.3 Results using Hayashi’s quantification theory type II

The 15 categories (factors) of four items (indices) (Table 3) are divided. The contributions of the 15 factors to tunnel damage due to earthquake by the algorithm presented in section 4.2 are listed in Table 4. Each evaluated factor is quantificational, measured in consideration of the category score and item range of the raw data by using Hayashi’s quantification theory type II. This allows to analyze the relative contribution of the distance to epicenter, the geological conditions, the overburden and the time since completion to the degree of tunnel damage. The contribution of each item can be shown in Figures 7 and 8 by the standard category scores and item ranges. The category score on x-axis in Figure7 expresses the contribution of the impact factors to the degree of tunnel damage. The larger the category score of factor is, the larger the contribution of factors to tunnel damage become. The positive value shows the corresponding category will promote the degree of tunnel damage; in contrast, the negative value shows the corresponding category will restrain the degree of tunnel damage.

The 83.7% discriminative ratio and the 0.656 correlative ratio indicate that the precision satisfies statistical significance. From the results (Figure 8), we can see that the item ranges decrease with the following order: the distance to epicenter, the completion time, the overburden and the geological conditions, in which their values are 1.7773, 1.5130, 0.8893 and 0.4263, respectively. The contribution percentage of the distance to epicenter, especially the distance within 1km, is larger than other item categories.

In order to assess the degree of tunnel damage using the results of Hayashi' quantification theory type II, the assessment score for each tunnel is calculated using the formulation,

$$\text{Assessment score} = \sum_{i}^{4} \text{analysis score} \times \text{contributing weight} \qquad (9)$$

Based on the assessment score and the assessment rule (Table 5), the degree of tunnel damage is assessed as shown in Figure 9. Comparing with the field investigation (Figure 3), the assessment results are in close agreement with field observations except for Myoken tunnel (No. 24 in Figures 3 and 9) and Nakayama tunnel (No. 29 in Figures 3 and 9).

4.4 Discussion

The tunnels that sustained heavy damage from the earthquake were located within about 10km from the presumed epicenter, but there were cases where, in the same location, some places were heavily damaged and others were not damaged at all. Moreover, from Table 1 and Figure 9, we can see that not all the tunnels within 10km are damaged seriously. Therefore, except the above 4 influence factors, the angle between the presumed fault and the tunnel axes is also an important influencing factor. Figure10 shows the influence of the angle between the presumed fault and the tunnel axes on tunnel damage. Among 12 tunnels in the damage ranking A1, 8 damaged tunnels locate in the angle 60º~90º. Within the same distance to the epicenter, the damage degree of the tunnels which locate in the angle 60º~90º are greater than the tunnels in the angles 30º~60º and 0º~30º. For example, the angle between Uonuma Tunnel (No. 23 in Table 1 and Figure 9) axes and the presumed fault is about 60º~90º. This tunnel is seriously damaged and is observed as the damage ranking A1. The damage mechanism may be related to the direction of seismic wave propagation and should be further studied. The results show that the degree of tunnel damage is associated with the distance from the epicenter, the geological conditions, the completion time or the lining aging, the overburden cover, and the angle between the presumed fault and the tunnel axes.

The GIS-based damaged tunnels database presents the basic information and spatial distribution of the tunnels. The further study is that all the tunnels, including the railway tunnels and road tunnels and the digital active fault map of Japan (Nakata and Imaizumi 2002) will be added into the GIS-based tunnels database. The database will serve for the production of hazard and risk assessment for tunnel damage induced by earthquake. This information is basic to emergency and useful to identify vulnerable areas that may require planning considerations and in prioritizing mitigation measures that may need to be implemented to reduce future losses.

5. Conclusions

The summary and analysis have been presented for the damaged tunnels in the 2004 Mid Niigata Prefecture Earthquake. Among the 138 investigated tunnels, 49 tunnels suffered various degrees of damage. In order to store the information of the investigated tunnels, such as the location, length, width, height, geology, and the photos taken to show the damaged conditions, a tunnel database has been created and a querying tool has been developed using ArcObject within ArcGIS environment.

The damage patterns are mainly spalling and cracking of lining. The extent of damage to the tunnels was influenced by the distance to the epicenter, the geological conditions, the overburden, the completion time (or the aged time of concrete lining). The quantificational assessment of the degree of tunnel damage caused by the 2004 Mid Niigata Prefecture Earthquake using Hayashi's quantification theory type II has been performed and the influence order for these factors has been analyzed. The 83.7% discriminative ratio and the 0.656 correlative ratio provide the evidence that Hayashi's quantification theory type II is a reliable insight that is statistically sound. The 49 damaged tunnels has been also assessed using Hayashi' quantification theory type II. Comparing with the field investigation, the assessment results are in close agreement with filed survey.

The tunnel damage due to earthquakes is synthetically caused by several influencing factors, such as the distance to epicenter, the geological conditions, the completion time, the overburden and the angle between the presumed fault and the tunnel axes. Considering all the influence factors, the damage mechanism should be further studied using experimental and numerical analysis so as to enhance understanding of seismic response of tunnels and improve seismic design procedures for tunnels.

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Tables

Table 1 The damaged tunnels in the 2004 Mid Niigata Prefecture Earthquake

No.	Tunnel name	Usage	Tunneling method	Completion time	Ling (cm)	Length (m)	Overburden (max: m)	Width (m)	Height (m)	Geology	Damage degree	Damage description
1	Wanantu	road	CTM	1963	C (50)	300	40	8.2	4.6	Ss	A1	spalling in arch, spalling crack, and deformation in side wall
2	Kosendani2	road	CTM	1983	C (60)	1088	62	9.5	4.8	Ss	A2	crack, spalling in arch and sidewall
3	Yamamotoyama	highway	CTM	1981	C (60)	1839	140	10.2	7.5	Absm	B	crack
4	Yamanaka	road	CTM	1972	C(60-75)	1307	200	6.5	4.5	Ss, Ms	B	longitudinal crack
5	Takeisi	road	CTM	1986	C(50-60)	331	140	7.0	7.74	Ss, Ms	B	longitudinal crack
6	Higasiyama	road	CTM	1987	C	220	35	7.0	4.7	Ss, Ms	B	crack in arch
7	Takezawa	road	CTM	1965	C	18.2	6	6.0	4.5	Ss, Ms	A2	crack in arch, side and bed
8	Siroyama	road	CTM	1997	C	128	150	7.0	4.7	Ss, Ms	B	longitudinal crack in side wall
9	Orinaka	road	CTM	1994	C	374	60	9.25	4.7	Ss, Ms	B	crack in arch and sidewall

Table 1 (continued)

No.	Tunnel name	Usage	Tunneling method	Construction time	Ling (cm)	Length (m)	Overburden (Max: m)	Width (m)	Height (m)	Geology	Damage degree	Damage description
10	Obirou	road	CTM	1991	C	390	90	9.25	4.7	Ss, Ms	B	crack
11	Sibumi	road	CTM	1995	C	860	150	6.0	4.7	An, Tu, Ms	B	spalling in arch
12	Haneguro (roadway)	road	CTM	1967	C(50)	506	100	5.60	5.20	St	A1	Compressive buckling in bed, crack in arch and sidewall
13	Haneguro (pavement)	road	NATM	1994	C(30)	550	100	2.20	2.85	St	A2	spalling
14	Junidaira	road	CTM	1987	C(50-80)	210	40	8.5	4.7	St	A1	Spalling, deformation in sidewall
15	Rangi	road	CTM	1989	C(60)	590	180	6.00	4.70	Ss, Ms	A2	longitudinal crack in arch, upheave in bed
16	Siotani	road	CTM	1983	C(50-60)	512.5	110	7.50	5.85	Ss, Ms	A2	Crack in arch,
17	Kizawa	road	NATM	1991	C(30-70)	305	30	6.00	4.7	Ss, Ms	A1	deformation, spalling, opening in roadbed

Table 1 (continued)

No.	Tunnel name	Usage	Tunneling method	Construction time	Ling (cm)	Length (m)	Overburden (Max: m)	Width (m)	Height (m)	Geology	Damage degree	Damage description
18	Araya	road	CTM	1977	C(60)	292	45	7.50	5.64	Ss, Ms	A1	Compressive buckling,crack, opening in bed
19	Tochio	road	NATM	2001	C(30-50)	854	150	10.35	4.7	An, Ms	B	Water leakage from juncture
20	Okimitouge	road	NATM	2000	C	1080	150	8.5	4.7	Ms, Ss	B	longitudinal crack in sidewall
21	Hosa	Shinkansen	CTM	1979	C(70-90)	6087	15	9.6	8.3	Tb	B	crack in roadbed
22	Horinouti	Shinkansen	CTM	1978	C(70-90)	3300	100	9.6	8.3	Cm	A2	spalling in sidewall
23	Uonuma	Shinkansen	CTM	1977	C(50-90)	8624	70	9.6	8.3	Ms, Absm	A1	spalling, upheave in bed, crack
24	Myoken	shinkansen	CTM	1976	C(70-90)	1459	65	9.6	8.3	St	A1	Crack, upheave in roadbed
25	Takitani	shinkansen	CTM	1977	C(70-90)	2673	55	9.6	8.3	St, Ss	A2	crack
26	Sinfukuyama	railway	CTM	1963	C(45)	1468	75	4.8	5	Sr	A2	crack
27	Fukuyama	railway	CTM	1923	CB(39)	1350	7	4.8	5.6	Sr	B	crack

Table 1 (continued)

No.	Tunnel name	Usage	Tunneling method	Construction time	Ling (cm)	Length (m)	Overburden (Max: m)	Width (m)	Height (m)	Geology	Damage degree	Damage description
28	Wanantu	railway	CTM	1965	C(50)	725	41	8.5	7.5	St	A1	Spalling, crack, failure in the juncture of arch and sidewall
29	Nakayama	railway	CTM	1966	C(50)	1205	92	8.5	7.5	Sh, Ss	B	crack
30	Usigazima	railway	CTM	1966	C(50)	432	14	8.5	7.5	Sh, Ss	A2	crack in portal
31	Tenou	railway	CTM	1966	C(45-60)	285	11	4.7	5.1	Sh, Ss	A1	crack
32	Sintouge	railway	CTM	1967	C(30-50)	1372	75	4.7	5.1	Sh, Ss	A1	crack
33	Touge	railway	CTM	1921	CB(23-56)	641	70	4.8	5.1	Sh, Ss	A2	crack
34	Hanada	railway	CTM	1967	C(60)	880	28	8.6	6.3	Sh, Ss	B	spalling
35	Tukayama	railway	CTM	1966	C(50-60)	1766	150	8.7	6.3	Sh, Ss	A2	crack
36	Higasiyama	railway	CTM	1968	C(60)	166	22	8.8	6.4	Ms, Ss	B	spalling
37	Iwayama	railway	CTM	1927	CB(39-56)	652	54	4.7	5.2	Ss	B	spalling
38	Iwazawa	railway	CTM	1927	CB(39-47)	203	36	4.6	5.1	St	B	spalling
39	Myoukouzan	railway	CTM	1927	CB(23-91)	1465	151	4.6	5.2	Ar	A2	crack
40	Kouyouzan	railway	CTM	1970	C(45-60)	500	67	4.8	5.1	Sr	A2	crack
41	Utigamaki	railway	CTM	1927	CB(47-87)	425	30	4.6	5.2	Ms	A2	crack

Table 1 (continued)

No.	Tunnel name	Usage	Tunneling method	Construction time	Ling (cm)	Length (m)	Overburden (Max: m)	Width (m)	Height (m)	Geology	Damage degree	Damage description
42	Akakura	railway	CTM	1974	C(45-70)	10471	440	4.36-8.54	6.16-6.96	Ms, Ss	B	spalling, crack in arch and sidewall, water leakage
43	Jusanmachi	railway	CTM	1975	RC(55)	1695	40	5.05	5.68	Cm	B	water leakage
44	Yakusitoge	railway	CTM	1979	C(45-60)	6199	250	4.36-8.54	5.60-6.96	Ms,	B	spalling, crack in arch and sidewall, water leakage
45	Yabukami	water	CTM	1941	C(40)	4856	100	4.85	4.85	Ch	B	spalling in arch
46	Kamijo	water	CTM	1927	C(24.2)	3265	95	3.83	3.42	Ch	B	crack
47	Suhara	water	CTM	1913	C(30)	1324	25	2.98	2.42	Gr	B	crack
48	Ikazawa	water	CTM	1920	C(47.6)	1322	49	2.12	2.52	Cm	B	crack
49	Noborikawa	water	CTM	1942	C(20)	2723	237	1.5	1.8	Gr	B	crack

C: concrete; CB: concrete block; RC: reinforced concrete

Ss: sandstone; Absm: alternating beds of sandstone and mudstone; Ms: mudstone; An: andesite; Tu: tuff; St: siltstone; TB: tuff breccia; Cm: conglomerate; Sr: soft rock; Sh: shale; Ar: aqueous rock; Ch: chert; Gr: granite

CTM: conventional tunneling method; NATM: New Austrian tunnelling method

Degree of damage is shown in Table 2.

Table 2 Degree of tunnel damage

Degree of damage		Description
A	A1	heavy damage requiring large-scale repair and reinforcement
	A2	damage requiring repair and reinforcement
B		slightly damage not requiring repair and reinforcement

Table 3 Items and categories for Hayashi's quantification theory type II

Item	Category	Number of damaged tunnels	
		A*	B*
Construction year	~1959	5	7
	1960~1969	10	2
	1970~1979	6	5
	1980~1989	4	4
	1990~	0	6
Overburden	~50m	16	9
	51~100m	7	7
	101~200m	2	5
	201m~	0	3
Geology conditions	soft bedrock	20	11
	hard bedrock	5	13
Distance to epicenter	~1km	3	0
	1~5km	8	2
	5~10km	11	6
	10km~	3	16

*: The meanings of A and B are listed in Table 2.

Table 4 results of quantification theory type II analysis

Item	Category	Category score	Analysis score	Range	Partial correlation coefficient	Contributing weight
distance to epicenter	~1km	1.0583	100	1.7773	0.4653	0.3859
	1~5km	0.4602	67			
	5~10km	0.3461	64			
	10km~	-0.7190	9			
construction year	~1959	0.0197	47	1.5130	0.3903	0.3285
	1960~1969	0.6190	77			
	1970~1979	-0.0384	44			
	1980~1989	-0.2348	34			
	1990~	-0.8940	0			
overburden	~50m	0.1798	55	0.8893	0.2091	0.1931
	51~100m	-0.0545	43			
	101~200m	-0.2288	34			
	201m~	-0.7095	9			
geological condition	soft bedrock	0.1566	54	0.4263	0.1808	0.0925
	hard bedrock	-0.2697	32			

Table 5 The assessment rule

Score	Degree of tunnel damage	
51~80	A	A1
41~50		A2
20~40	B	

Figures

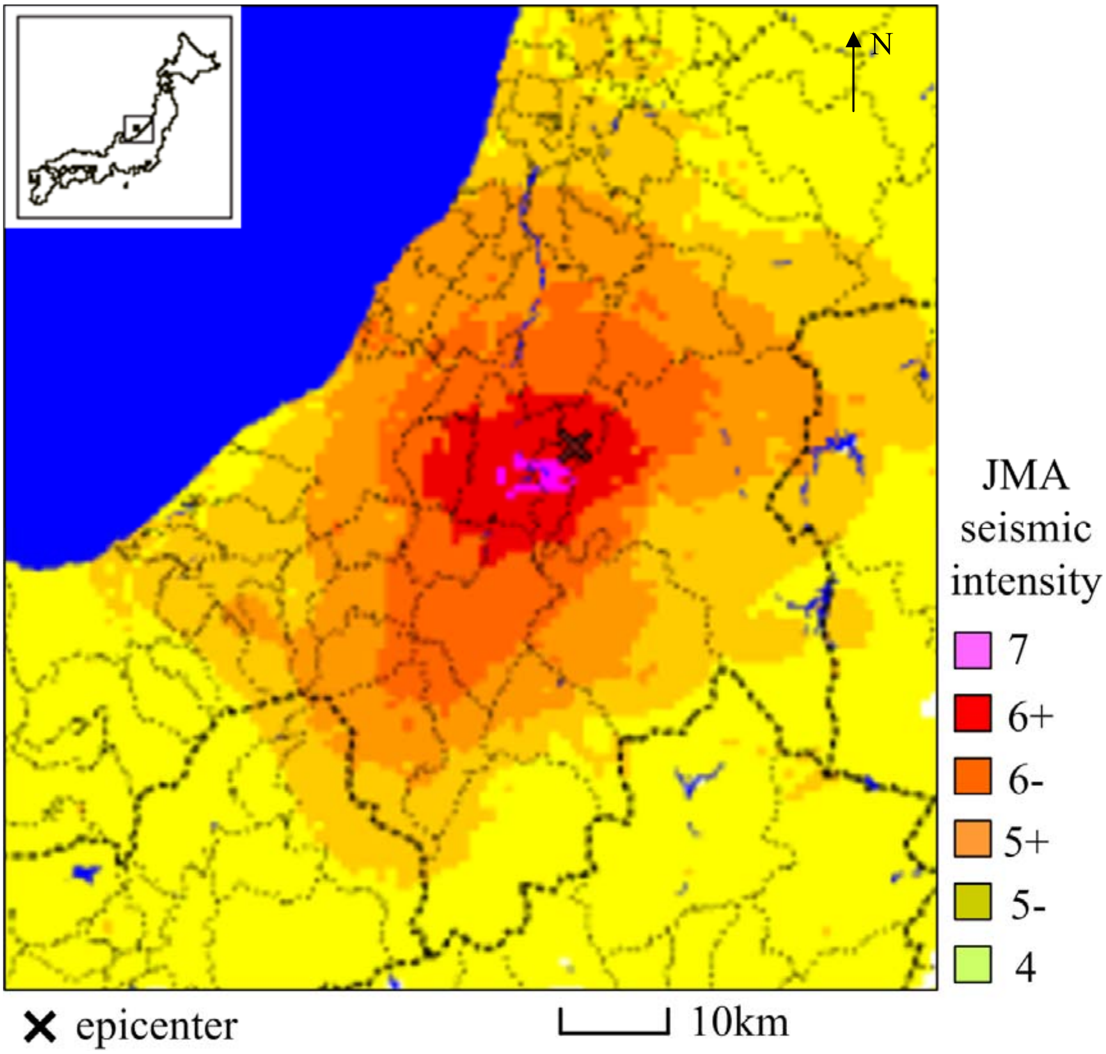
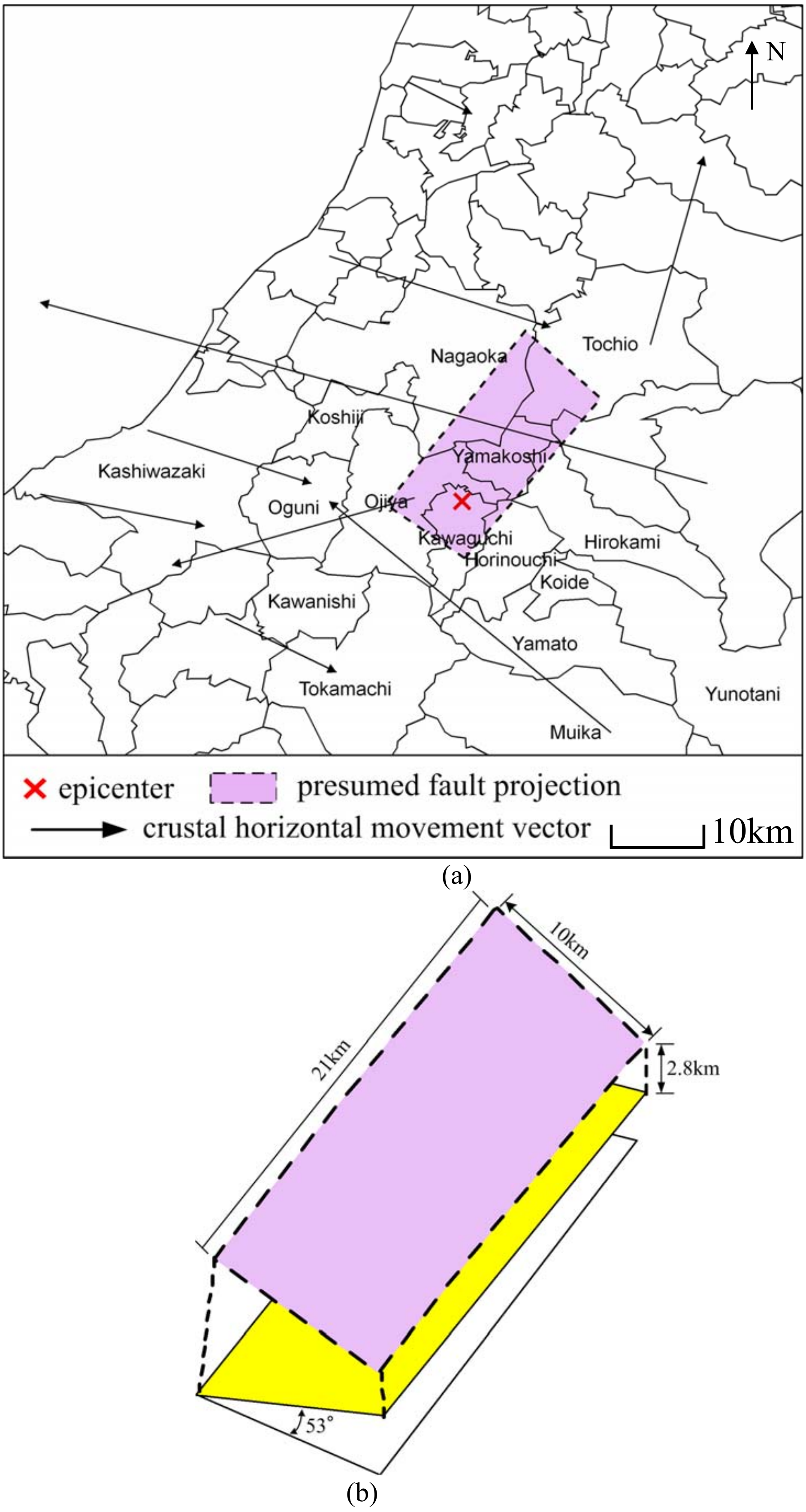


Figure 1 Intensity of the 2004 Mid Niigata Prefecture Earthquake (After JMA 2004)



(a)

(b)

Figure 2 The presumed fault and the crustal horizontal movement vector

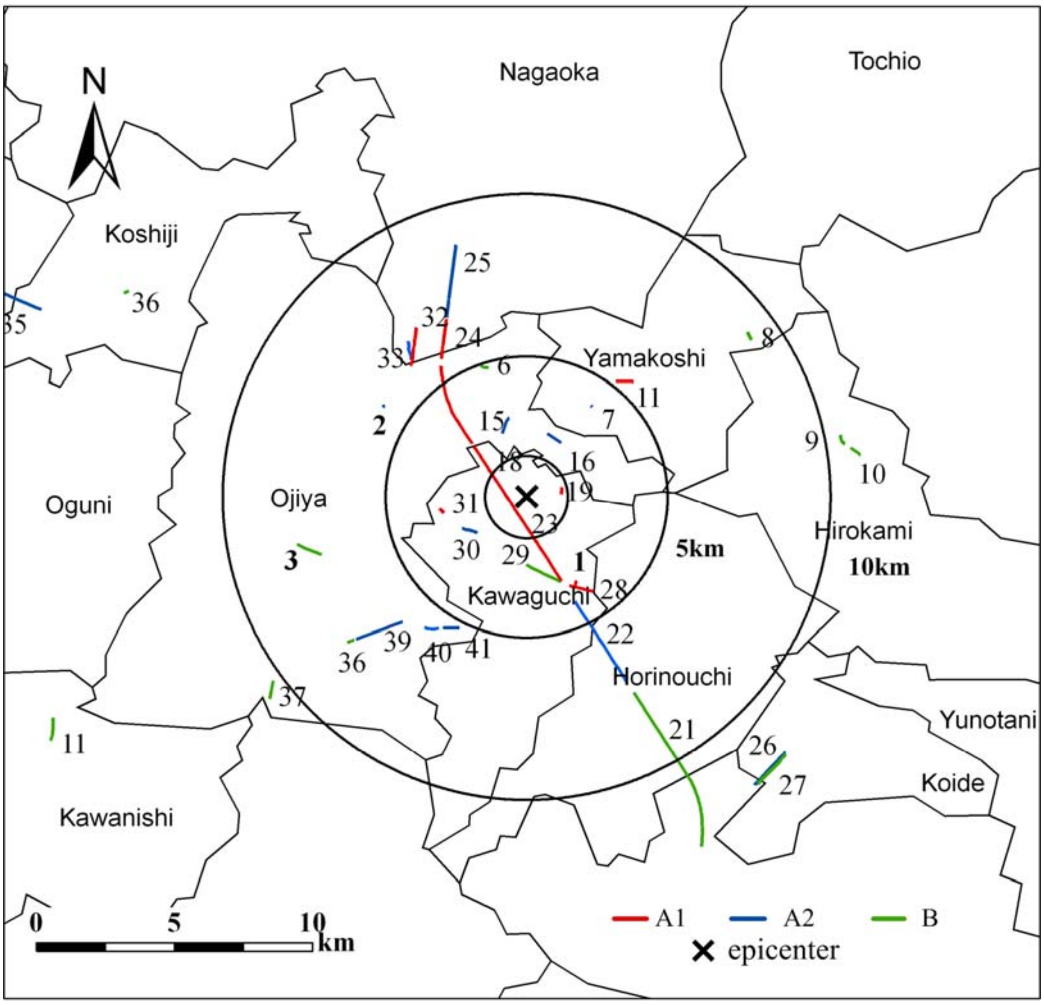
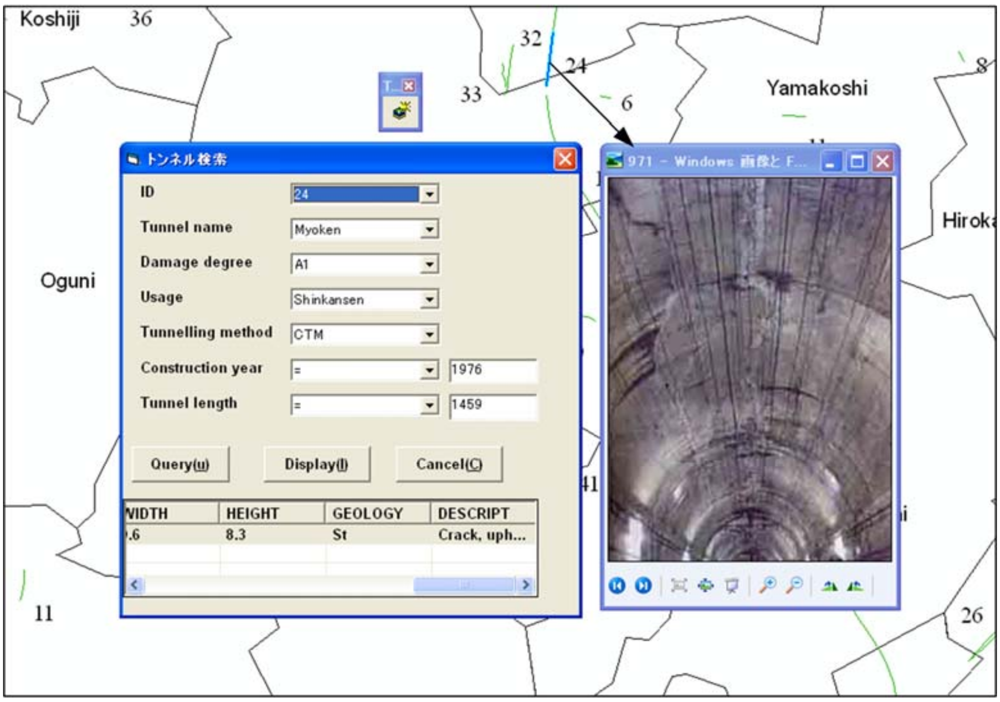


Figure 3 The distribution of the damaged tunnels (The numbers are the sequence number listed in Table 1. The color lines are the damage degree A1, A2 and B listed in Table 2).



ID 24
Tunnel name Myoken
Damage degree A1
Usage Shinkansen
Tunnelling method CTM
Construction year = 1976
Tunnel length = 1459

VIDTH	HEIGHT	GEOLOGY	DESCRIPT
.6	8.3	St	Crack, uph...

Figure 4 The query tool in the ArcGIS database

(a) Spalling of lining in Uonuma tunnel

(b) Crack and spalling of lining in Kizawa tunnel

Figure 5 Damage pattern – crack and spalling of lining (After Konagi et al. 2005)

(a) A landslide obstructed the portal entrance in Enoki tunnel

(b)Gravels obstructed the portal entrance in Sinotani tunnel

Figure 6 Damage pattern - landslide and debris flow obstructed the portal entrance (After Konagi et al. 2005)

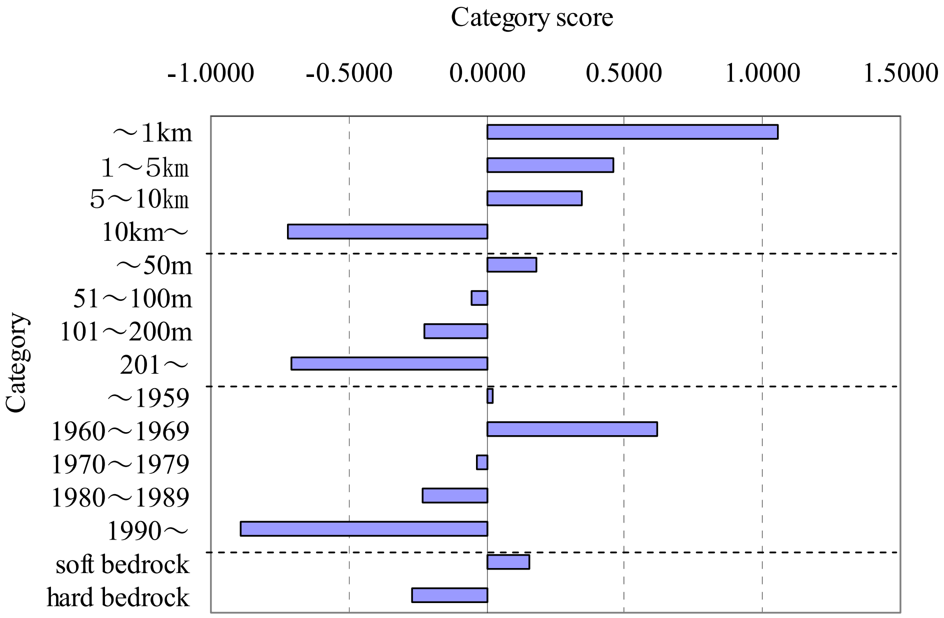


Figure 7 Category score in each item

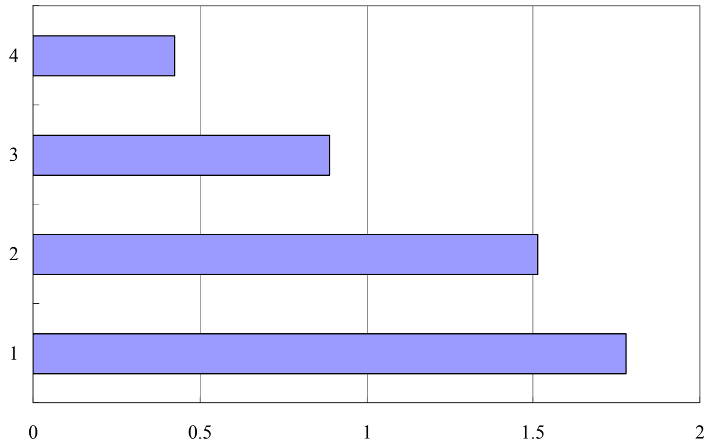


Figure 8 Item range (the number on y-axis represent indices 1: the distance to epicenter; 2: the completion time; 3: the overburden; 4: the geological conditions)

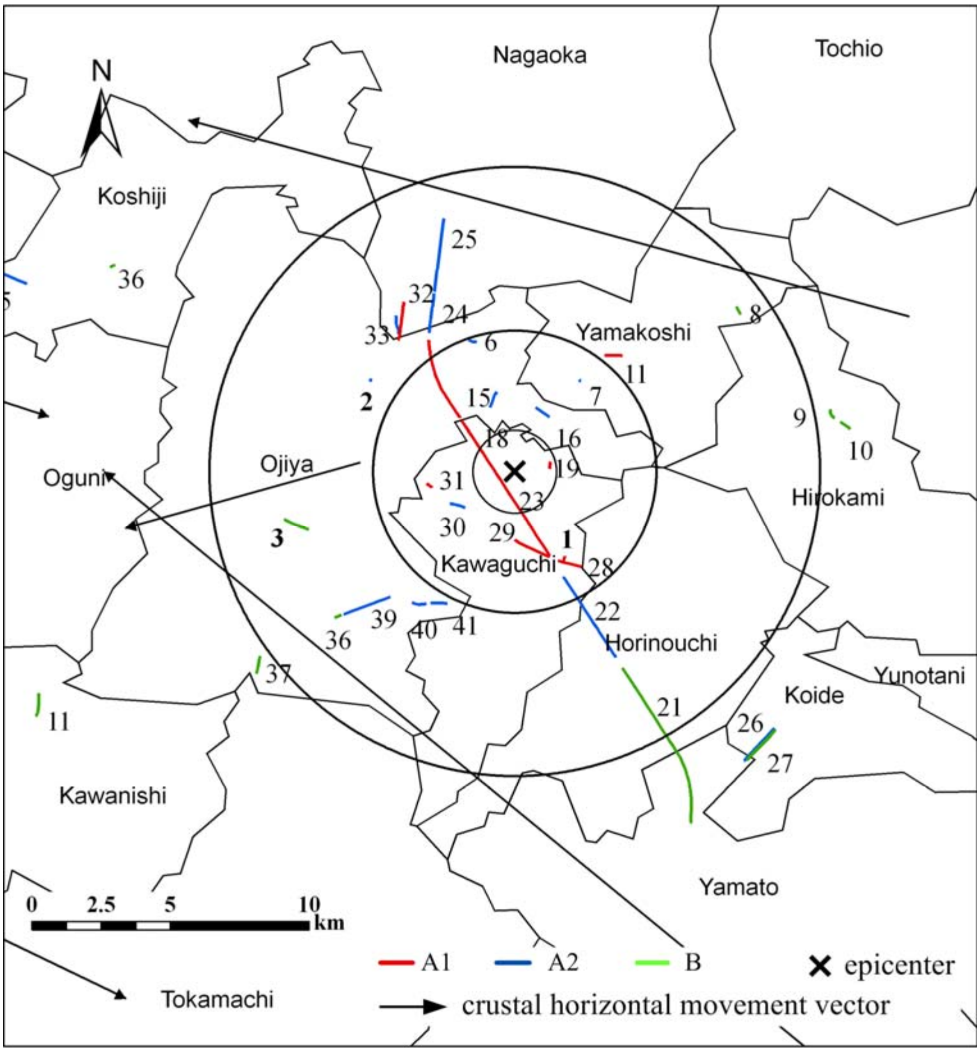


Figure 9 The assessment of the degree of tunnel damage using Hayashi's quantification theory type II

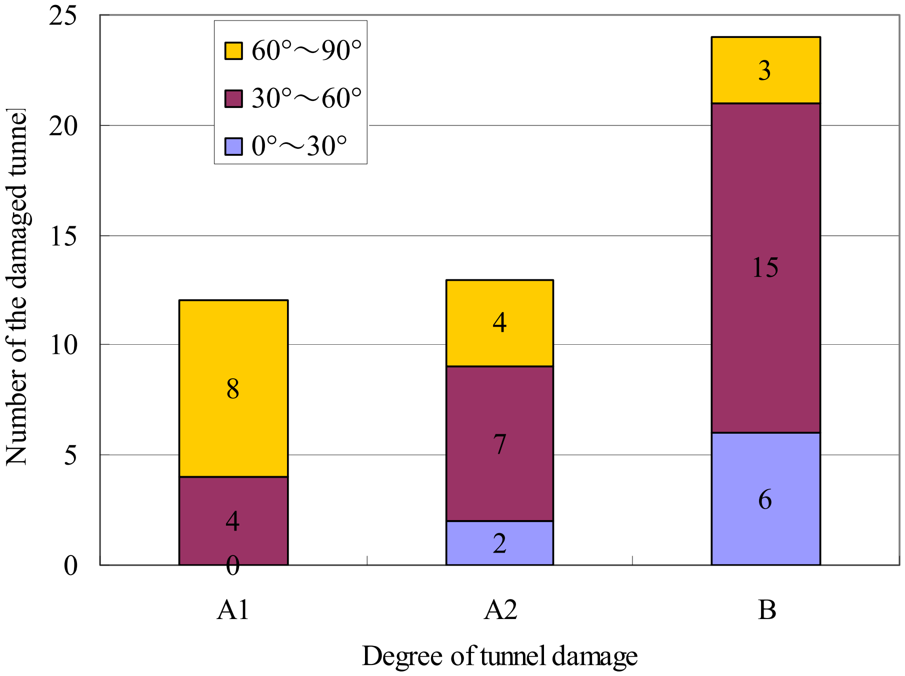


Figure 10 Influence of the angle between the presumed fault and the tunnel axes on tunnel damage