Damage Estimation of the Road Bridge Structure Using the Seismic Hazard map for BCM in Hokkaido, Japan

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SUMMARY:
The 2011 off the Pacific coast of Tohoku Earthquake, M9.0 occurred in 11th March, 2011, caused serious damage in the wide range of the Pacific coast in the Tohoku district. Because seismic activity of Hokkaido area is very high, a similar huge scale earthquake may occur in the near future. We performed the damage estimation of the road bridge structure using the seismic hazard map in Hokkaido as a part of earthquake measures for damage mitigation. It is thought that the estimation result contributes greatly to make BCM.

Keywords: BCM, Seismic hazard map, Road bridge structure, Disaster mitigation, Hokkaido-Japan

1. INTRODUCTION

Japan is located at one of the world's most seismologically active areas, and many of structures have been damaged by past large-scale earthquakes. Accordingly, it is important to minimize such damage through seismic design using seismic loads depending on regional characteristics and the importance of structures as well as by improving structural earthquake resistance through seismic reinforcement and repair.

In addition to direct structural damage, secondary damage caused by structural dysfunction must also be considered. Damage to bridges, tunnels and other road structures may cause road closures that hinder rescue activities (such as victim evacuation and relief supply transportation) and restoration and recovery activities.

It is therefore necessary to estimate the wide-area structural damage conditions expected when earthquakes occur in an area and to take appropriate measures in advance to prevent secondary damage.

In recent years, Business Continuity Management (hereafter BCM) is often introduced for such earthquake disaster mitigation management. BCM is a management process that identifies potential impacts that threaten an organisation and provides a framework for building resilience and the capability for an effective response which safeguards the interests of its key stake holders, reputation, brand and value creating activities. For the road infrastructure administration organization, the occurrence of the large scale earthquake and the damage of the road structure are equivalent to identify potential impact to threaten organization.

This paper presents the results of estimating seismic damage for bridge structures using seismic hazard maps for the purpose of the BCM making of road installations. The area of this study is Hokkaido which is the one of the highest earthquake risk in Japan

2. SEISMIC HAZARD MAP

The seismic hazard maps produced in this study are intended for use as basic data in making BCM for road infrastructure administration organization by estimating seismic damage to structures based on the seismic load of each earthquake and using structural damage indexes, and indicate both the seismic load and structural damage conditions. Figure 1 shows the algorithm for seismic hazard map production. It consists of three parts preparation of structural damage indexes, estimation of seismic loads and estimation of seismic damage.

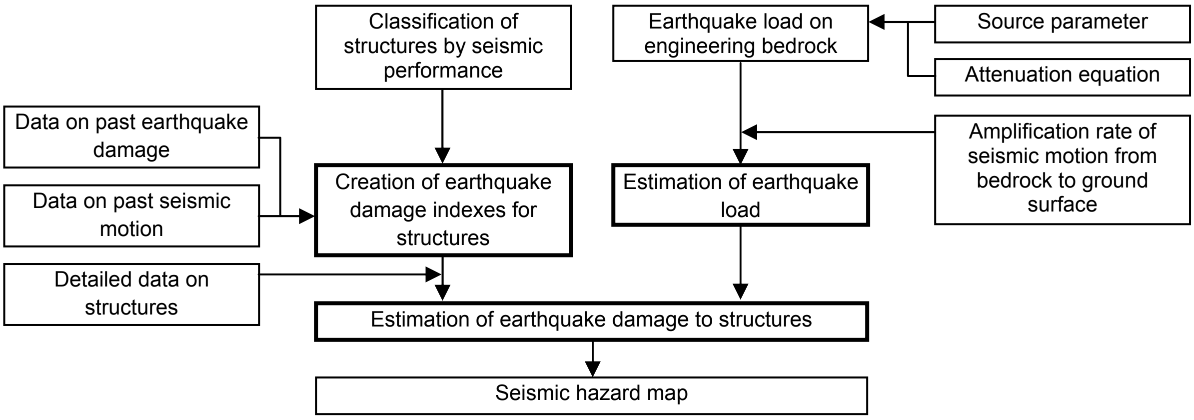

Figure 1. Algorithm for seismic hazard map creation

2.1. Damage index of road bridge structure

Since seismic performance varies by structure due to the variety of conditions involved (even for the same types of bridge, etc.), structures were first classified in accordance with the design criteria. Next, correlation analysis was conducted using past earthquake motion and damage data to identify the damage indexes of structures from seismic loads with relatively good correlations, and the damage index levels were determined by considering the likelihood of damage as estimated from the classified seismic performance.

2.2. Estimation of seismic loads

In the calculating of the earthquake load, first we extract surrounding seismic generation source such as active faults and subduction zones and set the source parameters comprised of a location, magnitude and so on. Next, the target area of the seismic hazard map was divided into small meshes, and the seismic load of the engineering base in each section as applied from the above sources was calculated using an attenuation relation. Here, the engineering base means the hard ground with shear wave velocity (hereafter Vs) more than around 400m/s. The seismic load at the ground surface was calculated by multiplying the load at the engineering base by the predetermined amplification factor for each type of surface ground [Sato, T. et al., (2006)]. If there were multiple seismic sources, the maximum value of the load calculated for each source was adopted as the seismic load in the mesh.

2.3. Estimation of seismic damage

Structures in the target area of the seismic hazard map were identified, and the seismic performance of each one was found based on the type of structure, the applicable design criteria and other factors. Structures were classified based on this seismic performance, and the seismic damage to them was estimated from the damage index depending on the seismic performance of each structure and the seismic load at the relevant construction site. The results were plotted on the seismic hazard map.

3. SEISMIC DAMAGE INDEXES FOR BRIDGE STRUCTURES

The degree of seismic damage to bridge structures was determined by combining the structural characteristics of each structure with the relevant earthquake motion. Since strong ground motion includes multiple factors such as period characteristics and duration time, it is difficult to predict damage conditions accurately with a single load index. However, it is considered possible to forecast these conditions easily using earthquake motion indexes that are highly correlated to the damage.

3.1. Classification of structures by seismic performance

Figure 2 shows the classification method for prediction of seismic damage to bridges. Seismic performance varies by the year of construction due to aging-related problems and differences in design criteria. Table 1. shows the changes in seismic design criteria for bridge structures. The two revisions in 1971 and 1996, in which the setting of seismic force was changed considerably, are seen as the boundaries of seismic performance. Advancement of the design system can be seen in the revision of 1971, which provided more detailed seismic design loads and measures to prevent bridge collapse. In the revision of 1996, the input earthquake motion for the design was increased by a factor of three to four based on damage resulting from the 1995 South Hyogo Prefecture Earthquake. Accordingly, these two years were set as the damage index boundaries. For bridges whose design criteria were unknown, two years before the time of construction was assumed to be the design year, and the closest design criteria before this time were assumed to have been used.

Seismic reinforcement work has also been conducted for a variety of structures since the 1995 South Hyogo Prefecture Earthquake. The level of seismic performance was therefore set higher for bridges with Seismic reinforcement even if they were old. The targets of this study were approximately 2,200 bridges over national highways in Hokkaido, Japan.

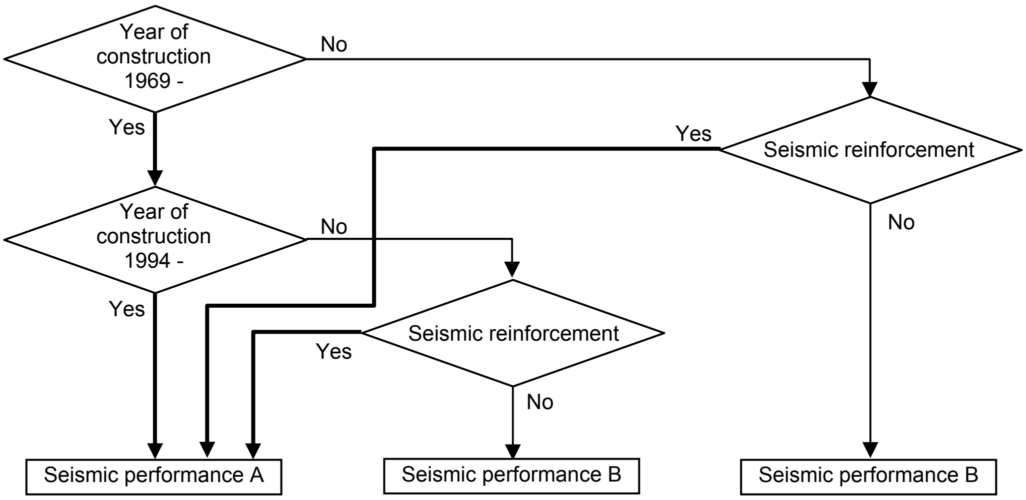

Figure 2. Flow chart of seismic performance classification for bridge structure

3.2. Seismic damage indexes for bridge structures

Table 2. shows the proposed damage indexes for bridge structures. The necessity of repair to ensure traffic ability serves as a guide to distinguishing the level of seismic damage to such structures. Accordingly, three indexes were used in this study for classification - Index I for non-damaged bridges, Index II for those with minor damage not requiring repair to ensure traffic ability, and Index III for those with serious damage (e.g., shear failure of piers) requiring large-scale repair.

Structural damage is affected not only by the maximum values of acceleration, velocity and other earthquake motion characteristics but also by the period characteristics and duration time. However, since it is difficult to model these characteristics simply, seismic damage was estimated in this study from the maximum velocity, which was found to be quite highly correlated with damage in past analysis. Based on previous studies conducted by the authors [Sato, T. et al., (2006)], three values (35 cm/s on the safe side from the value at which minor damage is observed, 50 cm/s (the value provided as Level 2 earthquake motion by the Architectural Institute of Japan), and 100 cm/s (the value observed at the time of the 1995 South Hyogo Prefecture Earthquake) were used as the standards for damage index classification.

Table 1. Changes in the bridge structure seismic design code

Series	Year of revision	Seismic force	Verification method
1926 (T15)	1926	Strongest seismic motion at the location	Allowable stress design method
1939 (S14)	1939	20% horizontal and 10% vertical load of the dead weight Conditions of the construction site must be considered.	Allowable stress design method
1956 (S31)	1956	Horizontal seismic intensity must be considered depending on ground conditions and regions. (Introduction of the coefficient of regional difference)	Allowable stress design method
1971 (S46)	1971	Change in the calculation method for horizontal seismic intensity	Allowable stress design method
1981 (S56)	1981	Change in the coefficient of regional difference	Allowable stress design method
1990 (H2)	1990	Change of ground types	Introduction of the ultimate earthquake resistance method
1996 (H8)	1996	Change in seismic force	Seismic design of seismic coefficient method and ultimate horizontal resistant force method

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

Table 2. Bridge structure seismic damage index

Seismic performance	Maximum velocity(cm/s)			
	35 50 100			
A	I	I	I	II
B	I	II	II	III
C	I	II	III	III

4. ESTIMATION OF SEISMIC LOADS

To determine the seismic loads to be used for seismic hazard maps, it is necessary to estimate the maximum earthquake motion in each area. This value varies by the setting of the location and shape of the seismic source, the magnitude of the earthquake and other initial conditions. Even if the seismic source is the same, ground motion observed at the ground surface varies greatly depending on geological formation, ground conditions and other regional characteristics. This section identifies the seismic sources affecting Hokkaido, and strong ground motion estimation taking account of site characteristics by using type of surface layer condition.

4.1. Seismic sources in and around Hokkaido

Figure 3. shows the hypocenter distribution of earthquakes with a seismic intensity of 3 or higher on the Japanese scale that has occurred around Hokkaido (1924–2009). It can be seen that, while seismic sources are observed throughout Hokkaido, they are basically concentrated in certain areas, such as along the subduction zone on the Pacific coast and the eastern marginal area of the Japan Sea. Although records of inland-type earthquakes in Hokkaido are scarce, the sources of such tremors were included among the targets because extremely large earthquake motion is generated around these sources when they do occur.

Based on the above, the seismic sources affecting earthquake risk in Hokkaido were classified into four types – HA (inland active fault), HB (subduction zone of the Pacific coast plate), HC (eastern margin of the Sea of Japan) and HD (other). Figure 4. show the target seismic sources along with magnitude values and other details of earthquakes.

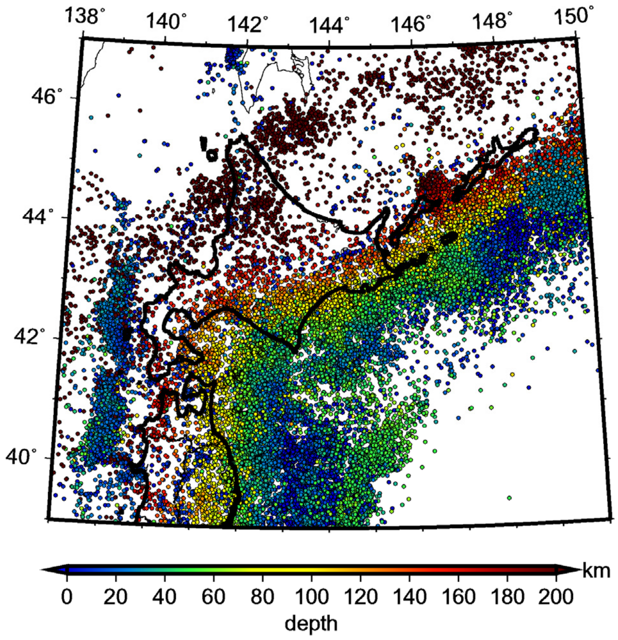

Figure 3. Hypocenter distribution map of earthquake around Hokkaido, Japan (Mj>=3.0)

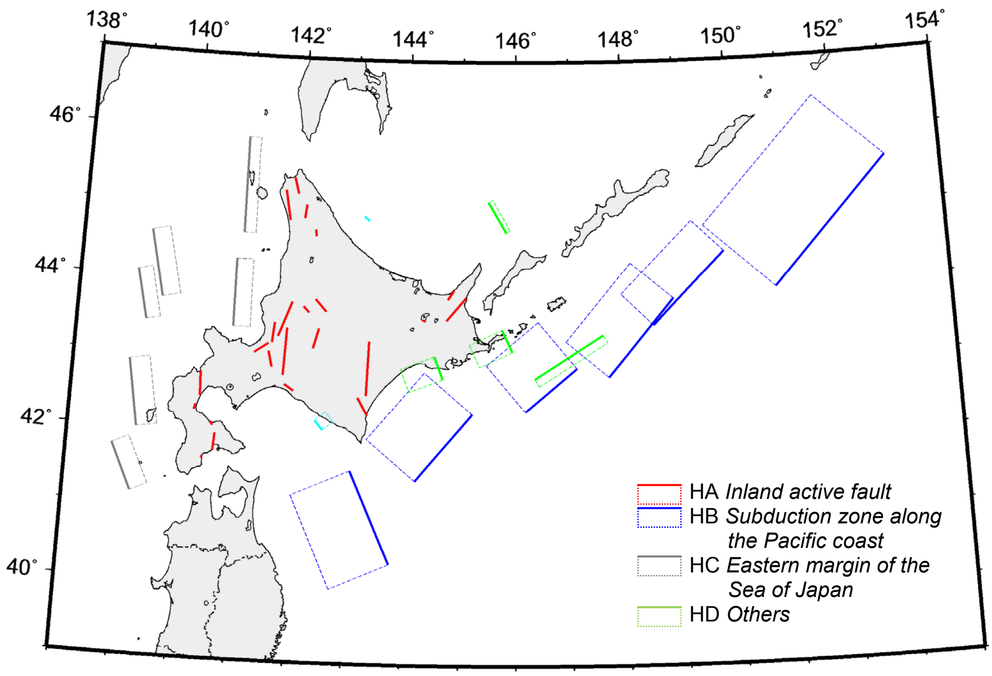

Figure 4. Seismic sources around Hokkaido, Japan.

4.2. Calculation of maximum velocity in consideration of site characteristics

The seismic load of each area with bridges depends mainly on the source of the tremor and its scale, as well as on the ground structure of the surface layer. It is therefore necessary to set an seismic load for each bridge structure location. In this study, the seismic source parameters were set based on past earthquakes in Hokkaido and other database [Sato, R. (1989)]. Using source parameters and the attenuation relationship outlined by Si and Midorikawa [Si and Midorikawa, (1999)], the maximum velocity of the engineering base was calculated for sections divided into meshes. The resulting values were then multiplied by the amplification rate of the surface ground in Hokkaido as found by the authors in the past [Sato, T. et al., (2008)] to ascertain the maximum velocity of the surface layer.

In this study, earthquake motion distribution at the maximum velocity was calculated for the 42 seismic sources shown in Figure 1. These results are used separately or in combination to produce seismic load maps depending on their purpose.

5. DISCUSSION

Table 3. shows the numbers of bridge structures categorized for damage indexes by differences in seismic source. We discuss the damage situation and the distribution of the road bridge structure in Hokkaido using seismic hazard map.

Table 3. Numbers of road bridge structures categorized for damage indexes depending on differences in assumed earthquakes

Assumed earthquake	Index I	Index II	Index III
Inland crustal earthquake	1,666	336	215
Subduction zone earthquake	2,207	10	6
Earthquake on the Sea of Japan’s eastern margin	2,215	2	9
Other types	2,217	0	0

5.1. Damage to road bridge structures assuming an inland crustal earthquake

Figures 6. show maps for earthquake damage indexes I to III, respectively, assuming an inland crustal earthquake. As can be seen from Table 3., the total of damage indexes I and III reached nearly 25% in the case of the assumed inland crustal earthquake HA. However, while such earthquakes are highly destructive, their rate of occurrence is extremely low. Accordingly, the results of estimation for this type of damage do not necessarily mean that all structures lack safety.

Looking at the areas where the assumed damage is concentrated in Figs. 6(b) and (c), it can be seen that damaged bridges are concentrated around points where the maximum velocity exceeds 50 cm/s. However, in Figure 6(a), some bridges are categorized as damage index I around faults. It is therefore important to determine the priority of measures against damage in line with the results of estimation for damage to bridge structures, rather than assuming that all bridges located around faults will sustain serious damage.

5.2. Damage to bridges assuming a seismic source in the subduction zone on the Pacific coast

Figures 7 show maps for earthquake damage indexes I to III, respectively, assuming a seismic source in the subduction zone on the Pacific coast. For the assumed earthquake HB in this case, 10 bridges are categorized as damage index II and 6 as damage index III. Since the seismic source is on the Pacific coast, the seismic load in the coastal zone becomes larger, causing damage to bridges in the area.

Earthquakes in the subduction zone on the Pacific coast occur most frequently around Hokkaido according to seismic records, and damage to bridges there was reported at the time of the 2003 Tokachi-oki Earthquake [Monthly Report of the CERI(2003)]. While the Chiyoda Ohashi bridge suffered relatively serious damage as a result of this tremor, damage to it in this study was minor (index I) in contrast to the actual damage conditions.

The main reasons for this may be that the earthquake assumed in the study did not completely reproduce past tremors, and that the seismic performance of bridges is set only in a simplified manner. However, while simulated damage to individual bridge structures may differ from actual damage as mentioned above, past damage is roughly reproduced on the seismic hazard map concerning the distribution of damaged bridges along the Pacific coast and the number of damaged bridges, indicating the effectiveness of the map in two-dimensional damage estimation.

5.3. Damage to bridges assuming a seismic source at the eastern margin of the Sea of Japan

Figures 8. show damage maps for earthquake damage indexes I to III, respectively, assuming a seismic source at the eastern margin of the Sea of Japan. A characteristic of the earthquake from this source is that more bridges are categorized as damage index III than II, indicating that bridges with low seismic performance are concentrated in the area where strong vibrations emanate from this seismic source.

5.4. Damage to bridges assuming other seismic sources

As can be seen from Table 3, earthquakes with other seismic sources are deemed not to cause damage to bridge structures in the results based on these damage indexes. The damage maps for such earthquakes are therefore omitted.

6. CONCLUSION

To prevent secondary damage to bridges in earthquakes, it is necessary to monitor the damage conditions of structures two-dimensionally in advance and take appropriate measures. This study focused on a method of estimating earthquake damage to structures using seismic hazard maps, and damage to bridge structures was estimated for the Hokkaido area a region of Japan with a relatively high risk of earthquakes. The seismic hazard maps produced enabled seismic load calculation depending on assumed earthquakes and two-dimensional identification of the corresponding damage to bridge structures. We will make BCM of the road bridge structure using seismic hazard map in future.

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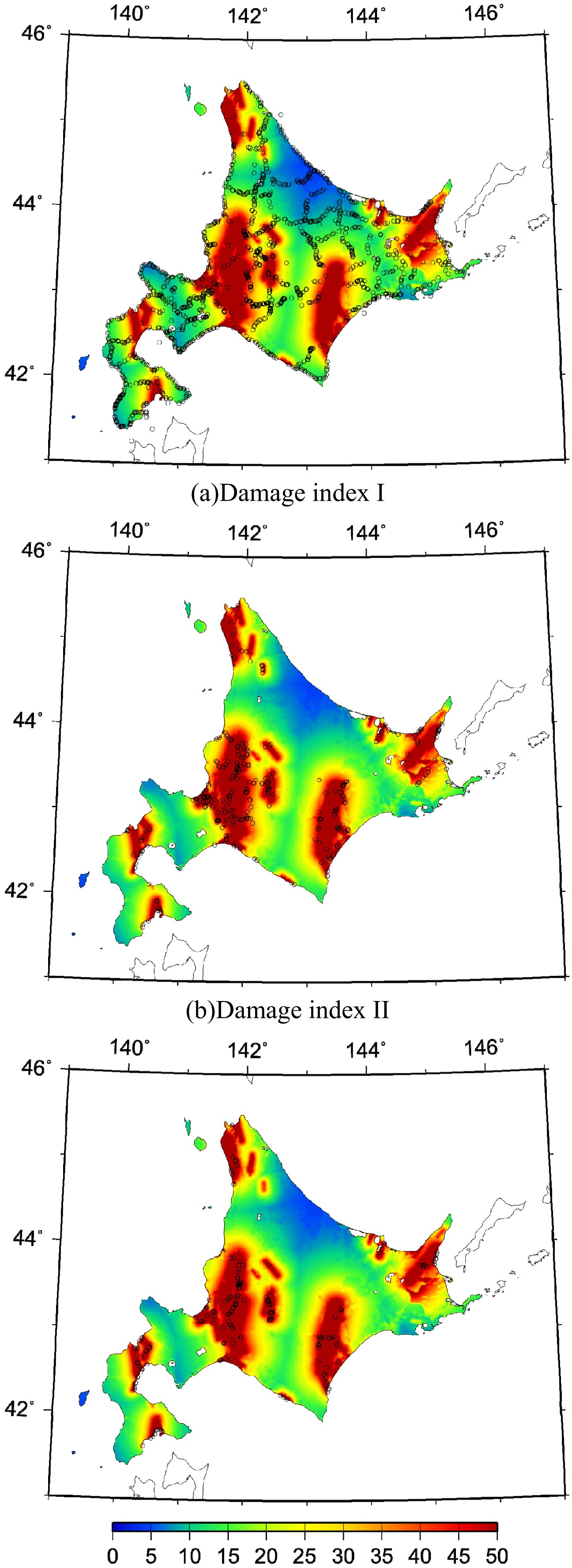
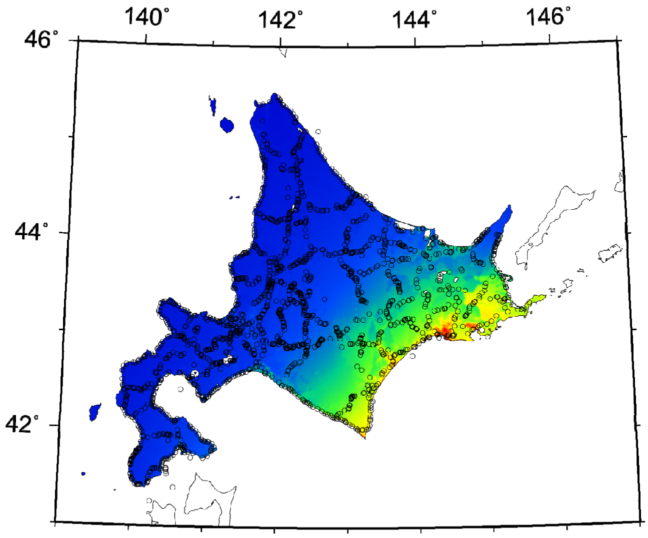


(a)Damage index I

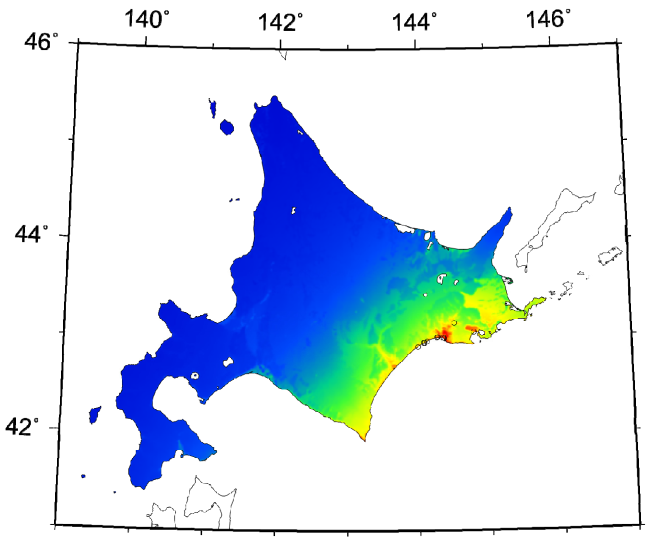
(b)Damage index II

(c)Damage index III

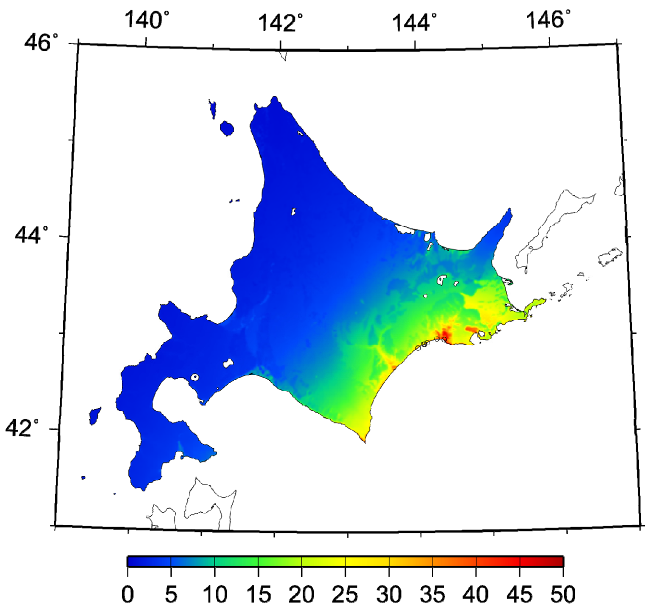
Figure 6. Inland Crustal Earthquake Hazard Map For Bridge Structures



(a)Damage index I

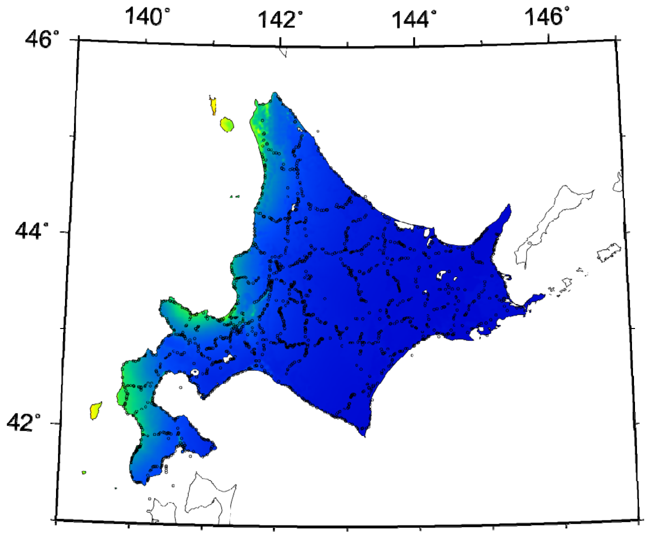


(b)Damage index II

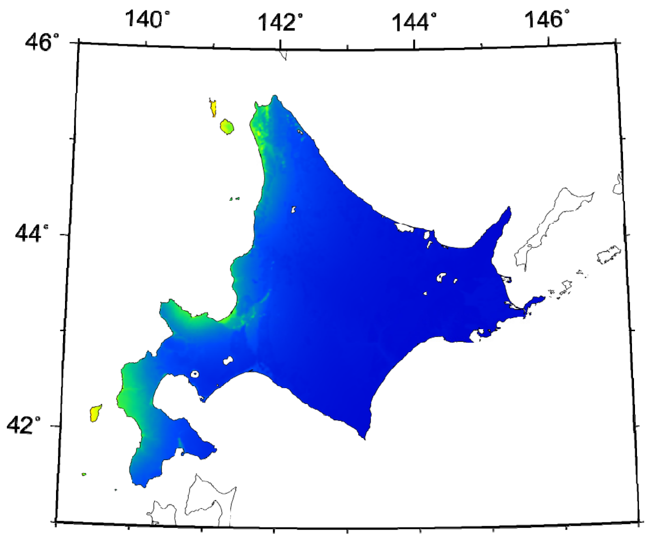


(c)Damage index III

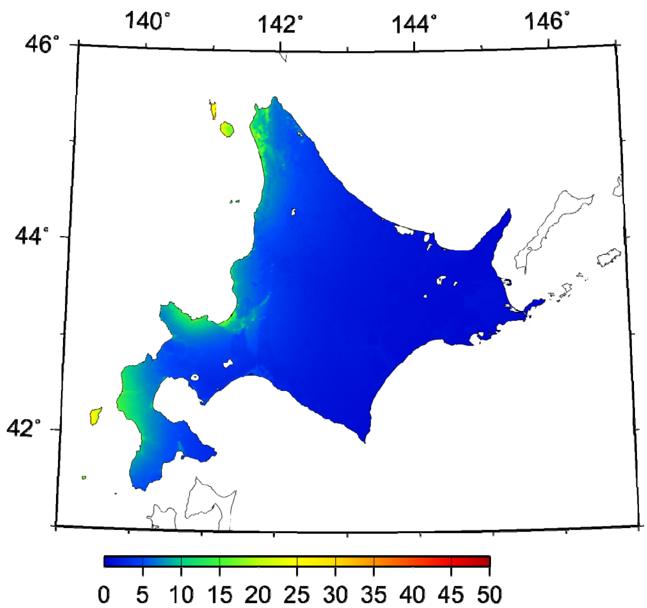
Figure 7. Subduction zone earthquake hazard map for bridge structures



(a)Damage index I



(b)Damage index II



(c)Damage index III

Figure 8. Sea of Japan eastern margin earthquake hazard map for bridge structures