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DESING INPUT GROUND MOTION BASED ON REGIONAL SEISMISITY

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SUMMARY

In the seismically active Japanese archipelago, earthquakes are generated by plate subduction, movement at inland active faults, and other movement. Seismic activity in Japan varies by region, with earthquake type and impact also differing by region. When considering the safety and economy of structures, earthquake motion inputs for aseismic design need to be based on accurate estimates of the seismic activity of the region. This paper aims to establish design-based earthquake motion inputs for intra-slab earthquakes by focusing on Hokkaido, where two large-scale intra-slab earthquakes occurred in recent years, and by simulating intra-slab earthquakes and related earthquake motions. Using parameters such as earthquake magnitude, average stress drop, and number and area of asperities, the magnitude of earthquake motions and the characteristics of seismic spectra were analyzed using the stochastic Green's function method. It was found that earthquake motions are dependent on key parameters including location of source fault, rupture starting point, and average stress drop. It was also revealed that spectral types of intra-slab earthquakes more closely resemble those of inland events than those of interplate events that occur in subduction zones.

INTRODUCTION

The activities of plates in the Japanese archipelago are known to be complex. In the Pacific Ocean to the east of the Japanese archipelago, the Pacific plate and Philippine Sea plate subduct under the continental plate, causing frequent earthquakes along the plate boundary. The Great Kanto Earthquake (Mw7.9) of 1923 originated at the boundary between two of these plates.
The Japanese archipelago experiences continuous east-west compressive force from this plate subduction. This causes active faults to form at relatively shallow depths, causing many earthquakes. When such inland earthquakes occur near a large city, they can cause tremendous damage and casualties, as in the Hyogo-ken Nanbu Earthquake (Mw6.8) of 1995.

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The two types of earthquake described above differ in seismic ground motion. Therefore, ground motion inputs for aseismic design of civil engineering structures in Japan normally take into account both types of earthquake[1].

Other types of earthquake that occur around the Japanese archipelago include intra-slab earthquakes, which originate from within the subducting plate. The seismic waves that are generated are typically dominated by high-frequency components and, as a result, are characterized by relatively large maximum acceleration. In addition, it has been observed that source stress drop is substantially higher in these earthquakes than in other types[2].

Intra-slab earthquakes can occur in any region of Japan. In Hokkaido, two major intra-slab earthquakes occurred in recent years, inflicting great damage to structures: the Kushiro-Oki Earthquake (Mw7.6) of 1993, and the Hokkaido-Toho-Oki Earthquake (Mw8.2) of 1994. In light of this, it is important that ground motion inputs for aseismic design of structures in the target regions of Hokkaido include inputs for intra-slab earthquakes. To ensure the safety and economy of structures, it is essential that design ground motion inputs be based on the seismic activity of the region in question.

The following study describes seismic ground motion analysis under the assumption of intra-slab events occurring directly beneath a city, for related design ground motion input modeling. Two sites were selected, both in the Kushiro region, which is near the sources of the two intra-slab earthquakes described above. General intra-slab source characteristics were assumed based primarily on the source characteristics of the two intra-slab events. Using parameters such as the location and number of asperities, the location of source, and stress drop, strong motion was calculated by means of the stochastic Green's function method and wave characteristics and intensity distribution were studied.

SEISMIC ACTIVITIES OF THE HOKKAIDO REGION

Figure 1 shows the Kushiro region, where the study sites are located, and the epicenters of the two intra-slab earthquakes in and around that region. Figure 2 shows the distribution of epicenters for earthquakes recorded in the region during 1990 - 2001. As shown, earthquakes concentrate in subduction zones in the Pacific Ocean. Epicenters concentrate particularly heavily off Nemuro, at the eastern tip of Hokkaido. Also shown in Figure 2 is the cross-sectional distribution of source depths in a section within ±1.5 degree of Long. 114.25 E, the longitude of Kushiro. Source locations are seen to increase in depth as one moves northward, a trend that is attributed to plate subduction.

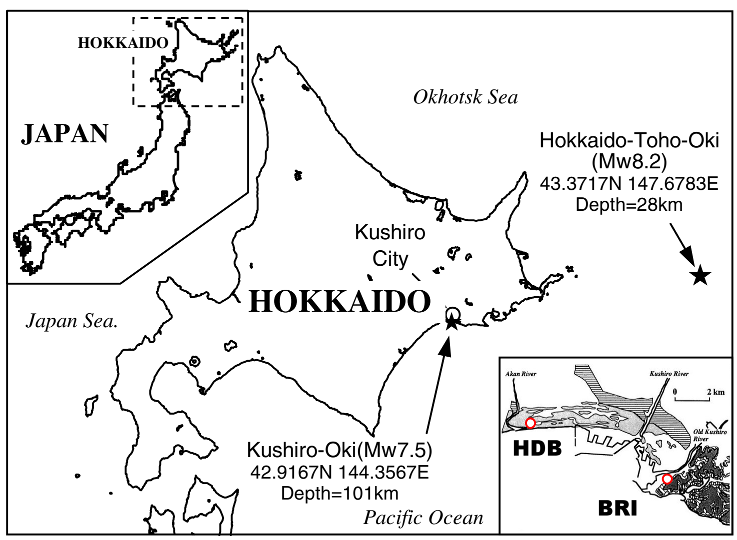


Figure 1 Investigation Site and Epicenter of 2 Large size Intra-Slab Earthquakes

The hypocenter of the Kushiro-Oki Earthquake of 1993 is almost directly below the Kushiro region, where the study sites are located. As shown in Figure 2 (distribution of source depths), the source depth (101 km) is fairly great. Based on the related distribution of aftershocks, the fault plane is assumed to be almost horizontal.

The epicenter of the 1994 Hokkaido-Toho-Oki Earthquake is in a seismically active area. The source is fairly shallow, at 28 km, as it was located before the plate begins to subduct. Based on the related aftershock distribution, the fault plane is assumed to be almost vertical.

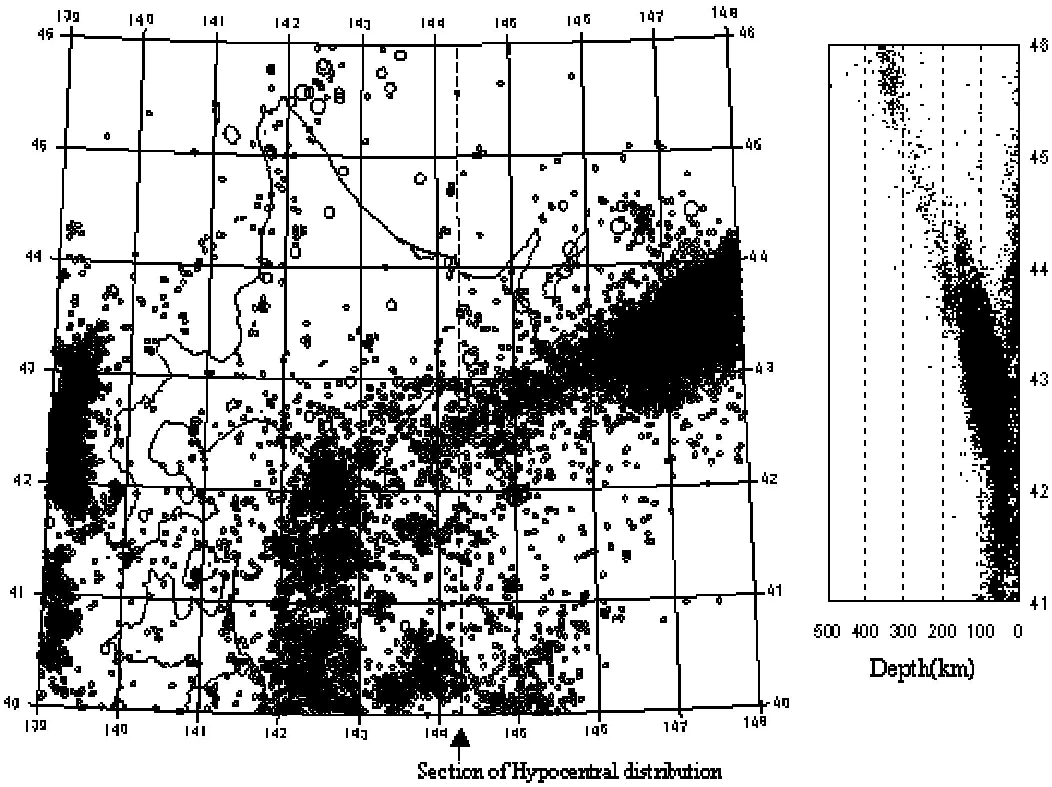


Figure 2 Seismic activities around Hokkaido Region
(Epicentral distribution from 1990 to 2001)

Figure 2 also indicates that, in addition to the concentration of epicenters along the subduction zone in the Pacific Ocean, there is another seismically active epicentral concentration along the east end of the Sea of Japan.

SOURCE CHARACTERISTICS OF INTRA-SLAB EARTHQUAKE

To analyze the strong motions of a specific earthquake source, it is essential to correctly analyze the characteristics of the source. Characterized source models[3)] are known to be effective for certain types of earthquake, but their effectiveness has not been established for intra-slab earthquakes. While the source characteristics of intra-slab earthquakes are largely unknown, the two major intra-slab earthquakes in Hokkaido have been the subject of several studies and some of the related source characteristics have been identified.

Morikawa et al.[2)] established source models for the two intra-slab earthquakes using empirical Green's function-based forward modeling and studied the related asperity characteristics. Those authors did not include background regions in their study, assuming that strong motions are generated only by asperities. Table 1 shows the source parameters used.

The earthquakes both had a higher stress drop of asperity than that for other types of earthquake, with the maximum value being approx. 400 MPa for each. This is far higher than the maximum stress drop of asperity of 16 MPa which Kamae and Irikura [4)] estimated for the Hyogo-ken Nanbu Earthquake of 1995. Morikawa et al., performing similar study on two other intra-slab earthquakes, determined relationships between asperity area and seismic moment for the four earthquakes and pointed out that the stress drops for the intra-slab events are lower than those for interplate events (Figure 3). Based on these results, Morikawa et al. pointed out that interplate earthquakes generate large seismic wave energy from within a relatively small area and, because of this, are dominated by short-period seismic waves. They also raised many questions that need to be clarified, including why the maximum stress drop for intra-slab earthquakes outside Hokkaido is only 50 MPa and why the relationship between stress drop and source depth varies for each event.

Sasatani et al.[5] analyzed source characteristics of the Kushiro-Oki Earthquake of 1993 using strong motion records. Those authors posit that (1) source spectra for the high-frequency region of 1 Hz and above cannot be explained by the ϖ^2 model which is based on macroscopic source parameters from perigean strong motion records, (2) the levels of the high-frequency region in the acceleration source spectra are substantially higher than average, and (3) the earthquake source can be expressed by asperity models[6),7)].

Table 1 Source parameters of intra-slab earthquakes, which occurred in Hokkaido region[2)]

	1993 Kushiro-oki			1994 Hokkaido-toho-oki				
Mo	$2.3\times10^{20}\,Nm$			$2.3\times10^{21}\,Nm$				
Asperity	No.1	No.2	No.3	No.1	No.2	No.3	No.4	No.5
Sa (km^2)	51.8	72.0	34.6	400	256	144	144	256
$\Delta\sigma_a$ (MPa)	109	381	163	82	82	382	300	137
τ (s)	0.50	0.60	0.45	1.80	1.40	1.10	1.10	1.40

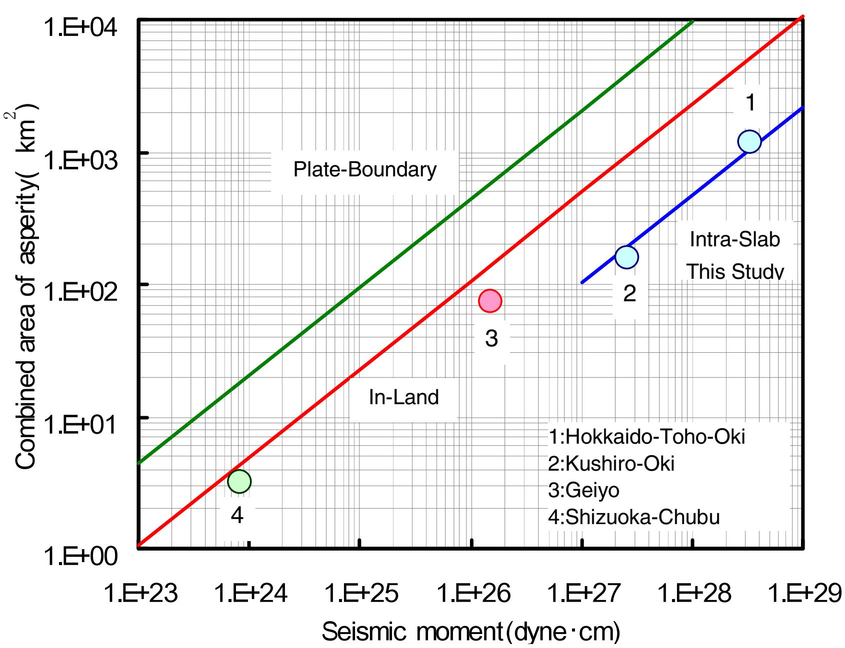


Figure 3 Relation between the combined area of asperity and seismic moment for intra-slab earthquake

STRONG GROUND MOTION ESTIMATION OF INTRA-SLAB EARTHQUAKE

(1) Analysis method

Strong motion was estimated for assumed intra-slab earthquakes in the Kushiro region of Hokkaido. The magnitude and characteristics of strong motion are heavily dependent on factors such as the location and size of the source, the number of asperities and their stress drops, and the rupture starting point. These were used as parameters to study the characteristics of the strong motion.

Two sites in Kushiro were selected for the analysis: one site (HDB) belong to the Hokkaido Development Bureau, the other site (BRI) belong to the Building Research Institute. And strong motion records from the Kushiro-Oki Earthquake of 1993 were available for both. Figure 1 shows the site locations. The stochastic Green's function method was used to analyze strong motion[8]. In this method, artificial small seismic motions are merged on fault planes[9] to simulate strong motions of major earthquakes. To create small seismic motions, Boore's stochastic waveform simulation method[10] is used in which source spectra follow $\varpi - 2$. As the small seismic motions had wave patterns of the seismic basement, waveforms of seismic motion at the ground surface were calculated based on site characteristics. Site characteristics were established based on ground structure.

(2) Source modeling

To obtain appropriate values for the model, we referred to the relationship between source parameters of the two intra-slab earthquakes that occurred near each other and to the procedures used to develop the characterized source models. Asperities were used as source models, following the recommendation of Sasatani et al.[5]. The asperity model used was of multi-asperity[3] expanded from the dynamic single asperity model proposed by Das and Kostorov[6]. Basic source parameters included the area, average stress drop and seismic moment of the source fault, and the area and stress drop of the asperity.

1) Area of source fault

The area (S) of source was assumed to be equivalent to the area of a circular crack ($S = \pi R^2$), and is expressed using Equation (1).

$$\Delta\sigma_c = \frac{7}{16}\frac{Mo}{R^3} \qquad (1)$$

where:
$\Delta\sigma_c$ = average stress drop
Mo = seismic moment
R = radius of equivalent circular crack

2) Average stress drop

Average stress drop ($\Delta\sigma_c$) has been empirically established as approx. 2.3 MPa for inland earthquakes and approx. 3.0 MPa for interplate earthquakes[3),11]. Little is known about intra-slab earthquakes except that their typical stress drop is higher than that for other types of earthquake. No other parameters have been quantitatively established. In light of this, average stress drop of 15 MPa was chosen for the analysis, based on the average stress drops of the two intra-slab earthquakes.

3) Seismic moment

Seismic moment (M_o) was obtained substituting magnitude into an empirical equation (2)[12]. While the applicability of Equation (2) to intra-slab earthquakes has not been verified, seismic moments obtained by applying the equation to the Kushiro-Oki Earthquake of 1993 and the Hokkaido-Toho-Oki Earthquake of 1994 roughly agreed with those obtained by corresponding waveform analyses.

$$LogM_o = 1.5(M_j + 0.2) + 16.2 \qquad (2)$$

where:
M_o = seismic moment
M_j = magnitude

4) Area of asperity

Morikawa et al.[2] applied empirical Green's function-based forward modeling to four intra-slab earthquakes to obtain asperities, and expressed the relationship between seismic moments and asperities as in Figure 3. (The two earthquakes other than the Kushiro-Oki (1993) and Hokkaido Toho-Oki (1994) earthquakes occurred outside Hokkaido.) The figure shows that the relationship for inland earthquakes[11] is similar to that for interplate earthquakes[13]. As shown, the area of asperity for intra-slab earthquakes with a given seismic moment is smaller than those for the other types of earthquake. Also, intra-slab earthquakes in Hokkaido differ in characteristics from those outside Hokkaido. Based on limited data available for the two earthquakes in Hokkaido, the relevant relationship between seismic moment and area of asperity can be expressed using Equation (3).

$$Sa = 1.03 \times 10^{-16} \times Mo^{2/3} \qquad (3)$$

where:
Sa = area of asperity
Mo = seismic moment

5) Stress drop of asperity

Stress drop of asperity can be obtained based on the area of source fault and that of asperity. This can be expressed using Equation (4). As asperity modeling was employed, the same stress drop was used for all asperities.

$$\Delta\sigma_a = \Delta\sigma_c \frac{S}{Sa} \qquad (4)$$

where:
$\Delta\sigma_a$ = stress drop of asperity
$\Delta\sigma_c$ = average stress drop
S = area of source fault
Sa = area of asperity

(3) Study cases

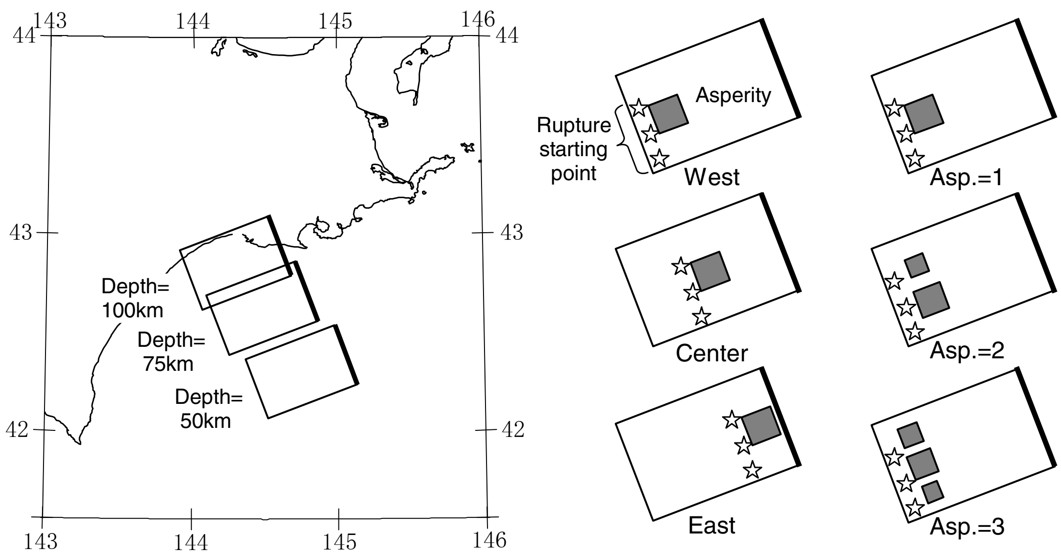
Table 2 shows the source parameters used in our analysis. These are source fault location, earthquake magnitude, average stress drop, rupture starting point, asperity location, number of asperities, and area of asperity. Considering the distribution of each parameter, three levels were used for each parameter. These parameters were combined to create 2,187 study cases for each site.

Because intra-slab earthquakes originate in the subducting slab, source fault locations are dependent on source depth and subduction pattern. With the source fault for the Kushiro-Oki Earthquake of 1993 (located directly below the city of Kushiro) used as a reference, two source faults shallower than the reference were established. The source model proposed by Morikawa et al.[2] was used in study of the Kushiro-Oki Earthquake of 1993.

Magnitude was used as a measurement of the earthquake size. M7.5, the magnitude of the Kushiro-Oki Earthquake of 1993, was used as the reference (dispersion of ±0.5 M). The reference average stress drop was 15 MPa (dispersion of ±5 Mpa). Results of Equation (3) were used as reference areas of asperity. The related dispersion was set as $\sigma = 1.34$, which Miyake and Irikura obtained for inland earthquakes. The number of asperities was set between 1 and 3. When 2 or 3 asperities were used, the relevant areas were divided according to the ratios of 2:1 and 5:3:2, respectively. Figure 4 shows schematics of source faults, asperity locations, and rupture starting points.

Table 2 Parameter to use for strong ground motion evaluation of intra-slab earthquake
Parameters are independent of each other

Parameter	1	2	3
Depth	100km	75km	50km
Magnitude (Mo)	M7.0 ($1.00*10^{20}$ Nm)	M7.5 ($5.62*10^{20}$ Nm)	M8.0 ($3.16*10^{21}$ Nm)
Average stress drop	10 MPa	15 MPa	20 MPa
Rupture starting point	North	Center	South
Position of asperity	West	Center	East
Number of asperity	1	2	3
Combined area of asperity	$Sa/1.34$ km^2	Sa km^2	$Sa*1.34$ km^2



Location of source area
Location of asperity and rupture starting point
Number of asperity

Figure 4 Source area and asperities used for evaluation

(4) Study results

Figure 5 shows the maximum accelerations at the HDB site for an average stress drop of 15 MPa. Looking at the influence of source depth (D), the maximum value for directly below the study sites (D = 100 km) is smaller than that for the locations further south along the fault (D = 75 km and D = 50 km). This is probably because sources become shallower and the distance to sources decreases as one moves south along the fault (Figure 4). In the cases of D = 75 km and D = 50 km, the distance to source in general is slightly longer in D = 75 km cases than in D = 50 km, although in some cases, this is reversed. This is probably because at shallower sources the fault plane and the sites are more closely parallel with each other, intensifying directivity more for D = 50 km cases than for D = 75 km cases. It was revealed that among seismic events of equivalent magnitude in the Kushiro region, even those events in locations

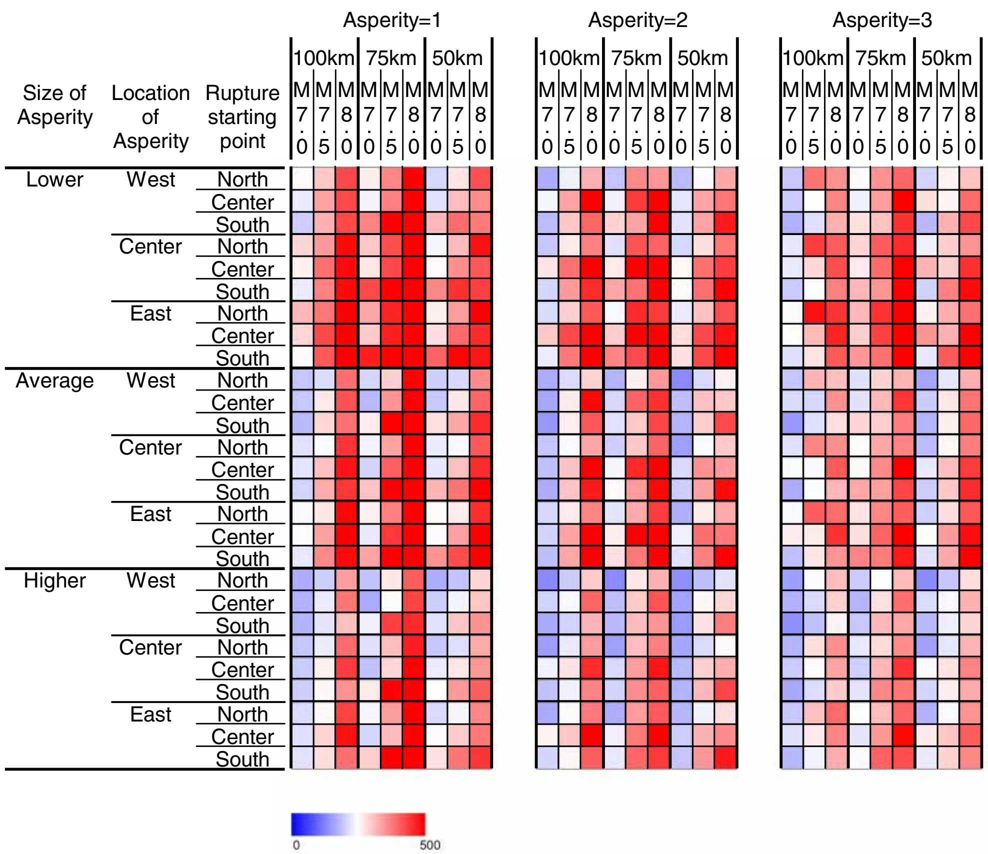
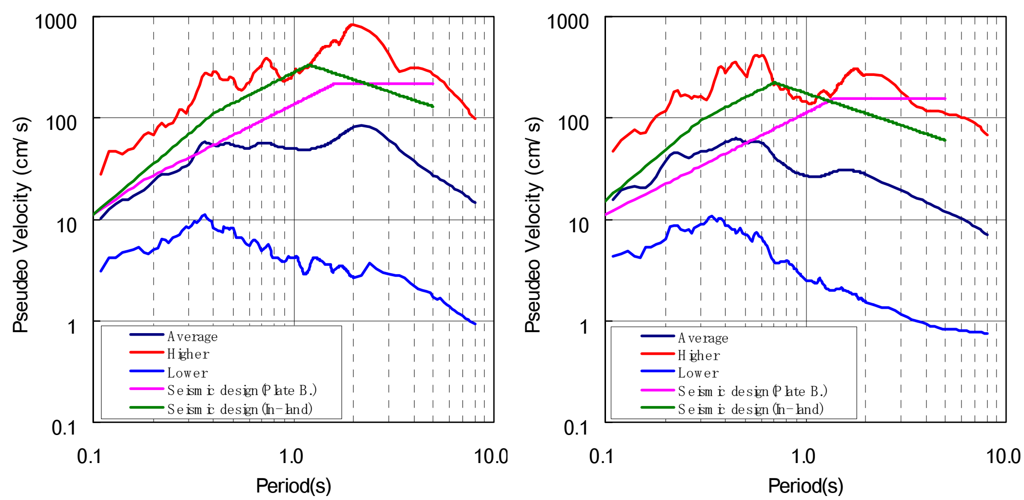


Figure 5 Maximum acceleration of HDB site for intra-slab earthquake
($\Delta\sigma_c$=15MPa)



HDB Site BRI Site

Figure 6 Response spectra distribution of HDB and BRI

not directly below the area can generate greater strong motion than intra-slab earthquakes whose source is directly under the measuring point.

As the area of asperity becomes smaller, the maximum value of the relevant strong motion becomes larger. This is because for an equal area of source fault and average stress drop, smaller area of asperity leads to higher stress drop of asperity.

Rupture starting points located south, or on the forward-directivity side, of the study sites have larger maximum values. This indicates that the location of rupture starting point is a key parameter.
No significant trends were observed with respect to the number and location of asperities. This is probably because of multiple asperities lined up towards the study sites as well as source faults arranged in the direction of strike-slip.
Figure 6 shows the estimated upper and lower limits as well as the average of pseudo-velocity response spectra (with an attenuation constant of 5%) for strong motions at HDB and BRI for all study cases. At both sites, the spectra have a substantial gap between the upper and lower values, suggesting that estimates of strong motion can vary widely depending on the selection of source parameters.
At both sites, the response spectra show a decline in the long-period range. The figure shows the current design response spectra[1)]. The shape of design response spectra for interplate earthquakes closely resembles that for inland earthquakes, because decline of spectrum level in the long-period range is not taken into consideration in the former. This is probably because source characteristics of intra-slab earthquakes resemble those of inland earthquakes, in that the source fault area is relatively small while the stress drop is relatively large.
The maximum acceleration and velocity at HDB are 904 cm/s/s and 136 cm/s, and 1,116 cm/s/s and 76 cm/s at BRI. These values exceed the strong motion (approx. 125 cm/s/s) measured at JR Takatori Sta. during the Hyogo-ken Nanbu Earthquake of 1995.

CONCLUSION

Toward developing design strong motion inputs based on the target region's seismic activity, strong motion was analyzed by applying the stochastic Green's function method to earthquakes assumed for the Kushiro region and the size of the strong motion was studied. The following are the results of the analysis.

(1) For earthquakes of equal sizes, those originating slightly to the south of Kushiro have larger strong motions than those originating directly below Kushiro. This is because the source becomes shallower and the distance to the source becomes shorter as one moves south along the source fault.

(2) Strong motions vary depending on the rupture starting point. This is a key parameter.

(3) Neither the number nor the location of asperities influences strong motion. However, this finding may have resulted from our selection of source fault locations and the arrangement of asperities. Further detailed study is required.

(4) The response spectra profile obtained from the strong motion analysis shows a decline in the long-period range, and this resembles the design spectra profile that assumes inland active faults. This is probably because source characteristics of intra-slab earthquakes resemble those of inland earthquakes, in that the source fault area is relatively small while the stress drop is relatively high.

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