RECIPE FOR PREDICTING STRONG GROUND MOTIONS FROM FUTURE LARGE INTRASLAB EARTHQUAKES

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ABSTRACT :

We examine source characteristics of intraslab earthquakes based on eleven source models estimated by the empirical Green's function (EGF) method. The asperity source model is used to characterize fault parameters (outer and inner fault parameters). We find self-similar scaling of total seismic moment to the asperity area and short-period level of the S-wave acceleration source spectrum. Based on these findings and theoretical relationships between the outer and inner fault parameters, we propose a recipe for characterizing the source model for future intraslab earthquakes. We make strong-motion prediction for the 1993 Kushiro-oki earthquake (Mw7.6) in the southern Kurile-Hokkaido arc by using the EGF method and the source model derived from the proposed recipe. A fairly good agreement between the observed and predicted waveforms is obtained at rock sites. However, the agreement is considerably decreased at soft-soil sites due to nonlinear soil response.

KEYWORDS: Intraslab earthquakes, Strong-motion prediction, Asperity source model, Nonlinear soil response, The 1993 Kushiro-oki earthquake

1. INTRODUCTION

After seismic damage due to the 1993 Kushiro-oki earthquake (Mw 7.6; depth~100km) in the southern Kurile-Hokkaido arc, we have recognized that large intraslab earthquakes are disastrous ones at subduction zones such as Japan, Mexico and so on. Morikawa and Sasatani (2003) clearly demonstrated peculiar sources of the large intraslab earthquakes that radiate strong short-period seismic waves compared with inland-crustal and plate-boundary earthquakes.

In this paper, we make source characterization of intraslab earthquakes based on eleven source models estimated by the empirical Green's function method. We use asperity source model to characterize fault parameters (outer and inner fault parameters). Next we propose a recipe for characterizing the source model of intraslab earthquakes based on our findings and theoretical relationships between the outer and inner fault parameters. Finally we make strong motion prediction for the 1993 Kushiro-oki earthquake (Mw 7.6) by using the empirical Green's function method and the source model derived from the proposed recipe. The predicted ground motions are compared with the observed ones at rock and soft soil sites.

2. SOURCE CHARACTERISRICS OF INTRASLAB EARTHQUAKES

Source modeling by the empirical Green's function method has been done for eleven intraslab earthquakes (Mw 5~8) occurring in and around Japan. Figure 1 shows their epicenters and focal mechanisms. We use the asperity source model to characterize fault parameters; the outer fault ones are the total rupture area and total seismic moment, and the inner fault ones are the area of asperities, stress drop on each asperity and short-period level of the S-wave acceleration source spectrum. These parameters for the eleven earthquakes have been shown in Sasatani et al. (2006). Here we show only a summary of source characteristics of intraslab earthquakes.

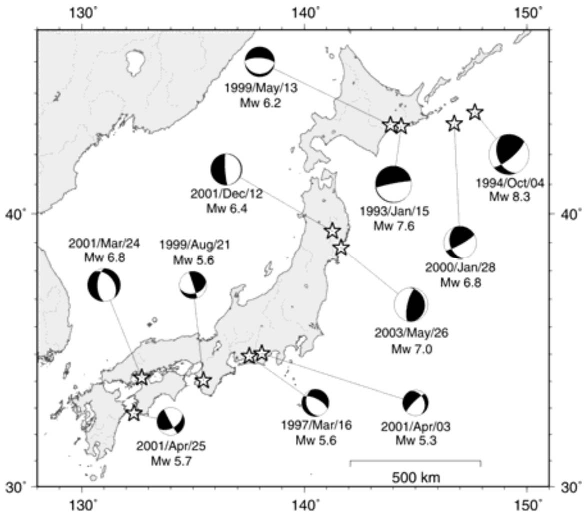


Figure 1 Eleven intraslab earthquakes whose source models were estimated by the empirical Green's function method

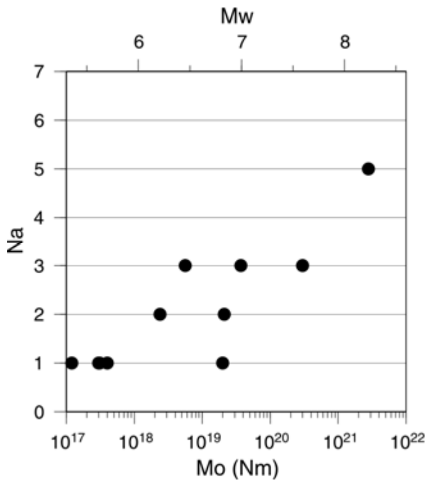


Figure 2 Number of asperities versus seismic moment

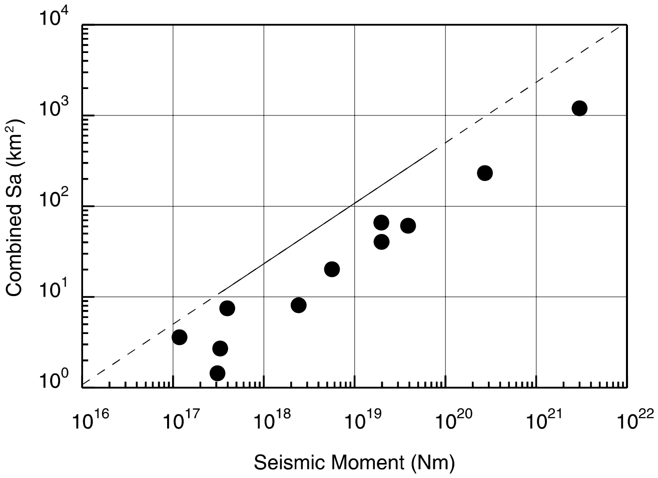


Figure 3 Empirical relationship between combined asperity area (*Sa*) and seismic moment (*Mo*)

2.1 Inner fault parameters

The number of asperities, *Na*, increases with earthquake magnitude (Mw) as shown in Fig. 2; one for events with Mw<6, two to three for events with Mw 6~7, and five for events with Mw>8. Figure 3 shows the relationship between the combined area of asperities (*Sa*) and seismic moment (*Mo*) for the eleven intraslab earthquakes. In the figure, a solid line indicates the relationship for inland-crustal earthquakes (Somerville et al., 1999). The *Sa* values for intraslab earthquakes increase with seismic moment; the scaling trend is similar to that for inland-crustal earthquakes. However, the *Sa* value for a given seismic moment is about one-fourth of that for inland-crustal earthquakes. The scaling relationship between *Sa* and *Mo* for intraslab earthquakes is roughly obtained as follows:

$$Sa(\mathrm{km}^2) \approx 5.8 \times 10^{-12} \times Mo^{2/3}(\mathrm{Nm}) \tag{2.1}$$

The short-period level of S-wave acceleration source spectrum, *A*, is estimated from an observed S-wave acceleration spectrum by correcting the propagation path and site effects; in general, the acceleration source spectrum has a flat level at high frequencies (> 1 Hz). Figure 4 shows the relationship between *A* and *Mo* for the eleven intraslab earthquakes. The *A* value is larger than that for inland-crustal earthquakes (Dan et al., 2001) which is shown by a solid line in the figure. The *A-Mo* relation shows a somewhat different trend from that for inland-crustal earthquakes. However, we think this is a hasty decision because the *A* value dots are not enough.

Figure 5 shows the *A-Mo* relation for subduction zone earthquakes (76 events) beneath the eastern part of Hokkaido (Sasatani et al., 2006). The *A-Mo* relation for plate-boundary earthquakes is similar to that for the inland-crustal earthquakes over the wide moment range. The *A-Mo* relation for intraslab earthquakes with *Mo* > $2\mathrm{x}10^{17}$Nm has also the same trend as that for the inland-crustal earthquakes. However the *A* value for a given moment is about four times larger than that for the inland-crustal earthquakes. The relation for intraslab earthquakes with *Mo* < $2\mathrm{x}10^{17}$Nm is somewhat different from that for larger events. These may apply to Figure 4. We roughly obtain the scaling relationship between *A* and *Mo* for intraslab earthquakes with *Mo* > $2\mathrm{x}10^{17}$Nm as follows:

$$A(\mathrm{Nm/s}^2) \approx 2.1 \times 10^{13} \times Mo^{1/3}(\mathrm{Nm}) \tag{2.2}$$

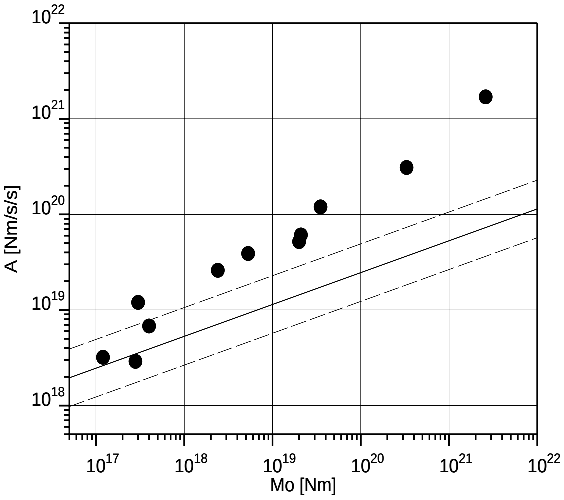
The short-period level is related to asperity area and stress drop on each asperity (Irikura et al., 2003; Dan et al., 2002), as follows:

$$A = 4\pi\beta^2 \sqrt{\sum (r_n \Delta\sigma_n)^2} \tag{2.3}$$

where r_n and $\Delta\sigma_n$ are the radius of the n-th asperity and the stress drop on it, respectively, and β is the S-wave velocity at the source region; a circular shape is simply assumed for the asperity. This formula is obtained assuming that the stress drop on the neighborhood of the asperities is zero. We examine the above relationship based on inner fault parameters for the eleven intraslab earthquakes and observed *A* values. Figure 6 compares the observed *A* values with those predicted from equation (2.3). The former *A* values coincide with the latter ones within a factor of 2 except one event. This fact concludes that the asperity source model is applicable to intraslab earthquakes as well as inland-crustal and plate-boundary earthquakes. Furthermore we can get information as to the asperity area and stress drop from the *A* value using equation (2.3).

2.2 Outer fault parameters

For inland-crustal earthquakes, the total rupture area (*S*) is estimated from geological, geodetic and seismic data, and empirical relationship between *S* and *Mo* has been obtained (e.g., Irikura et al, 2004). However, for intraslab earthquakes, only seismic data are available for estimating the total rupture area and reliable relationship between *S* and *Mo* has not been obtained. On the other hand, Irikura et al. (2003) and Dan et al.



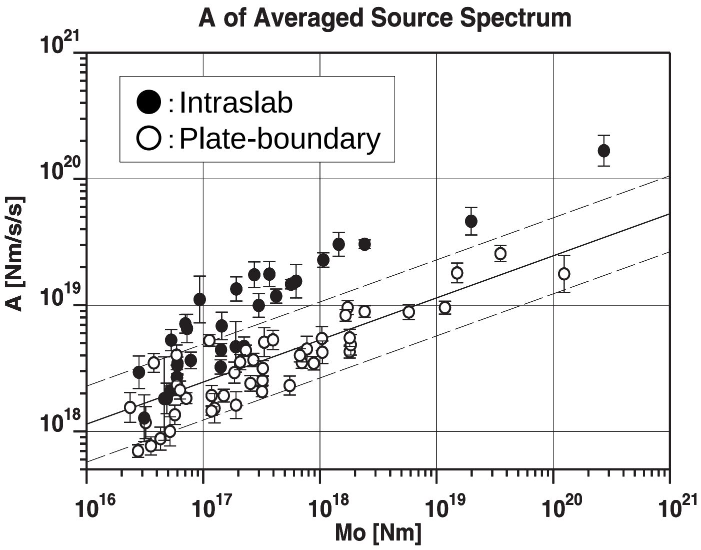


Figure 4 Empirical relationship between *A* and *Mo* for eleven intraslab earthquakes (Left)
Figure 5 Empirical relationship between *A* and *Mo* for subduction zone earthquakes in the eastern part of Hokkaido (Right)

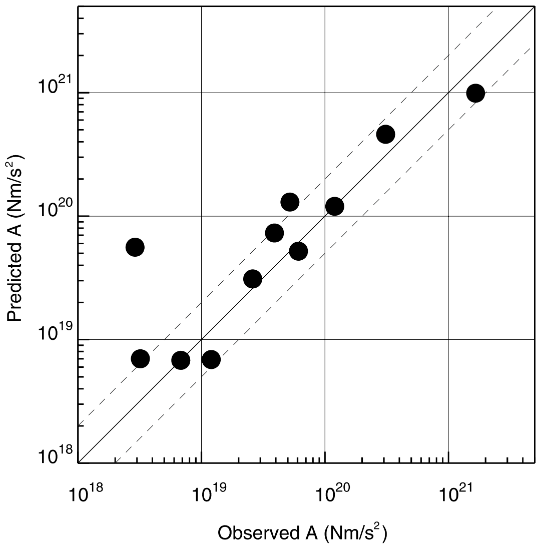


Figure 6 Comparison between predicted short-period level (*A*) from equation (2.3) and observed one

(2002) obtained the following relationship between the outer and inner fault parameters based on the multiple-asperity source model:

$$Mo = \frac{16}{7} r_f \times \sum (r_n^2 \Delta\sigma_n) \qquad (2.4)$$

where r_f is the radius of the total rupture area ($S = \pi r_f^2$). In practice, the asperity parameters are very important to predict strong ground motion for a future earthquake. The total rupture area is also important to define an extent on which multiple asperities are distributed. Since we have no empirical relationship between *S* and *Mo*, we consider it is better to use equation (2.4) for estimating the total rupture area based on seismic moment and asperity parameters.

3. RECIPE FOR CHARACTERIZING THE SOURCE PARAMETERS OF INTRASLAB EARTHQUAKES

We propose a recipe for characterizing the intraslab earthquake source model based on our findings and theoretical relationships between the outer and inner fault parameters; this recipe is somewhat different from that for the inland-crustal earthquake source model by Irikura et al. (2004).

Step 1: Estimating the total seismic moment (*Mo*)
Step 2: Estimating the area of asperities from the empirical relationship of *Sa* and *Mo*
(Fig. 3 and equation (2.1))
Step 3: Estimating the short-period level *A* from the empirical relationship of *A* and *Mo*
(Fig. 5 and equation (2.2))
Step 4: Estimating the number of asperities using Fig. 2
Step 5: Estimating the stress drop on each asperity using equation (2.3)
Step 6: Estimating the total rupture area using equation (2.4)

Furthermore we estimate extra fault parameters such as the rupture starting point, rupture propagating pattern, and rupture velocity to predict strong ground motion. For these parameters, we have to rely on information from past intraslab earthquakes at a target region.

4. PREDICTION OF STRONG GROUND MOTIONS FOR THE 1993 KUSHIRO-OKI EARTHQUAKE

The Kushiro-oki earthquake (Mw7.6) occurred beneath the eastern Hokkaido, Japan, on January 15, 1993, and the hypocenter lay within the subducting plate at a depth of about 100 km. Strong acceleration of about 900cm/s^2 was observed at Kushiro city just above the focus. We make strong motion prediction based on the proposed recipe and information as to the extra fault parameters derived from Takeo et al. (1993) and Morikawa and Sasatani (2004). Here we apply the empirical Green's function method to the prediction.

Based on the recipe, the fault model is estimated as shown in Fig. 7; the fault parameters are also shown in the figure. The asperity number is three and the size and stress drop for each asperity are assumed to be the same. The rupture stars at the eastern end on the fault (a star in Fig. 7) and propagates westward. Observed records from the 2/04/1993 event (Mw4.8) are used as the empirical Green's function. Stations used in a comparison between the observed and predicted waveforms (acceleration, velocity and displacement) are also shown in Fig. 7. At KUS (Kushiro city), there are two stations of JMA and PHRI. We show the comparison at several stations among these stations.

Fault Parameters:
$Mo=3.3 \times 10^{20}$ Nm
$Sa=277$ km^2
$A=2.5 \times 10^{20}$ Nm/s^2
$Na=3$
Stress drop=101 MPa
$S=820$ km^2

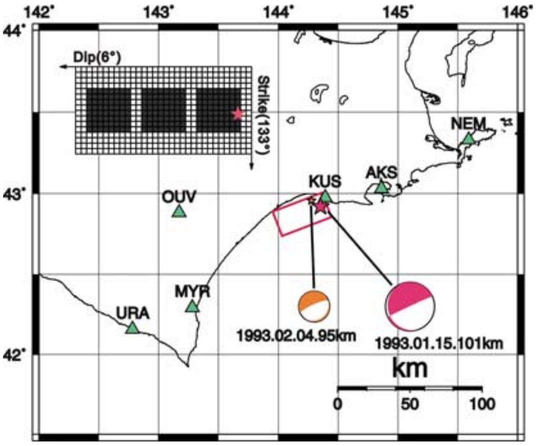


Figure 7 Fault model of the 1993 Kushiro-oki earthquake (Mw7.6)

Figure 8 shows the comparison at MYR and AKS; these stations located on a rock site were used in source modeling of the 1993 Kushiro-oki earthquake by Morikawa and Sasatani (2004). A fairly good agreement between the observed and predicted waveforms is obtained at these sites. Figure 9 shows the comparison at JMA and PHRI in Kushiro city (KUS); these stations located on a soft-soil site were not used in the source modeling by Morikawa and Sasatani (2004). At JMA, the predicted accelerations (3000~4000 cm/s^2) are considerably larger than the observed ones. However, the predicted displacements are nearly the same as the observed ones. This indicates overestimation of short-period ground motion. At PHRI, the predicted accelerations are about two times larger than the observed ones. However, the predicted velocities and displacements are considerably smaller than the observed ones. This indicates underestimation of long-period ground motion.

At JMA, the observed PGA is about 900 cm/s^2 and surface S-wave velocity is about 100 cm/s. So we can anticipate that nonlinear soil response occurred during the 1993 Kushiro-oki earthquake. To check this possibility we make a comparison between S-H/V (S-wave horizontal-to-vertical spectral ratio) for weak and strong motions (Wen et al., 2006; Noguchi and Sasatani, 2008). Figure 10 left shows the comparison at JMA. The S-H/V during the 1993 Kushiro-oki earthquake shows the peak shift from 4 Hz to 2 Hz and high frequency level reduction. This is an evidence of nonlinear soil response (Noguchi and Sasatani, 2008).

The observed acceleration at PHRI shows atypical waveform, that is, spiky acceleration, especially on the N-S component. Iai et al. (1995) concluded that the spiky acceleration is due to nonlinear soil response called cyclic mobility. The spiky acceleration increases amplitudes of velocity and displacement waveform. The S-H/V comparison clearly shows nonlinear soil response at PHRI; increase of low-frequency level and reduction of high frequency level during the 1993 Kushiro-oki earthquake (Fig. 10 right).

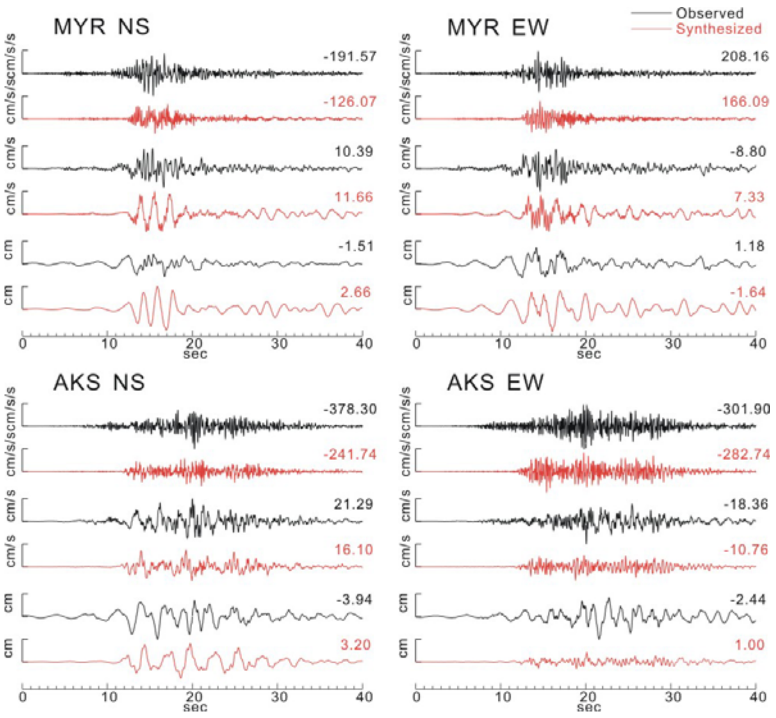


Figure 8 Comparison between the observed and predicted waveforms at MYR and AKS

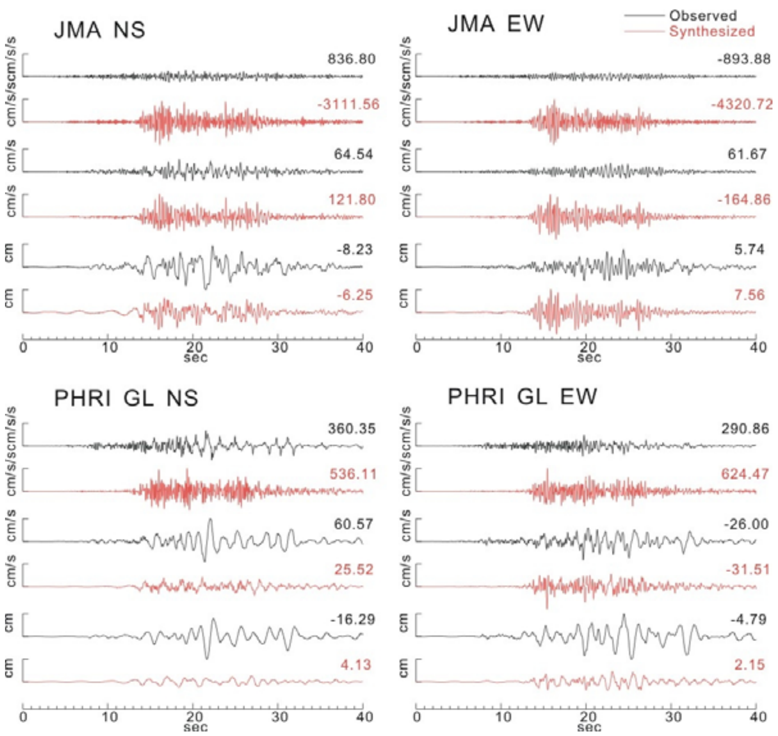


Figure 9 Comparison between the observed and predicted waveforms at JMA and PHRI

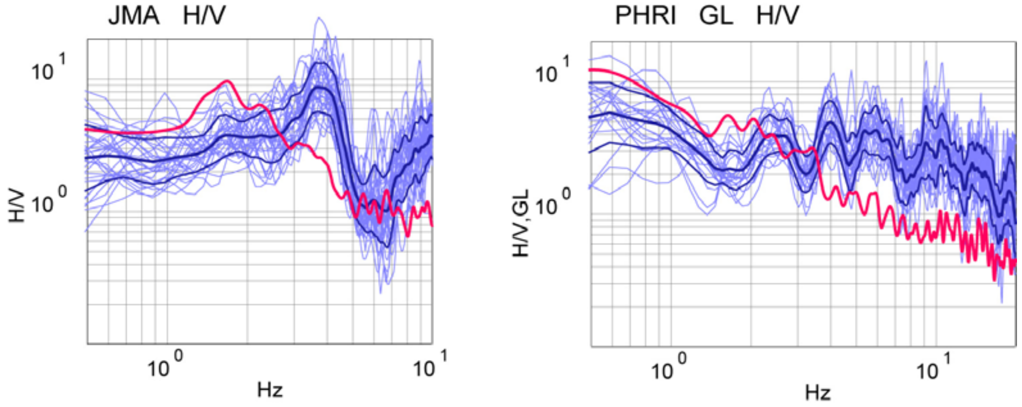


Figure 10 Comparison of S-H/V for weak (blue curve) and strong (red curve) motions (Left: JMA, Right PHRI)

5. CONCLUSIONS

We examined source characteristics of intraslab earthquakes based on eleven source models estimated by the empirical Green's function method. The multi-asperity source model was used to characterize the fault parameters. We found the scaling relationships of the total seismic moment with the area of asperities and short-period level of S-wave acceleration source spectrum. Based on these findings, a recipe for characterizing the source model for a future intraslab earthquake was proposed. We made strong-motion prediction for the 1993 Kushiro-oki earthquake by using the empirical Green's fuction method and the source model derived from the proposed recipe. A fairly good agreement between the observed and predicted waveforms was obtained at rock sites. However, the agreement was considerably decreased at soft-soil sites due to nonlinear soil response.

It is important for precise strong-motion prediction to take nonlinear soil response into account.

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REFERENCES

Dan, K., M. Watanabe, T. Sato, and T. Ishii (2001). Short-period source spectra inferred from variable-slip rupture models and modeling of earthquake faults for strong motion prediction by semi-empirical method, *J. Struct. Contr. Eng. AIJ.*, *545*, 51-62 (in Japanese with English abstract).

Dan, K., T. Sato, and K. Irikura (2002). Characterizing source model for strong motion prediction based on asperity model, *Proc. 11th Japan Earthq. Eng. Symp.*, 555-560 (in Japanese with English abstract).

Iai, S., T. Morita, T. Kameoka, Y. Matsunaga, and K. Abiko (1995). Response of a dense sand deposit during 1993 Kushiro-oki earthquake, *Soil and Foundations*, 35, 115-131.

Irikura, K., H. Miyake, T. Iwata, K. Kamae, H. Kawabe, and L. A. Dalguer (2003). Recipe for predicting strong ground motion from future large earthquakes, Annuals of Disas. Prev. Res. Inst., Kyoto Univ., No. 46B, 105-120 (in Japanese with English abstract).

Irikura, K., H. Miyake, T. Iwata, K. Kamae, H. Kawabe, and L. A. Dalguer (2004). Recipe for predicting strong ground motions from future large earthquakes, *Proc. 13th World Conference on Earthq. Eng.*, Paper No. 1371, 88-101.

Morikawa, N. and T. Sasatani (2003). Source spectral characteristics of two large intra-slab earthquakes along the southern Kurile-Hokkaido arc, *Phys. Earth Planet. Interiors.*, *137*, 67-80.

Morikawa, N. and T. Sasatani (2004). Source models of two large intra-slab earthquakes from broadband strong ground motions, *Bull. Seism. Soc. Am.*, *94***,** 803-817.

Noguchi, S. and T. Sasatani (2008). Quantification of degree of nonlinear site response, *Proc. 14th World Conference on Earthquake Engineering*, in press.

Sasatani, T., N. Morikawa, and T. Maeda (2006). Source characterization and strong motion prediction for intraslab earthquakes, *Proc. Third Int. Sym. on the Effects of Surface Geology on Seismic Motion*, 647-656.

Somerville, P., K. Irikura, R. Graves, S. Sawada, D. Wald, N. Abrahamson, Y. Iwasaki, T. Kagawa, N. Smith and A. Kowada (1999). Characterizing crustal earthquake slip models for prediction of strong motion, *Seism. Res. Lett.*, *70*, 59-80.

Takeo, M., S. Ide, and Y. Yoshida (1993). The 1993 Kushiro-oki, Japan, earthquake: A high stress-drop event in a subducting slab, *Geophys. Res. Lett.*, *20*, 2607-2610.

Wen, K-L, T-M Chang, C-M Lin and H-J Chiang (2006). Identification of nonlinear site response during the 1999, Chi-Chi, Taiwan earthquake from the H/V spectral ratio, *Proc. Third Int. Sym. on the Effects of Surface Geology on Seismic Motion*, 225-232.