A Prototype of Strong Ground Motion Prediction Procedure for Intraslab Earthquake based on the Characterized Source Model

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SUMMARY:
Strong motion predictions for anticipated earthquakes are important for seismic disaster evaluation and planning of disaster management. We proposed a prototype of the procedure to construct source models of intraslab earthquakes for strong motion prediction based on the concept of the characterized source model (Irikura and Miyake, 2011). Iwata and Asano (2011) characterized the heterogeneous source model for intraslab earthquakes based on the empirical scaling relationships between the asperity and the total rupture areas and the correspondence between the SMGA (strong motion generation area, Miyake *et al.*, 2003) and the asperity (large slip area). We proposed ta procedure to construct a source model or a intraslab earthquake to be used for strong ground motion prediction based on the characterized intraslab-earthquake source model by Iwata and Asano (2011). We applied this procedure to several observed events occurred in Japan and simulated ground motions in order to validate the procedure. Through those validation tests, we found that some source parameters show regional dependency and that appropriate choice for the target source region is crucial.

Keywords: Strong ground motion prediction, Intraslab earthquake, characterized source model

1. INTRODUCTION

Along the Pacific Rim, large intraslab earthquakes have caused disasters (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 on PGA attenuation relationships (e.g. Youngs *et al.*, 1997; Si and Midorikawa, 1999) have shown that deeper events cause larger PGA.

Strong motion prediction based on scenario earthquakes are recently carried out for earthquake disaster mitigation of urbanized societies and source modelling 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 asperities to the rupture area is constant in the moment magnitude ranging from 5.7 to 7.2. Miyake *et al.* (2003) showed that strong motion generation area (SMGA), defined as a restricted area with higher slip velocity and/or higher stress drop on the source fault, which mainly generates broad-band strong ground motions, coincides with 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 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).

Iwata and Asano (2011) compiled kinematic heterogeneous source models of intraslab earthquakes to compare source scaling properties with those of inland crustal (Somerville *et al.*, 1999) 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. Iwata *et al.* (2011) proposed a procedure for constructing the source model of intraslab earthquakes for strong motion prediction, and applied it to the past events to check the applicability of the procedure by comparing ground motion records and seismic intensity distributions. This paper will summarize the procedure shown in Iwata *et al.* (2011), apply it to the 2011 Miyagi-Oki intraslab earthquake, and discuss on applicability of the procedure.

2. 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,

$$S = 6.57 \times 10^{-11} M_0^{2/3} \tag{2.1}$$

$$S_a = 1.04 \times 10^{-11} M_0^{2/3} \tag{2.2}$$

$$D = 2.25 \times 10^{-5} M_0^{1/3} \tag{2.3}$$

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. 2.1. 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. Stress drops on the rupture area and the asperity are given by the following equations (Boatwright, 1988).

$$\Delta\sigma = \frac{7}{16}\frac{M_0}{R^3} \tag{2.4}$$

$$\Delta\sigma_a = \frac{7}{16}\frac{M_0}{Rr^2} \tag{2.5}$$

R and r are the equivalent radius of total rupture area and asperity area, respectively. From the Eqns. 2.1 and 2.2, they obtained those stress drops are 4.6 MPa for total rupture area and 28.9 MPa for asperity (c.f. 2.3 MPa and 10.5 MPa for crustal earthquakes).

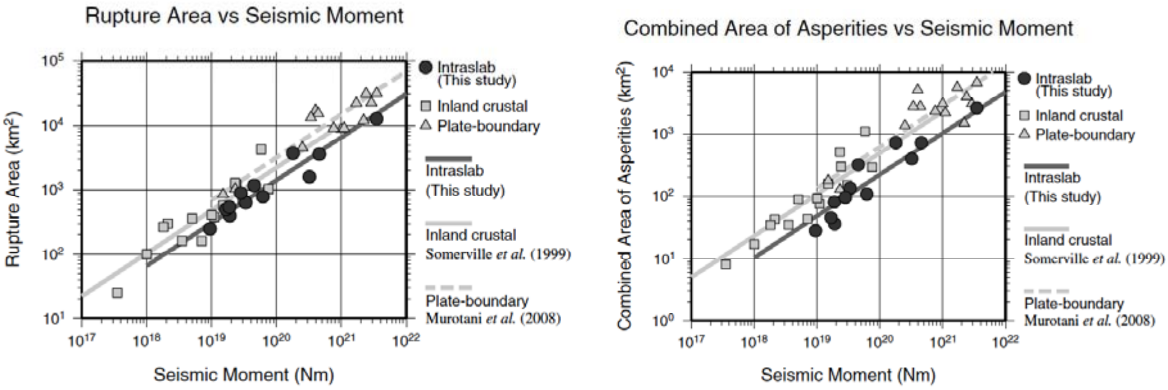

Figure 2.1. (Left) Empirical scaling relationships of rupture area and seismic moment. Intraslab events collected by Iwata and Asano (2011) are shown in solid circles, whereas inland crustal events (Somerville *et al.*, 1999) are shown in grey squares and plate-boundary events (Murotani *et al.*, 2008) are shown in grey triangles. Solid line indicates the empirical formulation for intraslab earthquakes obtained by Iwata and Asano (2011). Grey lines indicate those for inland crustal earthquakes (Somerville *et al.*, 1999) and for plate-boundary earthquakes (Murotani *et al.*, 2008). (Right) Those of asperity area and seismic moment.

SMGA for intraslab events are estimated by broadband strong motion waveform modelling (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 modelling results for intraslab earthquakes, and compared the sizes and the locations of the SMGA and the asperity area. In Fig. 2.2, 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 (Eqn. 2.2). The SMGA size is mostly following this empirical relationship. Using those characteristics of SMGA, the characterized source model of intraslab earthquakes can be modelled in the similar manner for 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. For inland crustal earthquakes, S_a/S (the ratio of asperity and total area) is about 0.22, whereas that for intraslab earthquakes is 0.16.

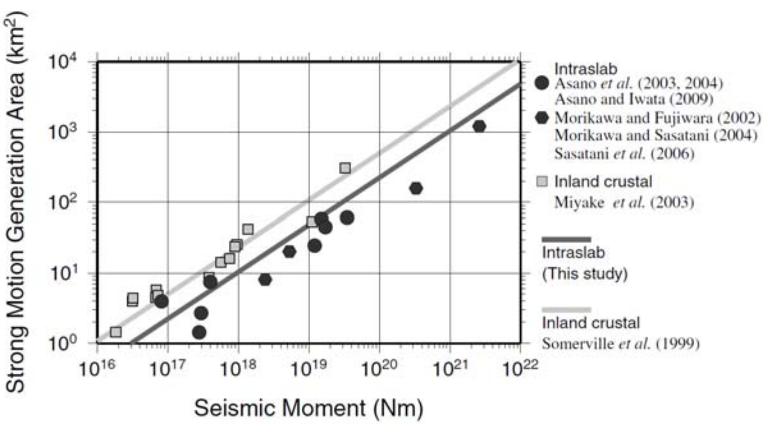

Figure 2.2. Scaling relationship of strong motion generation area to seismic moment for intraslab earthquakes. Circles show the strong motion generation areas for intraslab earthquakes studied in Asano *et al.* (2003, 2004) and Asano and Iwata (2009). Hexagons show the SMGAs studied by Morikawa and Fujiwara (2002), Morikawa

and Sasatani (2004), and Sasatani *et al.* (2006). Squares show the SMGAs for inland crustal earthquakes analysed by Miyake *et al.* (2003). The line indicates the empirical relationship of combined asperity area and seismic moment obtained by Somerville *et al.* (1999).

3. 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, S_a, and M_0 given by Eqns. (2.1) and (2.2)

[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.

Iwata *et al.* (2011) tested this procedure by simulating strong ground motions for several past earthquakes such as the 2001 Geiyo (M_W 6.8, hypocentral depth = 46 km, the Philippine-Sea plate), the 2003 Miyagi-Oki (M_W 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. They simulated the ground motions with the average – S.D. source model for total and asperity area sizes, which means higher stress drop source model than the average, and reproduced observations well. Here we will show the simulation results for the 7 April 2011 Miyagi-Oki intraslab earthquake.

3.1 Simulation for the 2011 Miyagi-Oki earthquake

The 2011 Miyagi-Oki earthquake occurred on 7 April 2011 (JST = UT + 9) in the subducting Pacific plate. This event is referred as an induced earthquake by the 2011 Great Tohoku earthquake. The hypocentral depth and M_W are 66 km and 7.1, respectively. The source mechanism is reverse fault type. Aftershock distribution shows the fault plane is down to East with the WNW-ESE direction. Following the procedure, we assumed the source model. The EGFM ground motion modelling is used for the forward simulation. We used records of an M_W 5.4 aftershock occurred at 18:42 on 9 April 2011 (JST) as an empirical Green's function. Target sites are K-NET and KiK-net strong motion stations. The simulated results using the average parameters, that means that the characterized source model parameters from the empirical relationships (2.1) and (2.2), show underestimation of PGA, PGV and JMA seismic intensity. Therefore, we demonstrate the average minus 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 (2.1) and (2.2). In other words, 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 6 MPa, respectively. The simulated PGA, PGV and JMA seismic intensities using the average – S.D. model are compared to the observation in Fig. 3.1. Reasonable reproduction is observed in this model simulation. For the case of the 2011 Miyagi-Oki earthquake, the average – one S.D. model is necessary for reasonable simulation, which is similar to the case of the 2003 Miyagi-Oki earthquake in Iwata *et al.* (2011).

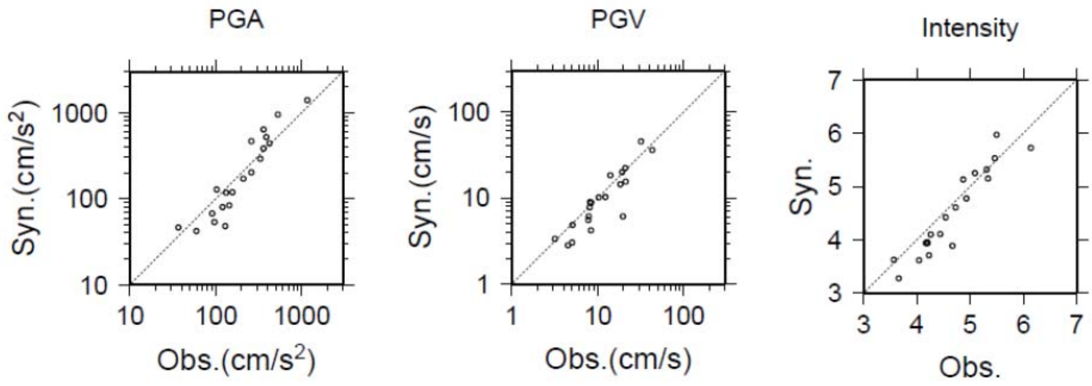

Figure 3.1. Comparison of PGA, PGV, and JMA seismic intensities of simulated ground motions by the average – one S.D. model (smaller fault and asperity size, i.e. larger stress drop model) to the observations.

4. 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 in Iwata *et al.* (2011) and this paper. Table 4.1 summarizes the application results. 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 and the 2001 Miyagi-Oki from the average empirical relationships are underestimated compared to the observations. We simulated the ground motions with the average – one S.D. source model that reproduced observations well. Going back to each source model in Iwata and Asano (2011), the source models of the 2001 Geiyo and the 2003 Miyagi-Oki events are used. There, 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 Fig. 4.1, 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 (28.9 MPa) in their database, whereas that of the 2003 Miyagi-Oki earthquake is about the stress drop from the average – S.D. model.

Table 4.1 Summary of the validation results

Event	M_W	Plate	Hypocentral depth	Preferred Model
The 1987 Chiba-Ken-Toho-Oki	6.7	Pacific Plate	58 km	average model
The 2001 Geiyo	6.8	Philippine Sea Plate	51 km	average model
The May 2003 Miyagi-Oki	7.0	Pacific Plate	71 km	ave. – one S.D.model
The April 2011 Miyagi-Oki	7.1	Pacific Plate	66 km	ave. – one S.D.model

The source models of the 1987 Chiba and the 2011 Miyagi-Oki events are not included in the heterogeneous source slip model data base in Iwata and Asano (2011). The strong motions of the 1987 Chiba event, whose focal depth is 47km, are well represented by the average model. In Fig. 4.1, there is a systematic change of stress drops on asperity between 30 and 70 km of the hypocentral depth. We could introduce depth dependency of stress drop values in this modelling. As a point of strong motion prediction model, we could recommend simulations by not only the average model but the average – one S.D. model (higher stress drop model) and recognize those ground motion characteristics.

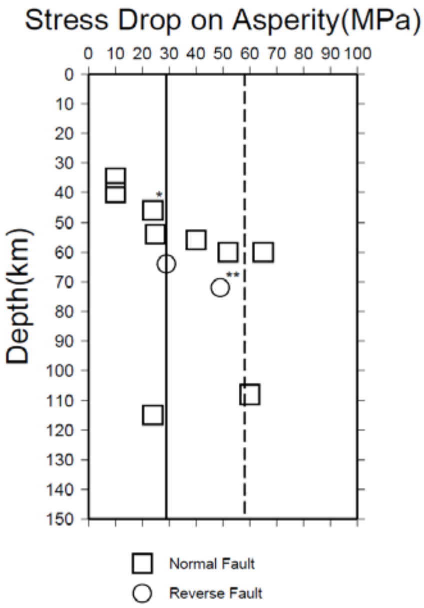

Figure 4.1. Stress drops on asperity for events in Iwata and Asano (2011). Stress drop values are plotted on the hypocentral depth for each event. * denotes the 2001 Geiyo, and ** denotes the 2003 Miyagi-Oki earthquakes. Thick and broken lines show the stress drop parameters of the average and average – S.D. characterized source model, respectively.

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