



STRONG GROUND MOTION ESTIMATION IN HOKKAIDO AREA AND DAMAGE ESTIMATION OF THE ROAD BRIDGE STRUCTURES

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ABSTRACT

Hokkaido is wide open with some major cities sparsely distributed, and road networks are important facilities. Once a deadly earthquake happens somewhere in the district, it can affect seriously major transportation services suspending rescue and restoring operations. Therefore mapping a rational tactics for re-covering transportation services based upon a reliable scenario of events is vital before everything. A scenario is developed for the island's largest metropolitan area, Sapporo, and its suburbs with Noppero Terrace fault system considered as causative. The empirical Green's function method is used to estimate seismic motions in the target area. Then its impact on the major road network is estimated assuming a strong correlation between peak ground velocity and extent of damage to bridges.

INTRODUCTION

Hokkaido is in one of the most seismically active regions in Japan. In just the previous two decades, major earthquakes have occurred in the subduction zone on the Pacific coast and in the active fault zone in the eastern margin of the Japan Sea. These include earthquakes off the coast of Kushiro in 1993 (M_J 7.5), off the southwest coast of Hokkaido in 1993 (M_J 7.8), off the east coast of Hokkaido in 1994 (M_J 8.2) and off the coast of Tokachi in 2003 (M_J 8.0). Bridges and earth structures were seriously damaged in the areas close to the hypocenters of these earthquakes. (Note: " M_J " refers to the seismic intensity scale defined by the Japan Meteorological Agency (JMA).)

The southern part of Sapporo, the capital of Hokkaido, had an M_J 3.0 earthquake on October 20, 2010, and an M_J 4.6 earthquake on December 2, 2010 (referred to as "EQ A" below). EQ A was the largest quake to hit the region since 1923 (JMA, 1923-2013). Because the epicenter was in the area where the Noppero Hill Fault Zone was thought to exist, EQ A is likely to have been caused by the fault zone.

It is predicted that an earthquake greater in magnitude than M_J 7.0 will occur when the Noppero Hill Fault Zone becomes active throughout its entire area. The Noppero Hill Fault Zone is in a densely populated area where the cities of Kitahiroshima and Ebetsu are located, and it is close to Sapporo. In light of this, the Noppero Hill Fault Zone is among the most dangerous active faults in Hokkaido. In the area where the Noppero Hill Fault Zone extends, there are highway networks connecting Sapporo to New Chitose Airport and Tomakomai Port. When highway bridges are damaged by an earthquake, transportation and distribution by highway networks becomes difficult or impossible. This will impede the rescue operations, such as evacuation of earthquake victims and delivery of relief supplies, that are needed immediately after the earthquake. Restoration and reconstruction activities will be also disrupted. Thus, the

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formulation of a business continuity plan (BCP) is required for securing operations that use highways. For this purpose, it is necessary to conduct a wide-area estimation of damage to highway bridges caused by an earthquake of the predicted magnitude. Based on the estimation, appropriate measures for mitigating damage and preventing secondary effects of the earthquake should be included in the BCP. In drawing up a BCP, it is necessary to accurately estimate the damage to highway bridges caused by an earthquake of the predicted magnitude, and to assess the impact of the damage on highway functionality. Research on techniques for estimating structural damage has been conducted, and the results have been used in simulations of earthquake damage conducted by municipalities (General Insurance Rating Organization of Japan, 2006). However, few studies have addressed structural damage and impairment of highway functionality (Okamoto et al. 2013).

In this paper, earthquake motion is evaluated and damage to highway bridges is estimated on the assumption of an earthquake in the Nopporo Hill Fault Zone. The damage estimate is used for analyzing the impacts of an earthquake on highway functionality. Additionally, motion waveforms are calculated for an area around the hypocenter that covers suburbs of Sapporo where highway bridges (i.e., seismological observation points) are located. For calculating the motion waveforms, the empirical Green's function, which is considered to be an optimum technique for estimating strong ground motions, is used. Based on the calculated waveforms, ground motions estimated by using attenuation relationships are examined and compared with the design seismic motions used in the current design guideline for highway bridges.

Outline of the Nopporo Hill Fault Zone and previous earthquakes

The Nopporo Hill Fault Zone is 20 km long, and faults lie at the eastern foot and western foot of Nopporo Hill, 15 km east of Sapporo (Okamoto et al. 2002). The fault strike is about 170 degrees, measured clockwise from north, and an earthquake as strong as M_J 7.0 is expected to occur (The Headquarters for Earthquake Research Promotion (HERP). 2013). According to the Headquarters for Earthquake Research Promotion, a governmental organization, the fault recurrence interval is about 7,900 years, and the probability of an M_J 7.0 earthquake in the next 30 years or 50 years is 0.38% or 0.63%, respectively (HERP, 2006). In figure 1, solid lines show the surface traces of the faults.

Earthquakes in and after 1923 were identified by referring to the Monthly Report on Earthquakes and Volcanoes in Japan (JMA, 1923-2013) issued by the Japan Meteorological Agency. Usami's Catalog2) was also used for collecting data on major earthquakes before 1923. Figure 1 shows the hypocenter distribution for earthquakes whose magnitude is M_J 2.0 or greater and whose focal depth is known. This figure also shows the observation point i002k001 (in the Warning Information System of Earthquake (WISE) of the Hokkaido Regional Development Bureau) 15 km from the epicenter of the earthquake on December 2, 2010. The strongest ground motion was recorded at this observation point.

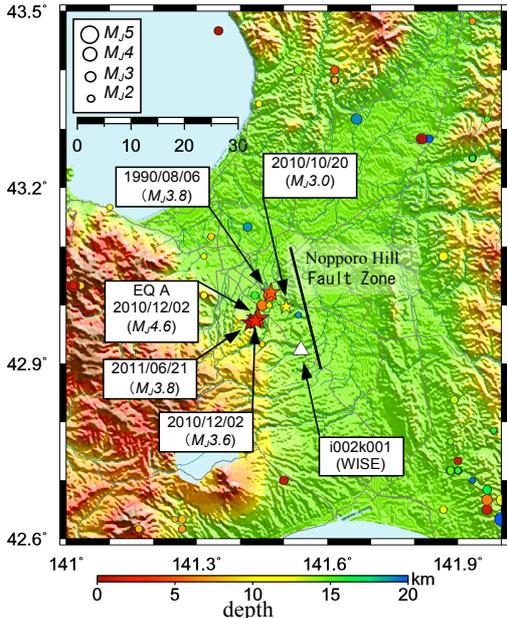


Figure 1 Epicenter in and around the Nopporo Hill Fault Zone (after 1923, M_J 2.0 or greater)

Analysis of the motions of earthquakes with hypocenters in or around the Nopporo Hill Fault Zone

The characteristics and the distribution of ground motions in and around the Nopporo Hill Fault Zone are analyzed regarding EQ A, the M_j 4.6 earthquake that occurred on December 2, 2010. Ground motions of EQ A were recorded at 73 observation points including those of WISE by the Hokkaido Regional Development Bureau and of K-NET and KiK-net by the National Research Institute for Earth Science and Disaster Prevention (NIED). The largest motion was recorded at i002k001 for WISE. Figure 2 shows the time-history waveforms of ground acceleration and velocity, along with the acceleration response spectra (attenuation constant $h = 5\%$).

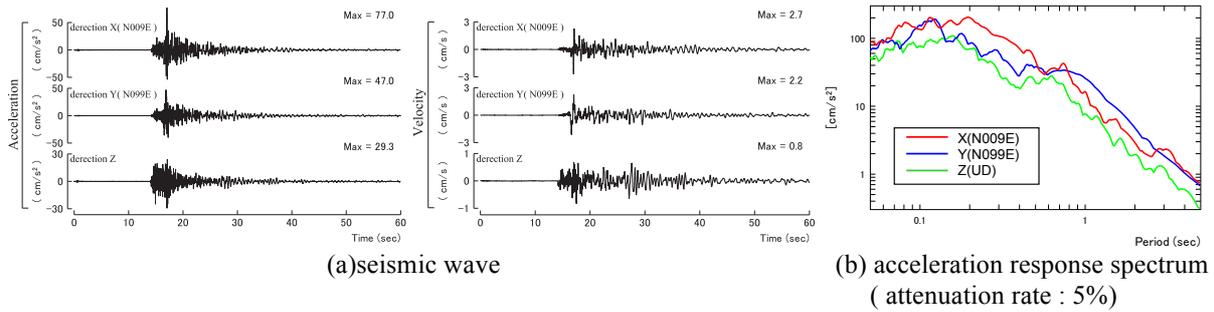


Figure 2 ground motion on the observation point i002k001 (EQ A)

The pre-dominant period of the acceleration response spectra is a relatively short 0.1-0.2 sec. This predominant period is shorter than the predominant period (i.e. 0.3-0.7 sec. of Type I Ground) with respect to Type II spectra of Level 2 seismic motions specified in the Specifications for Highway Bridges and in "Chapter V. Aseismic Design" of the related instruction manual (Japan Road Association (JARA), 2012) (collectively called "the Specifications for Highway Bridges" below), which are generally used as guidelines for aseismic design. The current quake-resistance standard for highway bridges is the predominant period of 0.3-0.7 sec.

The peak ground acceleration (PGA) and the peak ground velocity observed (PGV) in EQ A are analyzed in comparison with the attenuation relationships (Si and Midorikawa, 2008) developed by Si and Midorikawa. The value of moment magnitude M_w is set at 4.5, according to the calculations done by the Japan Meteorological Agency, and the distance to the hypocenter is assumed to be the shortest distance to a fault plane. Because the attenuation relationships are based on the engineering bedrock, the greatest observed value of the ground velocity is divided by the amplification factor of the peak ground velocity to obtain a peak ground velocity in the engineering bedrock. The amplification factor of the peak ground velocity used in this study was calculated by Sato et al. (2008) by taking into account the distribution of the velocity amplification factors specific to Hokkaido, as shown in Figure 3. The observed peak ground velocity and acceleration are correlated to the attenuation relationships in Figure 4.

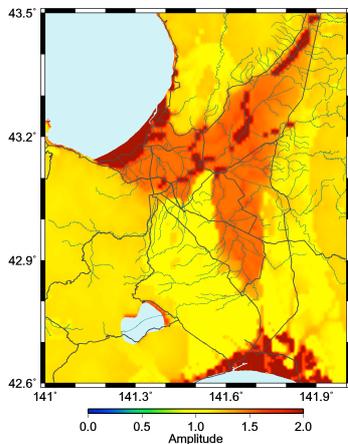
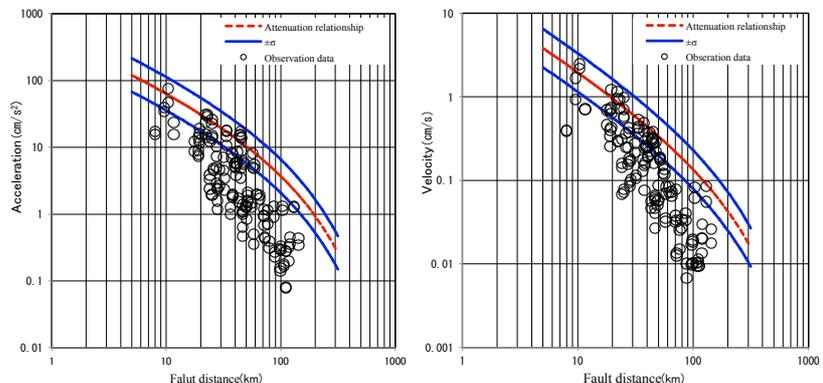


Figure 3. the site amplification factors for PGV (the area for analysis)



(a) PGA on ground surface (b) PGV on engineering bedrock

Figure 4. peak motion and attenuation relationship (EQ A ; MJ4.6, 2/12/2010)

In the attenuation relationships developed by Si and Midorikawa, both the peak ground acceleration and the peak ground velocity simulate the peak values recorded at observation points relatively close to the hypocenter, namely about 40 km from the hypocenter; thus, the attenuation relationships match the observed peak values.

On the other hand, at the observation points farther from the hypocenter, the values obtained by the attenuation relationships tend to be greater than the observed values. In Figure 5, the values of observed peak ground acceleration are compared with the values estimated by attenuation relationships for four small or moderate-sized earthquakes that occurred around the hypocenter of EQ A. For earthquakes (a) and (b), whose epicenters are closer to the Nopporo Hill Fault Zone than was that of EQ A, the attenuation with distance is greater than that for estimation by the attenuation relationships, although it is possible that the attenuation depends on the size of the earthquakes. In earthquakes (c) and (d), whose epicenters are closer to the epicenter of EQ A, the observed values correlate with the estimated values in a way similar to the correlation between the observed values and the estimated values for EQ A shown in Figure 4. This result suggests that earthquakes whose hypocenters are close to each other are similar in terms of the correlation between the observed values and the estimated values of peak ground acceleration.

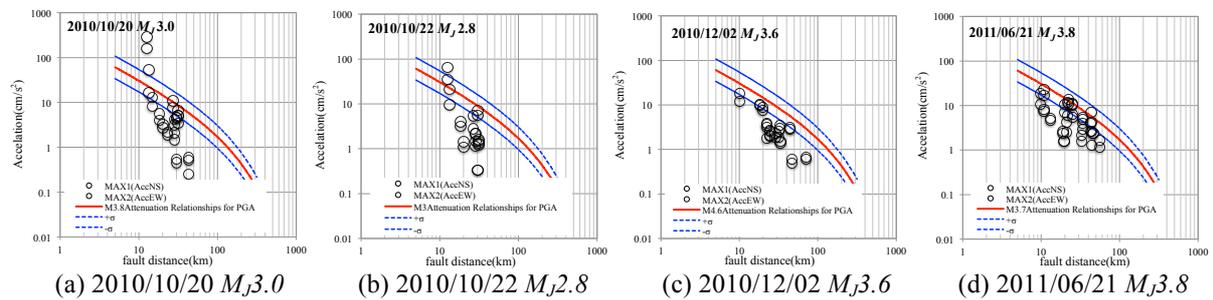


Figure 5. Peak motion and attenuation relationship (around the hypocenter of EQ A)

Estimation of damage to highway bridges

(1) Analysis conditions

Estimation of damage to highway bridges is conducted for the area between the latitudes of 42.6 and 43.5 degrees North and the longitudes of 141.0 -142.0 degrees East. This area includes the Nopporo Hill Fault Zone and major national highways connecting to Sapporo (e.g., R12, R36 and R274). Figure 6 shows the area for analysis. The heavy solid line indicates the surface trace of the Nopporo Hill Fault Zone.

The severity of damage to highway bridges varies depending on the peak value, the period/phase characteristics and the duration of earthquake motions. Thus, the peak ground velocity is provisionally used as a damage index in this study, because it has been reported that the structural response correlated closely with the peak amplitude of ground surface motions (Kitahara and Itoh, 1999) and that the damage index correlated closely with the peak ground velocity in a relatively wide range of the periodic band (Ando et al. 1990).

(2) Analysis method

Earthquake motions are evaluated according to the following procedures. First, attenuation relationships are used for calculating peak ground velocities in the bedrock of the Nopporo Hill Fault Zone. The magnitude of the earthquake is assumed to be $M_j 7.0$. Peak ground velocities in the engineering bedrock are estimated by using the equation of attenuation relationships developed by Si and Midorikawa (2008). The distance from the hypocenter to the point where earthquake motions are evaluated is represented by the shortest distance to the fault plane. The equation of Si and Midorikawa is often used for evaluating earthquake motions in a wide area. As mentioned above, the equation does not underestimate earthquake motions; thus,

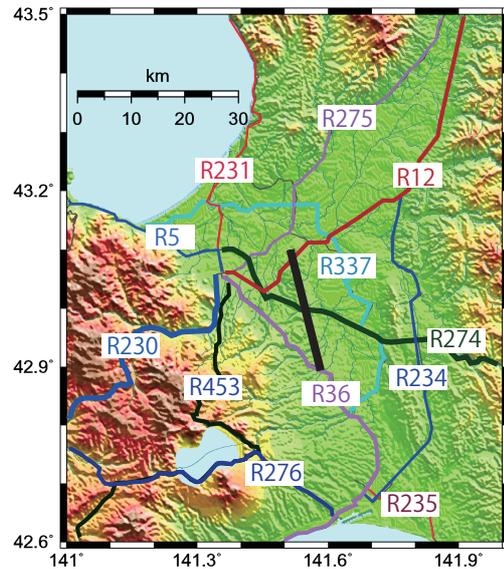


Figure 6. Nopporo Hill Fault and area for analysis

the evaluation results are useful for formulating proactive measures against earthquake disasters. Accordingly, the equation is applicable to the evaluation of earthquake motions in the area dealt with in this study.

Second, the peak ground velocity in the engineering bedrock is multiplied by the velocity amplification factor (Sato et al. 2008) at each point of motion evaluation for obtaining the peak ground surface velocity.

The authors reexamined the index of damage to highway bridges correlated with the estimated peak ground velocity on the basis of the information provided by Sato et al. (2010) The reexamination process is outlined below.

Table 1. Changes in the bridge structure seismic design code

Series	Year of revision	Revision standards	External force	Seismic Performance
1926 (T15)	1926	Detail of Road Design Standards (Draft)	Strongest seismic motion at the location	C
1939 (S14)	1939	Specifications for Steel Road Bridge (Draft)	20% horizontal and 10% vertical load of the dead weight Conditions of the construction site must be considered.	
1956 (S31)	1956	Specifications for Steel Road Bridge	Horizontal seismic intensity must be considered depending on ground conditions and regions. (Introduction of the coefficient of regional difference)	
1971 (S46)	1971	Seismic Design Guideline for Highway Bridge	Change in the calculation method for horizontal seismic intensity	
1980 (S55)	1981	Specifications for Highway bridges Part V Seismic Design	Change in the coefficient of regional difference	B
1990 (H2)	1990	Specifications for Highway bridges Part V Seismic Design	Change of ground types	
1996 (H7)	1996	Restoration Specifications	Change in external force	A
1996 (H8)	1996	Specifications for Highway bridges Part V Seismic Design	Change in external force	
2012 (H24)	2012	Specifications for highway bridges Part V Seismic Design	Change in external force	A+

T: Taisho; S: Showa; H: Heisei (names of Japanese eras)

As shown in Table 1, the required aseismic capacity of highway bridges has changed with revisions to design standards such as the Specifications for Highway Bridges. First, the required aseismic capacity was classified into four types depending on the design load specified in the applicable design standards, irrespective of the years elapsed since construction and the aging of highway bridges. The extent of damage to highway bridges was divided into three types, depending on trafficability: "no damage", "minor damage" and "major damage". "Minor damage" means that short-term traffic control is enforced when the highway bridge is repaired; "major damage" means that highway bridges need to be closed to traffic during repairs. Highway bridges in Hokkaido are different from those in other regions in that they typically have wall-type piers; thus, records of damage to highway bridges in Hokkaido alone were used for damage estimation. In the 1993 earthquake off the coast of Kushiro, horizontal ground motions of 29.6 cm/s or greater damaged highway bridges. Regarding the 2003 earthquake off the coast of Tokachi, the horizontal ground motion was 52.3 cm/s at an observation point (K-NET Ikeda) near the Chiyoda Ohashi Bridge along Nat'l Highway 242, which was damaged by the earthquake. In the same earthquake, the horizontal ground motion was 77.6 cm/s near the Tokachi Kakokyo Bridge, which was damaged and was closed to traffic for a brief period. Based on the records of these horizontal ground motions, and taking into account the likelihood of minor damage to bridges of aseismic capacity grade A as defined in the Specifications for Highway Bridges (JARA, 1996) revised after the Southern Hyogo Prefecture Earthquake, the authors set the threshold values of the peak ground velocity at 25 cm/s, 50 cm/s and 100 cm/s. These threshold values and the extent of damage are correlated in Table 2. The aseismic capacity grade of A+ is excluded from Table 2, because this grade was not introduced into the Specifications for Highway Bridges until the FY 2012 revision, due to modifications to applicable design load, and no records are available for bridges of aseismic capacity grade A+. Figure 7 shows the locations of the highway bridges used for estimation of damage. The aseismic capacity grades of these bridges were determined on the basis of Table 2. Figure 8 shows the distribution of the peak ground velocities. As mentioned above, because the attenuation relationships provide typical peak ground velocities, the estimated damage should be understood as typical damage.

Table 2. Bridge structure seismic damage index

Seismic Performance	Max. velocity(cm/s)			
	25	50	100	
A	I	I	I	II
B	I	II	II	III
C	I	II	III	III

I: Undamaged bridges
 II: Bridges with minor damage not requiring repair
 III: Bridges with serious damage requiring large-scale repair (e.g., shear failure of bridge piers)

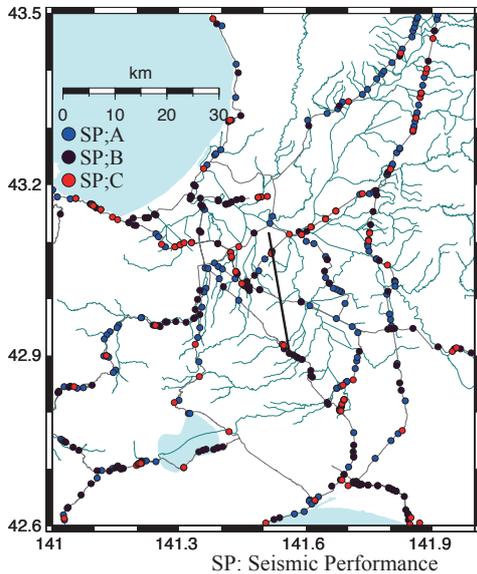


Figure 7. the locations of the highway bridges used for estimation of damage

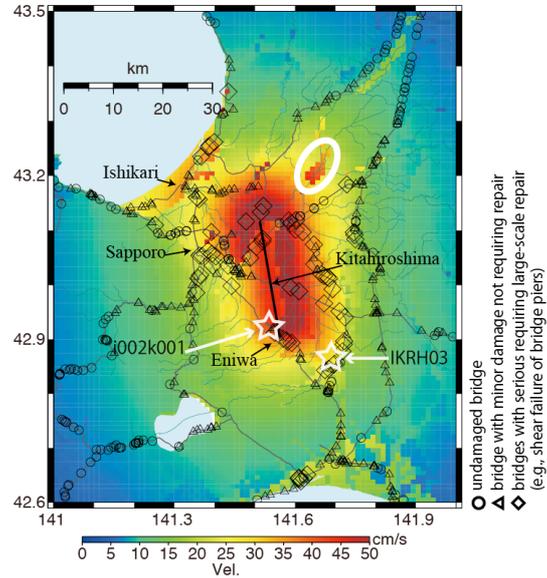


Figure 8. the distribution of peak ground velocities and the estimated damage to highway bridges on the assumption of an earthquake occurring in the Nopporo Hill Fault Zone

(3) Estimation of damage to highway bridges, and evaluation of how the damage affects highway functionality

Figure 8 shows the distribution of peak ground velocities and the estimated damage to highway bridges on the assumption of an earthquake occurring in the Nopporo Hill Fault Zone. Each circle (○), triangle (△) or diamond (◇) indicates no damage, minor damage, or major damage, respectively. Table 3 shows the details of the estimated damage. The number of the highway bridges used for damage estimation is 452: 70 with major damage, 218 with minor damage and 164 with no damage. Nat'l Highway 337 has the greatest number of bridges with major damage, namely 20 bridges. This national highway is east of the Nopporo Hill Fault Zone, running parallel to it. On Nat'l Highways 36 and 337, to the west and east of the fault zone, respectively, and on Nat'l Highway 231, along the Sea of Japan to the far north of the fault zone, the rate of major damage (i.e., the number of bridges suffering major damage per route/ the total number of bridges per route) was high, at around 30%. On Nat'l Highways 12 and 274, running perpendicular to the fault zone toward the north and in the center, respectively, the rate of major damage was about 10%.

Focusing on Nat'l Highways 12, 36 and 274, the effects of the assumed earthquake are examined below. Additionally, the effects of damage to highway bridges on travel to Sapporo are analyzed by comparing the travel distances to Sapporo via alternative routes. For this purpose, the distance to the center of Sapporo from the major intersection that is closest to the highway bridge suffering major damage and that is on the same route as said highway bridge was calculated.

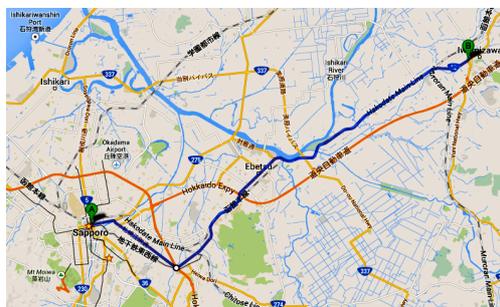
Table 3. details of the estimated damage

Route	object route length (km)	Number of bridges(a) (A)+(B)+(C)	number of the estimated damage bridge												Number of bridge (damage index III)(b)	rate of major damage		
			Seismic Performance: A			Seismic Performance: B			Seismic Performance: C			(b)Σ(a)	(b)Σ(b)					
			I	II	III	I	II	III	I	II	III							
5	38.2	28	16	0	0	0	16	0	6	0	0	6	2	3	1	6	0.2%	1.4%
12	80.1	60	21	1	0	0	22	3	3	2	8	7	15	8	30	10	2.2%	14.3%
36	76.4	35	2	2	0	0	4	0	16	5	21	0	4	6	10	11	2.4%	15.7%
230	59.5	40	4	0	0	0	4	6	12	0	18	13	5	0	18	0	0.0%	0.0%
231	56.2	27	3	0	0	0	3	1	12	0	13	1	2	8	11	8	1.8%	11.4%
234	69.6	37	7	0	0	0	7	0	11	0	11	1	15	3	19	3	0.7%	4.3%
235	35.1	36	3	0	0	0	3	4	26	0	30	0	3	0	3	0	0.0%	0.0%
274	64.9	38	8	0	0	0	8	1	22	4	27	0	0	3	3	7	1.5%	10.0%
275	68.9	26	2	1	0	0	3	1	2	1	4	10	7	2	19	3	0.7%	4.3%
276	67.8	38	5	0	0	0	5	15	8	0	23	6	0	4	10	4	0.9%	5.7%
337	81.6	65	10	7	0	0	17	0	28	2	30	0	0	18	18	20	4.4%	28.6%
453	88.5	22	5	0	0	0	5	3	1	0	4	4	6	3	13	3	0.7%	4.3%
total	786.8	452	86	11	0	0	97	34	147	14	195	44	60	56	160	70		

a) Nat'l Highway 12

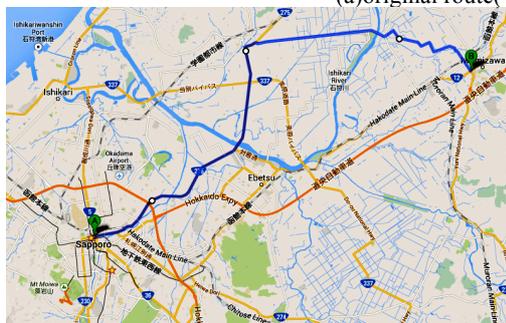
Nat'l Highway 12 is an important highway connecting Sapporo to the City of Asahikawa, and 60 bridges are on this highway in the area for analysis. As shown in Figure 8, Nat'l Highway 12 crosses the northern part of the Noppero Hill Fault Zone, and the estimated earthquake motions are large. The bridges that would suffer major damage are concentrated in the north of the fault zone. The rate of major damage on this highway is 15%, and the impacts of the assumed earthquake are estimated to be large.

On Nat'l Highway 275, which runs parallel to Nat'l Highway 12 on the north side, only three bridges would suffer major damage. By taking proactive damage mitigation measures for the bridges on this highway, Nat'l Highway 275 can be used as a detour to Sapporo. The number of bridges on Nat'l Highway 275 is relatively small; thus, it does not take long to take necessary measures. This means that the risks to the public in the event of an earthquake occurs are reduced. Two other routes that can be alternatives to Nat'l Highway 12 are shown in Figure 9, in which the distance of each route is compared with the distance of Nat'l Highway 12 to Sapporo. Alternative route 1 is not much longer than the travel distance via Nat'l Highway 12; thus, it is considered to be reasonable. However, this alternative route, which includes prefectural highways, passes through an area circled in white in Figure 8 where the peak ground velocities are estimated to be great. Damage to the bridges on the prefectural highways in this area has not been estimated. Alternative route 2 is 1.5 times as long as the travel distance via Nat'l Highway 12, and it is not the best option in an earthquake emergency.



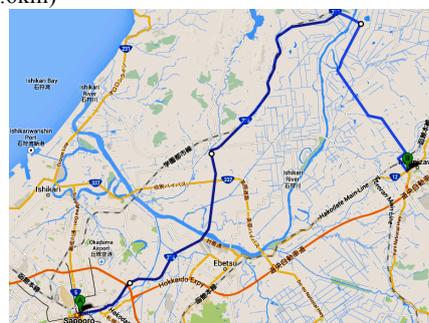
Map data ©2014 Google, ZENRIN

(a) original route(42.6km)



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(b) Alternative route 1 (47.6km)



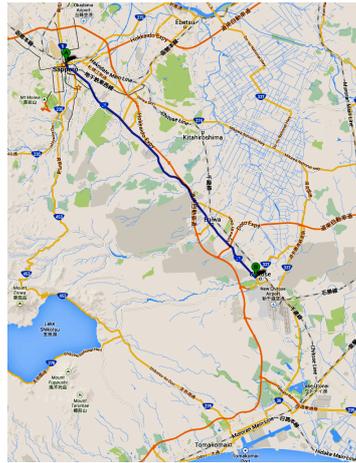
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(c) Alternative route 2 (67.9km)

Figure 9. Comparison with the alternative route(route 12)

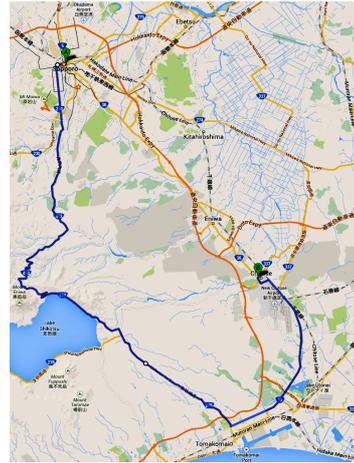
b) Nat'l Highway 36

Nat'l Highway 36 is a national highway connecting Sapporo to the City of Muroran, and 35 bridges are on this highway in the area for analysis. Nat'l Highway 36 is west of the Noppero Hill Fault Zone, running closest to this fault zone around the City of Eniwa, where peak ground velocities exceeding 50 cm/s are estimated. The earthquake load due to these ground velocities causes major damage. Specifically, it is estimated that four highway bridges on this route will suffer major damage. The proportion of bridges on this highway suffering major damage is 16%, and the effects of the assumed earthquake are estimated to be great. A route alternative to Nat'l Highway 36 is shown in Figure 10. This alternative route avoids areas suffering major damage and requires traveling southward on Nat'l Highway 36 and using Nat'l Highways 276 and 453. Consequently, while the distance to Sapporo via Nat'l Highway 36 is 36 km, the alternative route is 100 km, more than 100% longer. It is not useful in an emergency. As Figure 8 shows, major damage to highway bridges on Nat'l Highway 36 is only locally concentrated. By intensively reinforcing highway bridges that are predicted to suffer major damage, Nat'l Highway 36 will be available for traffic after the assumed earthquake.



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(a)original route (36.4km)



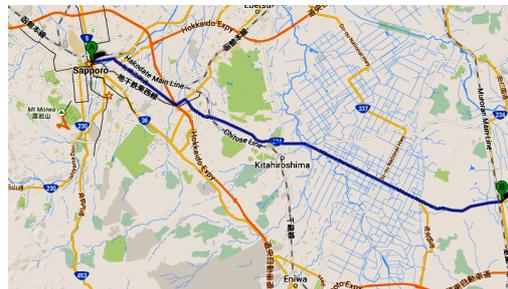
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(b)alternative route (101km)

Figure 10. Comparison with the alternative route (route 36)

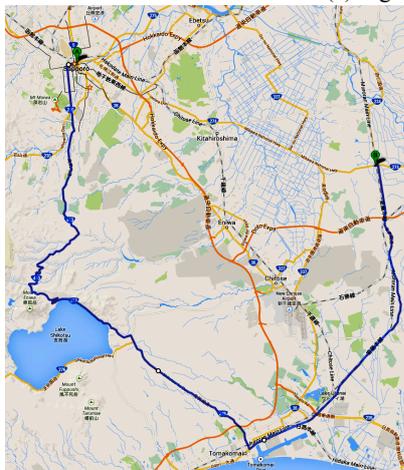
c) Nat'l Highway 274

Nat'l Highway 274 is a national highway connecting Sapporo to the Town of Shibechea via Kitahiroshima. In the area for analysis, 38 bridges are on this highway. Nat'l Highway 274 crosses the Nopporo Hill Fault Zone in the western part of the City of Kitahiroshima, where large-scale earthquake motions and major damage to highway bridges are expected. Both of the two alternative routes shown in Figure 11 are about 100 km in distance, or more than 100% longer than the distance to Sapporo via Nat'l Highway 274. As in the case of Nat'l Highway 36, major damage to highway bridges on Nat'l Highway 274 is only locally concentrated; thus, intensive reinforcement of highway bridges that are predicted to suffer major damage will be effective in ensuring trafficability of Nat'l Highway 274.



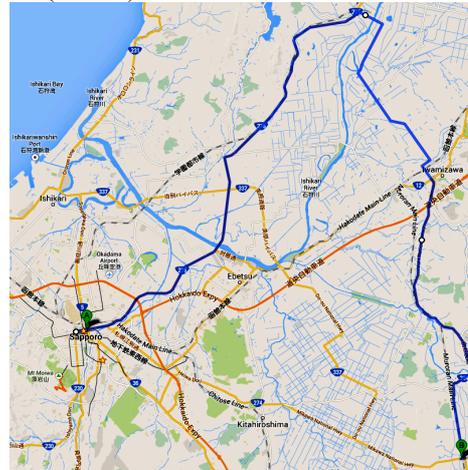
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(a)original route(41.3km)



Map data ©2014 Google, ZENRIN

(b) alternative route 1(118km)



Map data ©2014 Google, ZENRIN

(c) alternative route 2(99.6km)

Figure 11. Comparison with the alternative route (route 274)

Validation of the estimation of wide-area earthquake motions

The preceding sections used attenuation relationships for the purposes of evaluating earthquake motions and estimating damage to highway bridges around the Nopporo Hill Fault Zone. The evaluation of earthquake motions by means of attenuation relationships is effective in estimating the damage to highway bridges in a wide area. However, more de-tailed and accurate estimation of damage is not available with this evaluation technique.

For the purpose of evaluating the adequacy of the wide-area earthquake motion estimation, strong motions were calculated by using empirical Green's functions for two observation points used for the damage estimation, and the calculation results were compared with the earthquake motions evaluated by means of the attenuation relationships.

(1) Modeling of a hypocenter in the Nopporo Hill Fault Zone

As explained above, the Nopporo Hill Fault Zone is a 20-km-long, 15-km-wide fault zone about 15 km east of Sapporo. The fault strike is about 170 degrees measured clockwise from north, and an earthquake as strong as $M_j 7.0$ is expected to occur (HERP, 2013).

A hypocenter model is developed here by using empirical relational equations on the basis of the data on past earthquakes (HERP, 2013). While a hypocenter has a heterogeneous structure, a homogeneous, rectangular Strong Motion Generation Area (SMGA) is assumed on the fault plane according to the modeling technique of Kamae and Irikura (1997). The analysis factors in earthquake disaster prevention measures for highway bridges. Ground motions were assumed to have no directional bias in the area around the fault used for the analysis. An SMGA is placed at the center of the fault plane, and a rupture initiation point is located at the bottom center of the SMGA. A hypocenter model is shown in Figure 12. Because previous simulations of strong motions suggest that earthquake motions around a hypocenter are dominated by the strong motions generated in the SMGA (Ikeda et al. 2002), the SMGA alone is taken into consideration in evaluating strong motions, and the background area is excluded from analysis.

Observation data on an $M_j 4.6$ earthquake that occurred on December 2, 2010, were applied to empirical Green's functions. The epicenter is shown in Figure 13. The seismic moment was obtained from Centroid-Moment-Tensor Analysis of the Japan Meteorological Agency. To estimate the asperity area and the stress drop, corner frequencies were obtained from the displacement spectra of the hypocenter on the basis of the ground seismic waves observed at IKRH03 (i.e., one of the KiK-net observation points of NIED) near the hypocenter. Then a circular-crack model was used for estimating the asperity area and the stress drop. In consideration of effective long-period ground motions, a band-pass filter was used for passing frequencies in a range of 0.2 -10.0Hz. The rupture velocity and the shear wave velocity were assumed to be 2.5 km/s and 3.5 km/s, respectively. Irikura's method of waveform synthesis (Irikura, 1986) was applied to empirical Green's functions

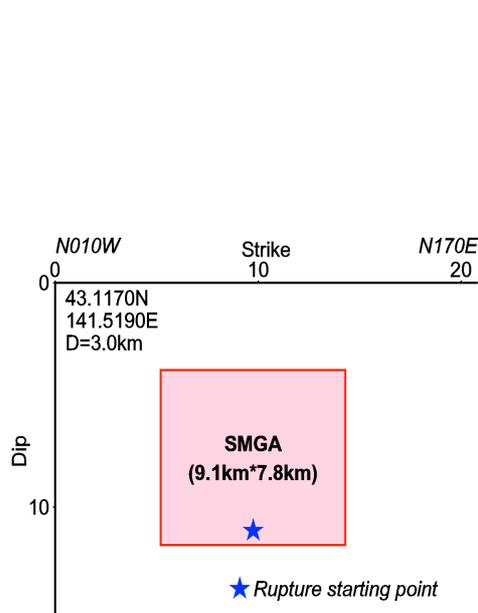


Figure 12. Model of a hypocenter in the Nopporo Hill Fault Zone

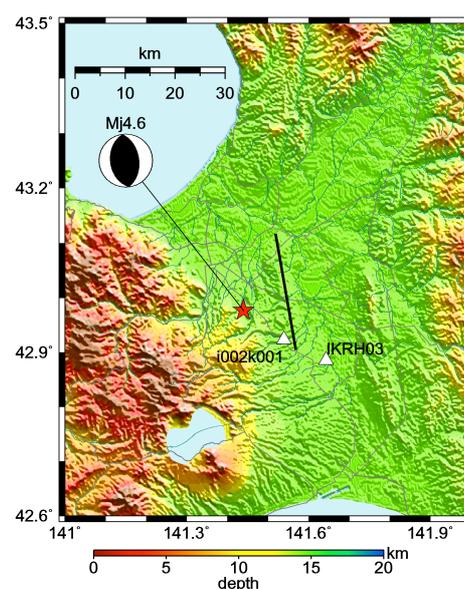


Figure 13. Strong-motion seismic evaluation and the epicenter of the earthquake to be used as the empirical Green's function

(2) Comparison between the strong motion evaluation results and the wide-area ground motion evaluation results

When empirical Green's functions are used for evaluation, synthesized waveforms are often overestimated in the soft ground where nonlinear behavior of ground is likely to take place (Ikeda et al. 2011). The reason is that the earthquake motions are expressed by superposition of empirical Green's functions based on the similarity law of hypocenter spectra and the similarity law of a major earthquake (i.e., the earthquake used for the wide-area ground motion evaluation) and a minor earthquake (i.e., the earthquake to which empirical Green's functions were applied in the analysis). In the analysis explained below, two observation points in relatively hard ground are used because these points are less affected by non-linear ground behavior. Specifically, i002k001 (i.e., a WISE observation point of the Hokkaido Regional Development Bureau in Shimamatsu, City of Kitahiroshima) and IKRH03 (i.e., an observation point in Kamaka, City of Chitose) are used for evaluating strong ground motions.

Figure 14 shows time-history waveforms of ground acceleration and velocity at these observation points. Because i002k001 is a point for observing the seismic response of a bridge, data is collected in the direction of the bridge long axis (X:N009E) and in the orthogonal direction (Y:N099E). The velocity waveforms obtained at i002k001 include pulsed waveforms that are possibly due to rupture directivity effects. Pulsed waveforms were confirmed near the hypocenter of the 1995 Southern Hyogo Prefecture Earthquake and of the 2000 Western Tottori Prefecture Earthquake. These waveforms are recognized as being responsible for damage to highway bridges. It should be noted, however, that the peak ground velocity at i002k001 is 40 cm/s and great enough to cause major damage. At the other observation point, IKRH03, the peak ground velocity is 78 cm/s, which is greater than that at i002k001, and the peak ground acceleration is not very high, at 370 cm/s². While pulsed waves are observed immediately after the arrival of S waves at i002k001, pulsed waves of high amplitude are observed about five seconds after the arrival of S waves at IKRH03. The acceleration response spectra (attenuation constant $h = 5\%$) of the strong motions are shown in Figure 15 (i002k001) and Figure 16 (IKRH03) along with the standard acceleration response spectra of the aseismic capacity grades A, B and C, shown in Table 1. Graph (a) shows Type II standard acceleration response spectra of Level 2 seismic motions specified in the Specifications for Highway Bridges and in "Chapter V. Aseismic Design" of the associated instruction manual revised in 1996. Graph (b) shows the standard acceleration response spectra according to the same specifications revised in 1990. To obtain the values shown in (c), the design horizontal seismic coefficients shown in the same specifications revised in 1971 were multiplied by a correction factor β specific to the natural period and by the gravitational acceleration. Each spectrum was multiplied by a region-specific correction factor, 0.85.

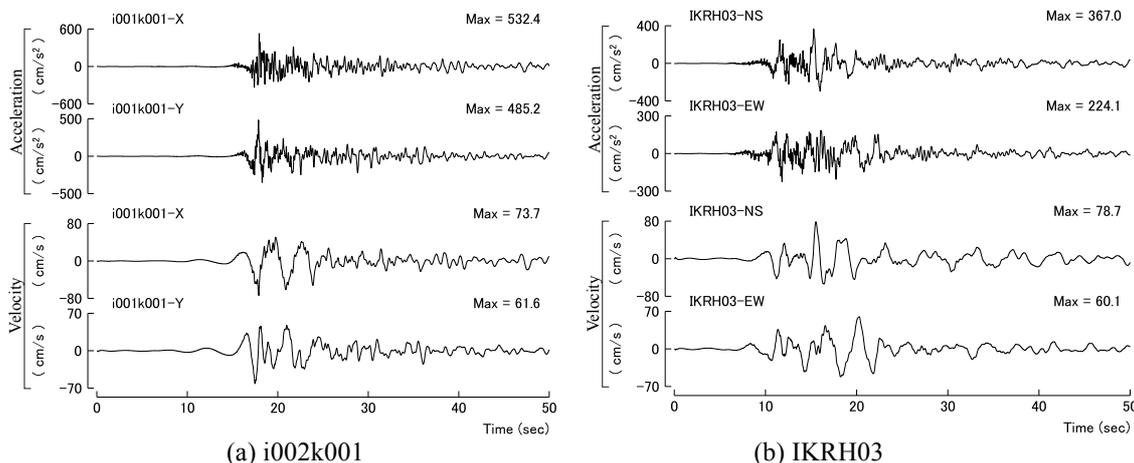


Figure 14. Strong motion evaluation results (time-history waveforms of ground acceleration and velocity)

The amplitude of the acceleration response spectra at i002k001 is relatively low in the time zone from 0.2 sec to 1.0 sec. In contrast to the acceleration response spectra of (b) and (c), the acceleration response spectra of (a) are similar to the spectra of Type I Ground in a limited range of the periodic band; thus, the acceleration response is expected to be on the same level as the yield stress. The amplitude of the acceleration response spectra of (a) is higher than the design amplitude in a range of the periodic band that is wider than the periodic band of the amplitude of the acceleration response spectra for (b) and (c). This result suggests that the risk of damage to highway bridges varies greatly depending on the years elapsed since construction.

At IKRH03, the response spectra in (a), (b) and (c) are similar in a wide range of the periodic band, and the spectral amplitude in the periodic band after 1.0 sec. is higher than the amplitude at i002k001. The acceleration response spectra of (a) are similar to the spectra of Type III Ground, being on the same level as the design spectra in a long-period range. As in the case of i002k001, the amplitude of the acceleration response spectra of (a) is 300 cm/s² higher on average than the design amplitude of (b) and (c) in every period.

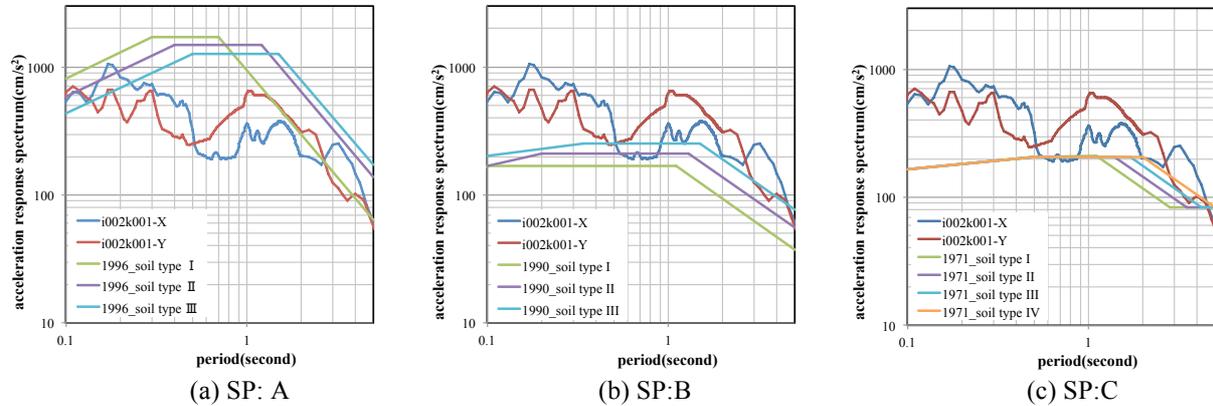


Figure 15. Strong motion evaluation results at i002k001 (acceleration response spectrums, attenuation rate : 5%)

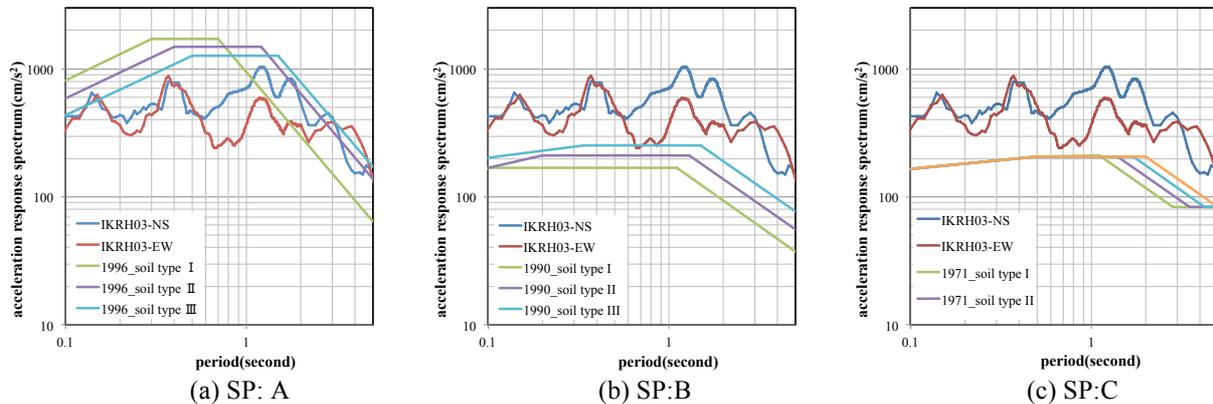


Figure 16. Strong motion evaluation results at IKRH03 (acceleration response spectrums, attenuation rate : 5%)

According to the wide-area ground motion evaluation results shown in Figure 8, the peak ground velocity at IKRH03 and i002k001 is 35 cm/s and 45 cm/s, respectively. The strong motion evaluation results show that the peak ground velocity at IKRH03 is greater, at 78.7cm/s. On the other hand, the peak ground velocity at i002k001 is 44.6 cm/s, al-most the same as the peak velocity estimated by using the attenuation relationships. It is necessary to examine the vari-ability of fault rupture properties and to conduct research in more areas for validating wide-area ground motion evalua-tion results.

CONCLUSIONS

Damage to highway bridges was estimated on the basis of the ground motion evaluations in and around the city of Sapporo, with the aim of helping to formulate a business continuity plan that achieves its ends by mitigating the loss of highway functionality that would occur from earthquake damage to highway bridges and by restoring highway func-tionality promptly after damage. The estimation results are summarized as follows:

- Based on records of past earthquakes, the Noppero Hill Fault Zone, which may be the origin of an inland earthquake affecting Sapporo, was used for the analysis of earthquake motions.
- Earthquake motions were evaluated by using the attenuation relationships developed by Si and Midorikawa as well as the amplification factor of peak ground velocities obtained from earthquake motions observed in Hokkaido. It was verified that this evaluation method is valid for estimating the peak ground acceleration and the peak ground velocity at observation points about 40 km from the hypocenter.

- Damage indices were evaluated in relation to peak ground velocities, and the degree of damage to highway bridges was estimated on the basis of the design standards applied to these bridges as well as the aseismic capacity grades of the bridges.
- The results of damage estimation provided important data that are useful for identifying alternative routes available in an emergency and the number of days necessary for restoring highways to their original functionality, as well as for prioritizing proactive measures necessary for reducing damage to highway bridges.

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