CONSTRUCTION OF PROCEDURE OF STRONG GROUND MOTION PREDICTION FOR INTRASLAB EARTHQUAKES BASED ON CHARACTERIZED SOURCE MODEL

Tomotaka IWATA
Disaster Prevention Research Institute
Kyoto University
Uji, Kyoto   611-0011
Japan

Kimiyuki ASANO
Disaster Prevention Research Institute
Kyoto University
Uji, Kyoto   611-0011
Japan

Haruko SEKIGUCHI
Disaster Prevention Research Institute
Kyoto University
Uji, Kyoto   611-0011
Japan

ABSTRACT

We proposed a prototype of the procedure to construct source models for strong motion prediction during intraslab earthquakes. The key is the characterized source model which is based on the empirical scaling relationships for intraslab earthquakes and involve the correspondence between the SMGA (strong motion generation area, Miyake *et al.*, 2003) and the asperity (large slip area). Iwata and Asano [2011] obtained the empirical relationships of the rupture area (S) and the total asperity area (Sa) to the seismic moment (M_0) as follows, with assuming power of 2/3 dependency of S and Sa on M_0,

$$S \ (\mathrm{km}^2) = 6.57 \times 10^{-11} \times M_0^{2/3} \ (\mathrm{Nm}) \tag{1}$$
$$Sa \ (\mathrm{km}^2) = 1.04 \times 10^{-11} \times M_0^{2/3} \ (\mathrm{Nm}) \tag{2}$$

Iwata and Asano [2011] also found that the SMGA approximately corresponds to the asperity area for several events. Based on the empirical relationships obtained above, we gave a procedure for constructing source models of intraslab earthquakes for strong motion prediction. [1] Give the seismic moment, M_0. [2] Obtain the total rupture area and the total asperity area according to the empirical scaling relationships between S, Sa, and M_0 given by Iwata and Asano [2011]. [3] Square rupture area and asperities are assumed. [4] The source mechanism is assumed to be the same as that of small events in the source region. [5] Plural scenarios including variety of the number of asperities and rupture starting points are prepared. We are testing this procedure by simulating strong ground motions for several observed events.

INTRODUCTION

Along the circum-Pacific area, large intraslab earthquakes have causeddisasters (e.g., the 1993 Kushiro-oki, Japan, the 2001 Nisqually, USA, and the 2008 Iwate-Engan-Hokubu, Japan, earthquakes). Generally, high-frequency-rich ground motion characteristics are pointed out for intraslab earthquakes. Studies of PGA attenuation relationships (e.g. Youngs *et al.*, 1997; Si and Midorikawa, 1999). have shown that deeper events give larger PGA.

Strong motion prediction based on scenario earthquakes are recently carried out for earthquake disaster mitigation of urbanized societies and source modeling methodologies have been developed. For inland crustal earthquakes, Somerville *et al.* [1999] compiled the kinematic source models and proposed a set of empirical scaling relationships for inland crustal earthquakes. They showed that the area ratio of the total asperities to the rupture area is constant in the moment magnitude ranging 5.7 to 7.2. Miyake *et al.* [2003] showed that strong motion generation area (SMGA), defined as an area on the source fault that generates broad-band strong ground motions, coincides to the asperity area by strong motion simulation using the empirical Green's function method. From those results, Irikura and Miyake [2001, 2011] proposed a manual so-called 'recipe' of the strong ground motion prediction including an idea of characterized source model. The characterized source model is defined by the finite source model consisting of the asperity area and the background area. The asperity area has larger stress drop than the background area following the asperity model proposed by Boatwright [1988] .

Following the concept of the characterized source model as mentioned above, Iwata and Asano [2011] compiled kinematic source models of intraslab earthquakes to compare source scaling properties with those of inland crustal and subduction-zone plate-boundary earthquakes (Murotani *et al.*, 2008). Characterization of heterogeneous slip distributions to extract rupture area, asperity, and average slip was done following the procedure proposed by Somerville *et al.* [1999]. They also compared SMGAs for intraslab events, and found that the asperity area coincides with the SMGA area, which assures direct usage of this characterize source models in broadband ground motion simulation by the empirical Green's function method or by the stochastic Green's function method.

In this paper, we show the procedure for constructing the source model of intraslab earthquakes for strong motion prediction, and we will apply it to the past events to check the applicability of the procedure by comparing ground motion records and seismic intensity distributions.

SCALING RELATIONSHIPS OF HETELOGENEOUS INTRASLAB EARTHQUAKE SOURCE MODEL AND CHARACTERIZED SOURCE MODEL.

Iwata and Asano [2011] collected twelve source models for eleven intraslab events of M_W 6.6-8.3. Using final slip models, they estimated the rupture area, the asperity area, the average slip amounts for the rupture area, and the average slip amounts for asperity area following to the criterion proposed by Somerville *et al.* [1999]. Their definition of the rupture area is a rectangle one consisting subfaults whose slips are more than 0.3 times of the average slip. That of the asperity area is the one in the rupture area consisting subfaults whose slips are more than 1.5 times of the average slip. If there are plural asperity areas in the rupture area, total asperity area is obtained. They obtained scaling relationship for rupture area (S), total asperity area (S_a), and average slip (D) by the lest-squares fit. They assumed the power coefficient of M_0 as 2/3 for S and S_a and 1/3 for D by the constraint of the self-similarity (Somerville *et al.*; 1999).

The empirical relationships are as follows,

$$S = 6.57 \times 10^{-11} M_0^{2/3} , \tag{1}$$

$$S_a = 1.04 \times 10^{-11} M_0^{2/3} , \tag{2}$$

and

$$D = 2.25 \times 10^{-5} M_0^{1/3} , \tag{3}$$

where the units of area, slip, and seismic moment are km^2, m, and Nm, respectively.

The relationships of the rupture area and the asperity area versus the seismic moment are shown in Fig. 1. Closed circles represent the intraslab earthquakes collected in this study. The inland crustal earthquakes (Somerville *et al.*, 1999) and the plate-boundary earthquakes (Murotani *et al.*, 2008) are also shown in the same figure. The empirical relationships of three categorized events are indicated by the lines. The assumption of self-similarity is quite reasonable because there is no systematic trend for intraslab earthquakes. Under the same seismic moment, a plate-boundary earthquake has the largest rupture area and the intraslab earthquake has a smallest rupture area. The empirical relationship for inland crustal and plate-boundary earthquakes seems to be similar and the total asperity area for intraslab earthquakes is approximately the half of other groups under the same seismic moment.

Following those empirical relationships, Iwata and Asano [2011] obtained stress parameters of the source model for intraslab earthquakes. Sress drops on the rupture fault and the asperity are given as follows (Boatwright, 1988),

$$\Delta\sigma = \frac{7}{16} \frac{M_0}{R^3} \tag{4},$$

and

$$\Delta\sigma_a = \frac{7}{16} \frac{M_0}{Rr^2} \tag{5},$$

where R and r are the equivalent radius of total rupture area and asperity area, respectively. From the formula (1) and (2), they obtained those stress drops are 4.6 MPa for total rupture area and 28.9 MPa for asperity.
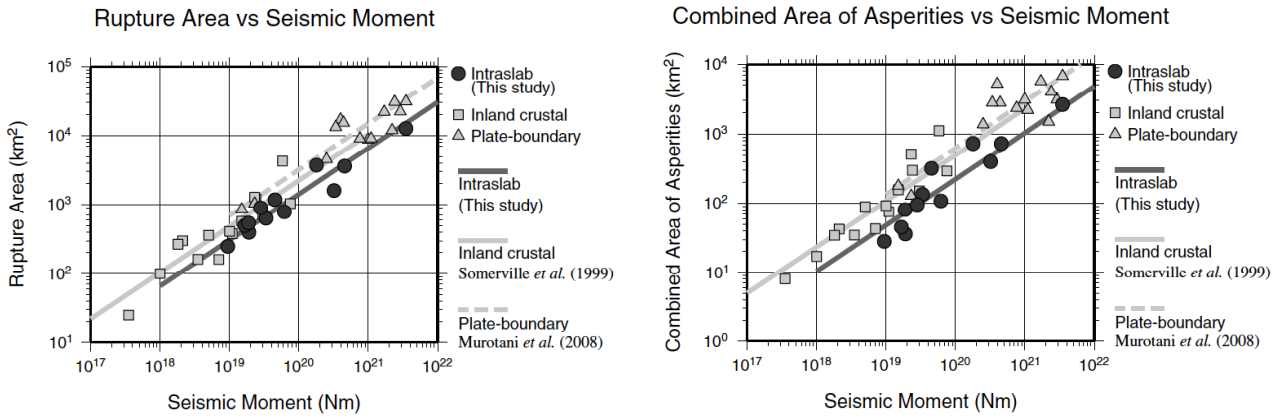
Fig. 1. (Left) Empirical relationships of rupture area and seismic moment. Intraslab events collected by Iwata and Asano [2011] are shown in solid circles, whereas inland crustal events (Somerville et al., 1999) are shown in gray squares and plate-boundary events (Murotani et al., 2008) are shown in gray triangles. Solid line indicates the empirical formulation for intraslab earthquakes obtained by Iwata and Asano [2011]. Gray lines indicate those for inland crustal earthquakes (Somerville et al., 1999) and for plate-boundary earthquakes (Murotani et al., 2008). (Right) Those of asperity are and seismic moment.

SMGA for intraslab events are estimated by broadband strong motion waveform modeling (e.g. Asano et al., 2003, 2004) using the empirical Green's function method (e.g. Irikura, 1986). Iwata and Asano [2011] collected the SMGA modeling results for intraslab earthquakes, compared the sizes and the locations of the SMGA and the asperity area. In Fig. 2, the scaling relationship of SMGAs to seismic moment for intraslab earthquakes is shown. For comparison, the SMGAs for inland crustal earthquakes discussed by Miyake et al. [2003] are also shown. Comparing to the empirical relationship of combined asperity area and seismic moment obtained by Somerville et al. [1999], the SMGAs of intraslab earthquakes are obviously smaller than the combined asperity area of inland crustal earthquake. The solid line indicates the empirical relationship of intraslab earthquake for the asperity and the seismic moment (formula 2). The SMGA size is mostly following this empirical relationship. Using those characteristics of SMGA, the characterized source model of intraslab earthquakes can be modeled in the similar manner for the inland crustal earthquakes, that is, the characterized source model composed of the asperity area and background area whose area ratio and stress drop parameters are different from inland crustal earthquakes.
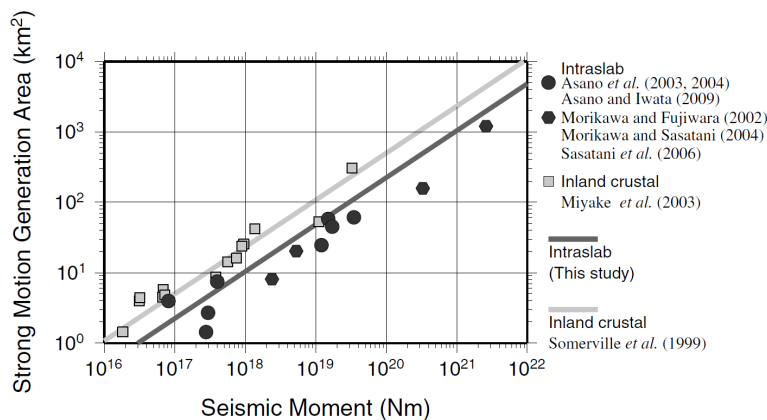

Fig. 2. Scaling of the strong motion generation area to seismic moment for intraslab earthquakes. Circles show the strong motion generation areas for intraslab earthquakes studied in Asano et al. [2003, 2004] and Asano and Iwata [2009]. Hexagons shows the SMGAs studied by Morikawa and Fujiwara [2002], Morikawa and Sasatani [2004], and Sasatani et al. [2006]. Squares show the SMGAs for inland crustal earthquakes analyzed by Miyake et al. [2003]. The line indicates the empirical relationship of combined asperity area and seismic moment obtained by Somerville et al. [1999].

PROCEDURE FOR SOURCE MODEL CONSTRUCTION OF INTRASLAB EARTHQUAKES FOR STRONG MOTION PREDICTION

As mentioned above, Iwata and Asano [2011] obtained the empirical relationships of the rupture size and the asperity size of the intraslab events. Following to those relationships, we give a procedure for constructing source models of intraslab earthquakes for strong motion prediction.

[1] Give the seismic moment, M_0.
[2] Obtain the total rupture area and the total asperity area according to the empirical scaling relationships between S, Sa, and M_0 given by (1) and (2) (Iwata and Asano. 2011).
[3] Square rupture area and asperities are assumed.
[4] The source mechanism is assumed to be the same as that of small events in the source region.
[5] Plural scenarios including variety of the number of asperities and rupture starting points are prepared.

We are testing this procedure by simulating strong ground motions for several observed events below.

The 2001 Geiyo earthquake

The 2001 Geiyo earthquake occurred on March 24th of 2001 in the subducting Philippine-Sea plate. The hypocentral depth and Mw are 46 km and 6.8 respectively. Kakehi [2004] obtained the complex rupture process on the bending fault model. We assume one planar fault model considering the aftershock distribution and give two asperities on the fault plane. The empirical Green's function method (Irikura, 1986) is used for the broad-band ground motion simulation. Map of the source and strong motion stations is shown in Fig. 3. JMA seismic intensity values are compared between the observed and simulated ground motions, as shown in Fig. 3. Among several scenarios, estimated (predicted) JMA seismic intensity values are well reproducing the observed ones. For comparison, we demonstrated ground motion simulations using the characterized source model parameters for inland crustal events (Irikura and Miyake, 2001). The estimated JMA seismic intensities are systematically underestimated compared to the observations. The model parameters for intraslab earthquakes seem to be reasonable for the ground motion modeling of this event.
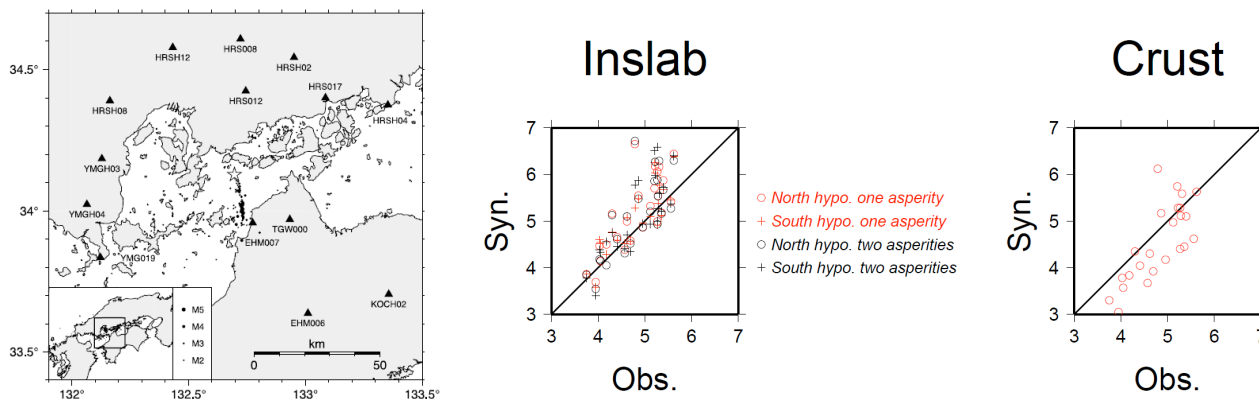

Fig. 3. (Left) Map of strong motion stations and aftershock distribution of the 2001 Geiyo earthquake. (Middle) Comparison of JMA seismic intensity values between synthesized and observed ground motions. (Right) Comparison of JMA seismic intensity values between synthesized and observed ground motions. The characterized source model parameters for crustal earthquakes are used.

The 2003 Miyagi-Oki earthquake

The 2003 Miyagi-Oki earthquake occurred on May 26th of 2003 in the subducting Pacific plate. The hypocentral depth and Mw are 70 km and 7.2 respectively. Asano *et al.* [2004] obtained the SMGA source model. Following their result, we assume the fault plane, position of asperities and rupture patterns. The EGFM ground motion modeling is used. Figure 4 shows the stations and the epicenter on the map. PGA, PGV and JMA seismic intensity of the simulated ground motions are compared to those observations, as shown in Fig. 5. The simulated results using the average parameters, that means that the characterized source model parameters from the empirical relationships (1) and (2), show underestimation of PGA, PGV and JMA seismic intensity, as shown in Fig. 5 (bottom). We demonstrate the average plus one-standard deviation model, which gives the smaller total fault size and the asperity size for the given

seismic moment using one standard deviation relationships of (1) and (2). In other word, the average + one S.D model gives small total size and asperity size, and higher stress drops for the asperity and total area, 58, and 6MPa, respectively. The simulated PGA, PGV and JMA seismic intensities using the average + S.D. model are compared to the observation in Fig. 5 (Upper). Reasonable reproduction is observed in this model simulation. For the case of the 2003 Miyagi-Oki earthquake, the average + S.D. model is needed for reasonable simulation.
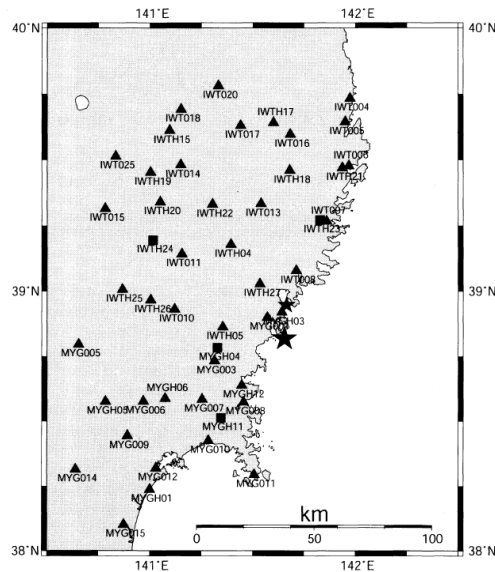

Fig. 4. Map showing strong motion stations and the epicenters of the 2003 Miyagi-Oki earthquake [after Asano et al., 2004]
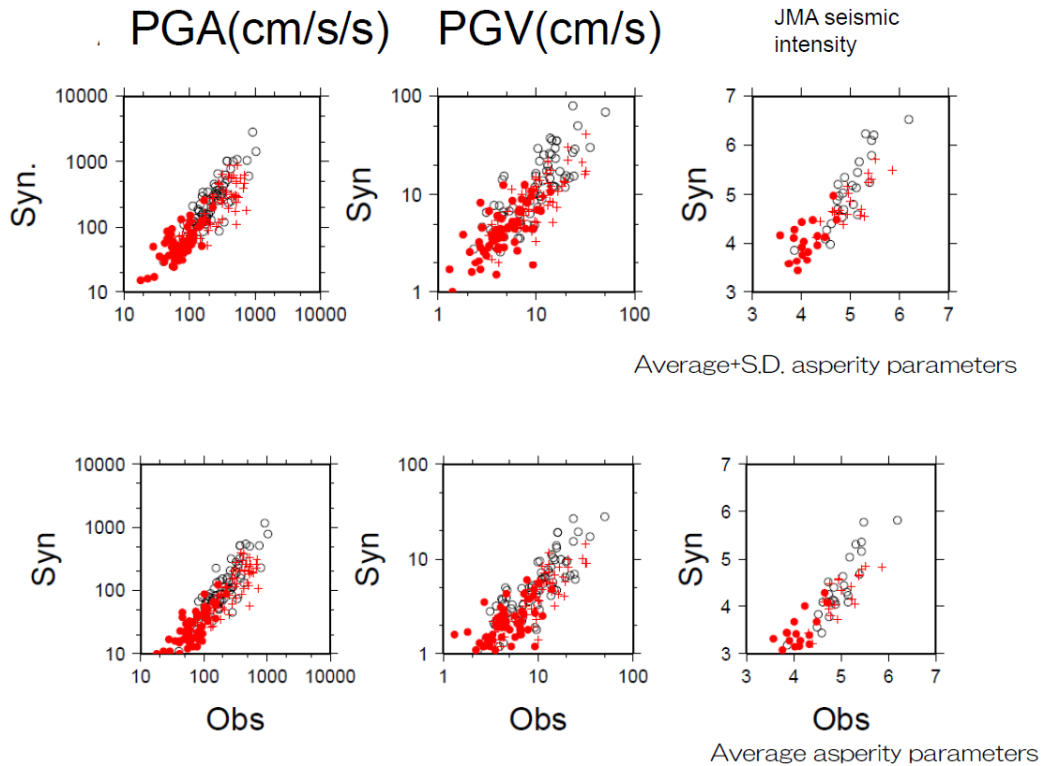

Fig. 5. (Upper) Comparison of PGA, PGV, and JMA seismic intensities of simulated ground motions by the average + S.D. model to the observations. K-NET and KiK-net stations are shown in open black circles and red closed circles, respectively. (Bottom) Comparisons by the average model parameter case.

5

The 1987 Chiba-Ken-Toho-Oki earthquake

The 1987 Chiba-Ken-Toho-Oki earthquake occurred on December 17th of 1987 in the subducting Pacific plate. The hypocentral depth and Mw are 47 km and 6.7, respectively. We referred to the source model of Fukuyama [1991] obtained by the waveform inversion. For the lack of event records, we used the stochastic Green's function method instead of using the EGFM. The underground velocity structure model proposed by Sekiguchi and Yoshimi [2011] is used. Figure 6 compares the simulated JMA seismic intensities to the observations for strong motion stations. The estimation reproduces the observation fairly well. In Fig. 7, the simulated JMA seismic intensity distribution is shown.
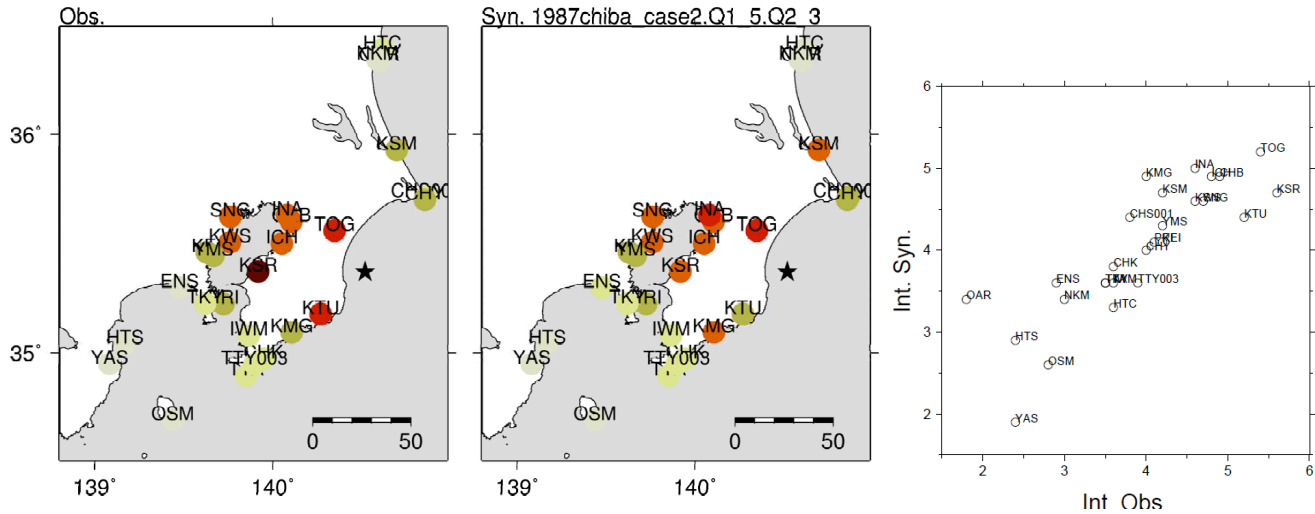

Fig. 6. (Left) Observed JMA seismic intensities for strong motion sites. (Middle) JMA seismic intensities of simulated ground motions. (Right) comparison of simulated and observed JMA seismic intensities.
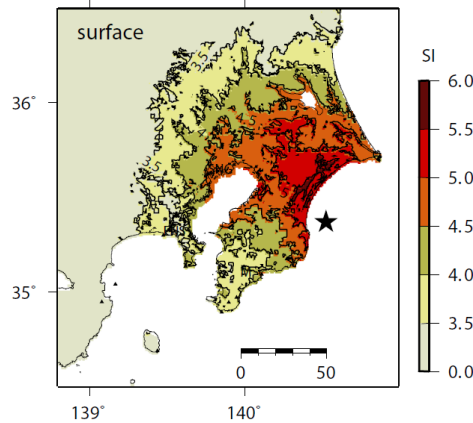

Fig. 7. Distribution of JMA seismic intensity of simulated ground motions. Star indicates epicenter.

DISCUSSION AND CONCLUSIONS

Following the empirical relationships of the total rupture area and the asperity area of the intraslab earthquakes (Iwata and Asano, 2011), we constructed the procedure of the characterized source models for strong motion prediction of intraslab earthquakes. In order to validate this procedure, we applied it to simulate strong ground motions for several observed events such as the 2001 Geiyo (Mw 6.8, hypocentral depth = 46 km, the Philippine-Sea plate), the 2003 Miyagi-Oki (Mw 7.0, 72 km, Pacific plate), and the 1987 Chiba-

Ken-Toho-Oki (*M*w 6.7, 47 km, Pacific plate) earthquakes. The simulated ground motions reproduced observations fairly well for the 2001 Geiyo and the 1987 Chiba earthquakes. On the contrary, the simulated ground motions for the 2003 Miyagi-Oki from the average empirical relationships are underestimated compared to the observations. We simulated the ground motions with the average + S.D. source model that reproduced observations well. Going back to each source model, the stress drop on the asperity is similar to the average one for the 2001 Geiyo earthquake and that is larger than the average one for the 2003 Miyagi-Oki earthquake. In Figure 8, stress drops on asperities in the data-base of intraslab events are plotted against its hypocentral depth summarized in Iwata and Asano [2011]. The asperity stress drop parameters of the 2001 Geiyo earthquake is almost same as the average values (28.9MPa) in their database, whereas that of the 2003 Miyagi-Oki earthquake is similar to the average plus S.D. model.

The source model of the 1987 Chiba is not included in the heterogeneous source slip model data base. The strong motions of the 1987 Chiba event, whose focal depth is 47km, are well represented by the average model. In Fig. 8, there is a systematic change of stress drops on asperity between 30-70km of the hypocentral depth. We could introduce depth dependency of stress drop values in this modeling.
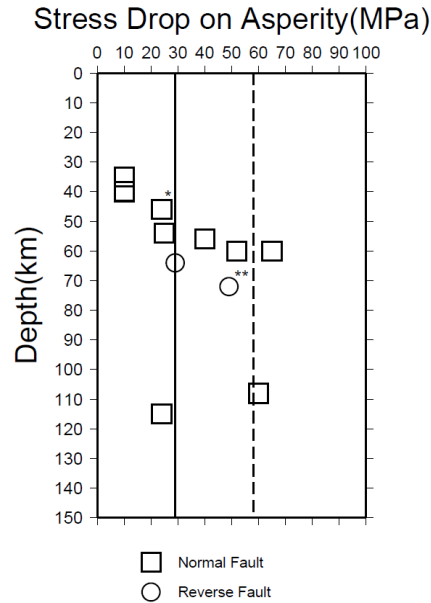

Fig. 8. Stress drops on asperity for Iwata and Asano [2011] data base. Stress drop values put on the hypocentral depth for each event. *the 2001 Geiyo, and ** the 2003 Miyagi-Oki earthquakes, respectively. Thick and broken lines show the stress drop parametes for the characterized source model, respectively, in this study.

ACKNOWLEDGMENTS

REFERENCES

Asano, K., and T. Iwata [2009], "Source model of the 2008 northern Iwate intraslab earthquake by the empirical Green's function method", *Abstracts of Japan Geoscience Union Meeting 2009*, S152-009 (CD-ROM).

Asano, K., T. Iwata, and K. Irikura [2003], "Source characteristics of shallow intraslab earthquakes derived from strong-motion simulations", Earth Planets Space, Vol. 55, No.4, pp. e5-e8.

Asano, K., T. Iwata, and K. Irikura [2004], "Characterization of source models of shallow intraslab earthquakes using strong motion data", *Proc. 13th World Conf. Earthq. Eng.*, paper no. 835.

Boatwright, J. [1988], "The seismic radiation from composite model of faulting", Bull. Seism. Soc. Am., Vol. 78, No. 2, pp. 489–598.

Fukuyama, E. [1991], "Inversion for the rupture details of the 1987 East Chiba earthquake, Japan, Using a fault model based on the distribution of relocated aftershocks", J. Geophys. Res., Vol. 96, No. B5, pp. 8205-8217.

Irikura, K. [1986], "Prediction of strong acceleration motion using empirical Green's function", *Proc. 7th Japan Earthq. Eng. Symp.*, Tokyo, pp. 151-156.

Irikura, K. and H. Miyake [2001], "Prediction of strong ground motions for scenario earthquake", J. Geography, Vol. 110, No. 6, pp. 849-875 (in Japanese with English abstract).

Irikura, K. and H. Miyake [2011], "Recipe for predicting strong ground motion from crustal earthquake scenarios", Pure Appl. Geophys., Vol. 168, No. 1-2, pp. 85-104.

Iwata, T. and K. Asano [2011], "Characterization of the heterogeneous source model of intraslab earthquakes toward strong ground motion prediction", Pure Appl. Geophys., Vol. 168, No. 1-2, pp. 117-124.

Kakehi, Y. [2004], "Analysis of the 2001 Geiyo, Japan, earthquake using high-density strong ground motion data: Detailed rupture process of a slab earthquake in a medium with a large velocity contrast", J. Geophys. Res., Vol. 109, No. B8, B08306, doi:10.1029/2004JB002980.

Miyake, H., T. Iwata, and K. Irikura [2003], "Source characterization for broadband ground-motion simulation: Kinematic heterogeneous source model and strong motion generation area", Bull. Seism. Soc. Am., Vol. 93, No. 6, pp. 2531–2545.

Morikawa, N. and H. Fujiwara [2002], "Scaling relationship for intra-slab earthquakes (2)", *Abstracts Japan Earth Planetary Sci. Joint Meet.*, S042-P013 (CD-ROM).

Morikawa, N. and T. Sasatani [2004], "Source models of two large intraslab earthquakes from broadband strong ground motions", Bull. Seism. Soc. Am., Vol. 94, No.3, pp. 803–817.

Murotani, S., H. Miyake, and K. Koketsu [2008], "Scaling of characterized slip models for plate-boundary earthquakes", Earth Planets Space, Vol. 60, No. 9, pp. 987–991.

Sasatani, T., N. Morikawa, and T. Maeda [2006], "Source characteristics of intraslab earthquakes", Geophys. Bull. Hokkaido Univ., Vol. 69, pp. 123–134 (in Japanese with English abstract).

Sekiguchi, H. and M. Yoshimi [2011], "Broadband Ground Motion Reconstruction for the Kanto Basin during the 1923 Kanto Earthquake", Pure Appl. Geophys., Vol. 168, No. 3-4, pp. 609-630.

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 the prediction of strong ground motion", Seism. Res. Lett. Vol. 70, No. 1, pp. 59–80.

Youngs, R. R., S.-J. Chiou, W. J. Silva, and J. R. Humphrey [1997], "Strong ground motion attenuation relationships for subduction zone earthquakes", Seism. Res. Lett., Vol. 68, No. 1, pp. 58-73.

Wessel, P. and W.H.F. Smith [1998], "New, improved version of Generic Mapping Tools released", EOS Trans. AGU, Vol. 79, No. 47, pp. 579.