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CHARACTERIZATION OF SOURCE MODELS OF SHALLOW INTRASLAB EARTHQUAKES USING STRONG MOTION DATA

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SUMMARY

Several differences of observed ground motion characteristics between crustal and intraslab earthquakes seem to be caused by not only propagation-path but also source characteristics. We studied the characterization of source models for shallow intraslab earthquakes based on strong motion simulations. Appropriate source models of several shallow intraslab earthquakes (M_W 5.2 - 7.0) that occurred in Japan were constructed to explain the broadband ground motion based on strong motion simulations using the empirical Green's function method. Our source model is expressed by one or several rectangular regions called strong motion generation area on an assumed fault plane, which can be thought to be equivalent to the asperities of heterogeneous source model by previous studies. We summarized the results and found that the strong motion generation area of the source model for each shallow intraslab earthquake is smaller than the prediction by the empirical relationship for inland crustal earthquakes proposed by Somerville *et al.* (1999). This means that the stress drop on the asperity or the strong motion generation area of a shallow intraslab earthquake is higher than that of an inland crustal earthquake. Among shallow intraslab earthquakes, relatively deeper event with the source depth of about 70 – 100 km has very high stress drop, that is more than 100 MPa, though shallower events with the source depth of about 30 km has relatively low stress drop, that is almost same or slightly higher than inland crustal events. Our result suggests that the stress drop on the asperity of shallow intraslab earthquakes depends on its depth. When we assume the value of the stress drop in case of the strong motion prediction for an intraslab earthquake, we have to consider include the focal-depth dependence of the stress drop.

INTRODUCTION

Shallow intraslab earthquakes occurring in subducting slab bring strong ground motion on surface despite its relatively deeper focal depths compared with inland crustal earthquakes. For engineering purpose, empirical attenuation relationships for peak ground acceleration and velocity have been developed considering the difference in the type of earthquake source and the focal depth by Si and Midorikawa [1]. According to their attenuation relationships, the peak ground motion from an intraslab event is larger than that from an interplate event. Such a large ground motion will be caused by not only the low-attenuation (high Q-value) along the propagation path but also the high stress drop on the source. Compared to

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shallow crustal earthquakes occurring at inland regions and interplate earthquakes occurring at subducting plate boundary regions, the study on source characteristics of shallow intraslab earthquakes in the view of strong motion seismology are not sufficient because the number of observed events seems to be smaller than other types of earthquakes and the place of large intraslab earthquake occurrences is believed to be limited. These intraslab earthquakes are thought to be related to the dehydration of hydrated oceanic crust and serpentinized mantle [2].

In recent years, Japan has been suffered by two large shallow intraslab earthquakes, which were the 2001 Geiyo earthquake and the 2003 off Miyagi earthquake. The strong motion waveforms from these earthquakes have been obtained through the dense Japanese strong motion networks, the K-NET [3] and the KiK-net [4], operated by the National Research Institute for Earth Science and Disaster Prevention (NIED). In this paper, we call the intraslab earthquake occurring at the depth of about 30-100 km the shallow intraslab earthquake. The detailed source processes of large earthquakes mentioned above have been obtained by several authors through the kinematic waveform inversion using the strong motion data [5-8]. However, the frequency range for these analyses is restricted to lower than about 1Hz because of the accuracy in the underground structure information to calculate Green's functions. To explain the realistic strong ground motions from shallow intraslab earthquakes quantitatively, it is needed to take more wide-range including high-frequency components of ground motions in consideration. One of the effective methods to simulate broadband ground motions is employment of observed aftershock records as the empirical Green's functions. Irikura [9] has developed the methodology to simulate strong ground motions using empirical Green's functions based on a scaling relationship of the ω^{-2} source spectrum [10]. The waveform for a large event is synthesized by summing the records of small events with corrections for the difference in the slip velocity time function between the large and small events following the scaling laws. Successive source modeling by the empirical Green's function method [9] has been done by Kamae and Irikura [11, 12], Ikeda *et al*. [13], Miyake *et al*. [14], Morikawa *et al*. [15], and others. In this study, we will construct source models for seven large and moderate-size shallow intraslab earthquakes by the forward waveform modeling using the empirical Green's function method [14], and will discuss on some remarkable features of obtained source models.

METHODOLOGY AND DATA

Methodology

In this study, a characterized source model consisting one or several "strong motion generation areas" in the fault plane is assumed. The strong motion generation area is defined as the extended area having relatively large slip velocity within the total rupture area [14]. We assume that the area has uniform slip and rise time. For broadband strong motion simulation up to about 10 Hz using the empirical Green's function method [9], such a simple source model is able to reproduce observed ground motions and is confirmed that the strong motion generation area is equivalent to the asperity area characterized from the heterogeneous slip distribution estimated by the kinematic waveform inversion using low-frequency waveforms [11-16].

We determined the number and the location of strong motion generation areas, the size and the rise time of each strong motion generation area, and the rupture propagation velocity by the forward modeling using the empirical Green's function method. Radial rupture propagation inside each strong motion generation area is also assumed. The best source model is chosen to minimize the residual of displacement waveforms and envelopes of acceleration waveforms using the criterion proposed by Miyake *et al*. [14]. The detailed description about the forward modeling and the summation technique of the empirical Green's function method are written by Irikura [9] and Miyake *et al*. [14].

Analyzed events and data set

We have analyzed seven shallow intraslab earthquakes listed in Table 1. The locations of epicenters are also indicated in Fig.1. The source mechanism determined from the moment tensor inversion using broadband seismograph data by the F-net and the Harvard University CMT project is also shown in Fig.1 using lower hemisphere projection. The focal depths of these events range from 30 to 72 km. Magnitudes determined by the Japan Meteorological Agency (JMA) are from 5.3 to 7.1. Horizontal components of the S-wave part at four strong motion stations are used to construct the source model by the forward waveform modeling.

Table 1: Information of target events and small events used as empirical Green's functions

Event No.	Origin time (JST)	Lat. (deg)	Long. (deg)	Depth (km)	M_{JMA}	M_0 (Nm) / M_W
1m	1997/03/16 14:51	34.925°N	137.528°E	39.12	5.9	2.97×10^{17} / 5.6
1s	1997/03/16 14:53	34.901°N	137.515°E	36.21	4.0	N.A.
2m	1999/08/21 05:33	34.028°N	135.473°E	65.83	5.6	2.79×10^{17} / 5.6
2s	2000/06/02 15:05	34.002°N	135.407°E	59.85	4.1	2.10×10^{15} / 4.2
3m	2000/01/28 23:21	43.006°N	146.749°E	58.51	7.0	1.21×10^{19} / 6.7
3s	2000/09/03 20:01	42.984°N	146.846°E	49.40	5.7	1.39×10^{17} / 5.4
4m	2001/03/24 15:27	34.129°N	132.696°E	46.46	6.7	1.51×10^{19} / 6.8
4s	2001/03/26 05:40	34.114°N	132.712°E	45.86	5.2	4.76×10^{16} / 5.1
5m	2001/04/03 23:57	35.021°N	138.097°E	30.34	5.3	8.17×10^{16} / 5.2
5s	2001/04/04 00:04	35.011°N	138.089°E	31.31	4.1	8.73×10^{14} / 3.9
6m	2001/04/25 23:40	32.796°N	132.342°E	39.30	5.8	4.00×10^{17} / 5.7
6s	1999/01/25 05:03	32.694°N	132.286°E	39.23	3.9	1.33×10^{15} / 4.0
7m	2003/05/26 18:24	38.818°N	141.654°E	72.03	7.1	3.49×10^{19} / 7.0
7s	2003/05/27 00:44	38.948°N	141.665°E	68.52	4.9	1.43×10^{16} / 4.7

Event No. with 'm' indicates the mainshock that is studied as the target event, and that with 's' indicates the small event that is used as the empirical Green's function.

Hypocentral information is provided from the Japan Meteorological Agency (JMA).

Seismic moment (M_0) was determined by the F-net (Full Range Seismograph Network of Japan), NIED [17]. These data is available via the World Wide Web (http://www.fnet.bosai.go.jp/).

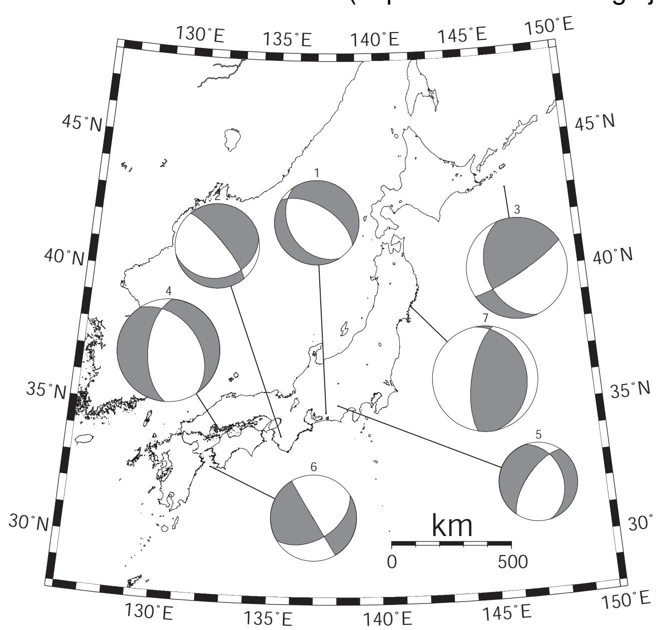

Figure 1: Locations and mechanisms of events studied

RESULTS

The 2001 Geiyo earthquake

The 2001 Geiyo earthquake (M_{JMA}=6.7, M_W=6.8) occurred at the depth of 46 km within the Philippine Sea slab on March 24, 2002 (JST). At this region, a large historical intraslab earthquake called the 1905 Geiyo earthquake (M=7.2) has occurred. The epicenters of the target and the small events are shown by the large and the small stars in Fig.2. Strong motion stations used for the source modeling are indicated by solid triangles in Fig.2.

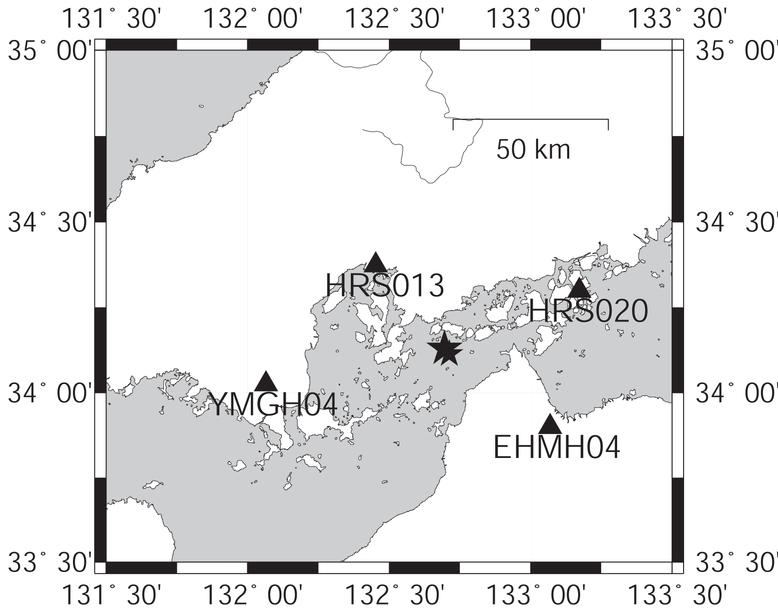

Figure 2: Map of the 2001 Geiyo earthquake

Our forward modeling result suggests that the 2001 Geiyo earthquake has two strong motion generation areas. The obtained source model is shown in Fig.3. The large star in Fig.3 is the starting point of the whole rupture fixed at the hypocenter determined by the JMA, and the small star is the rupture starting point for the strong motion generation area. The rupture of the second (southern) strong motion generation area started at 4.81 s after the rupture of the first (northern) strong motion generation area.

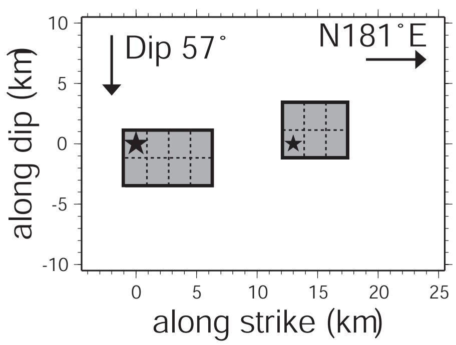

Figure 3: Obtained source model of the 2001 Geiyo earthquake

Observed and synthetic acceleration, velocity, and displacement waveforms of each component are shown in Fig. 4. These records are band-pass filtered between 0.2 and 10 Hz. The number between observed and synthetic waveforms of each component is the maximum amplitude of the observed records. Observed waveforms are well reproduced by synthetic waveforms.

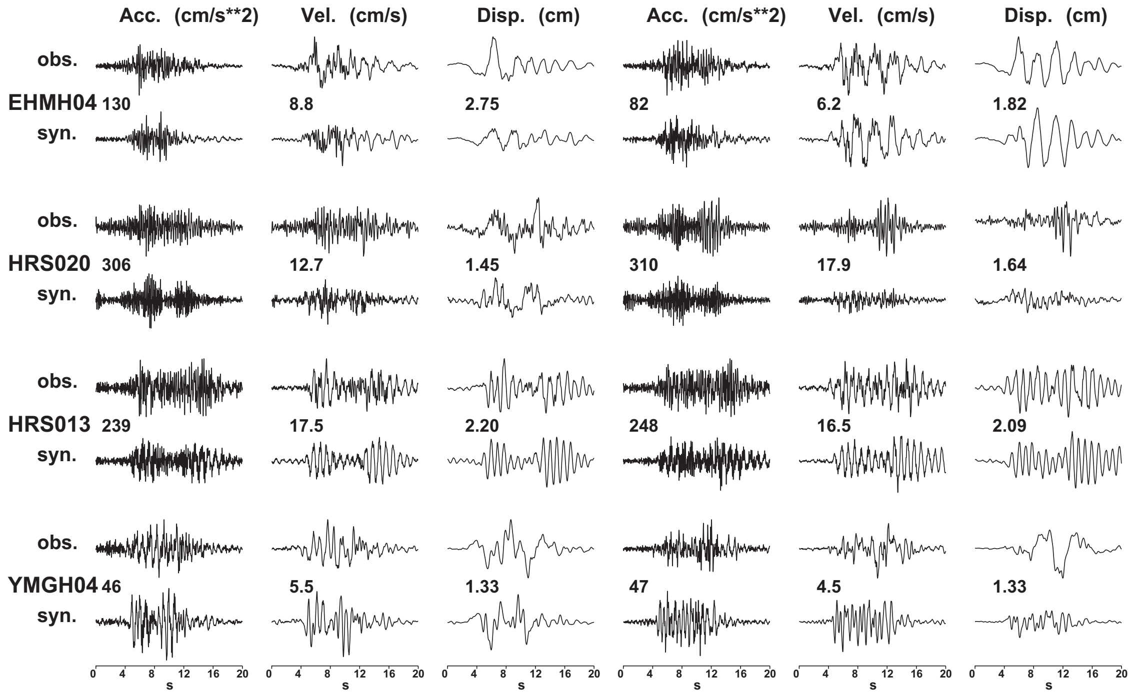

Figure 4: Comparison of observed and synthetic waveforms for the 2001 Geiyo earthquake

The 2003 Off-Miyagi earthquake

The 2003 Off-Miyagi earthquake (M_{JMA}=7.1, M_W=7.0) occurred at the depth of 72 km near the coast of Northeastern Honshu, Japan, within the Pacific slab on May 26, 2002 (JST). The epicenters of the target and the small events are shown by the large and the small stars in Fig.5. Strong motion stations used for the source modeling are indicated by solid triangles in Fig.5.

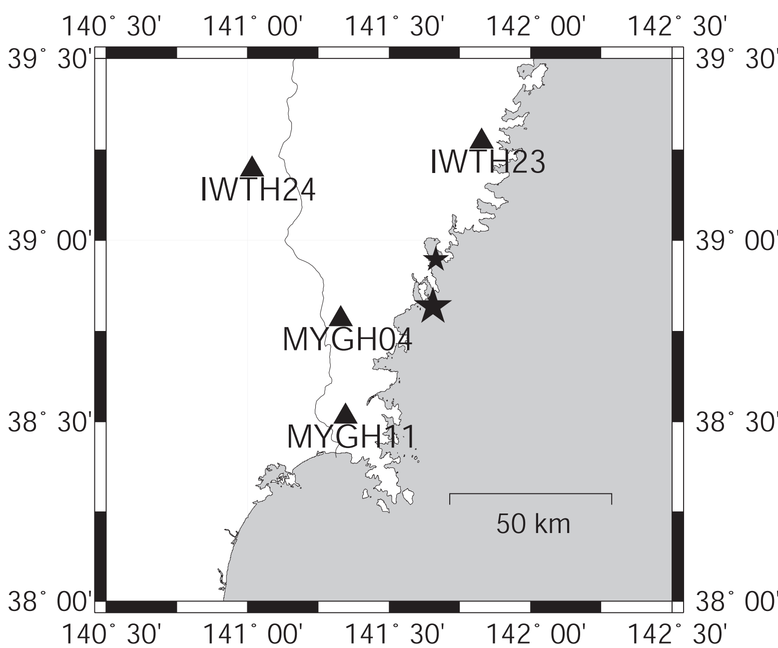

Figure 5: Map of the 2003 Off-Miyagi earthquake

Our forward modeling result suggests that the 2003 Off-Miyagi earthquake has three strong motion generation areas within a total rupture area. The obtained source model is shown in Fig. 6. This spatial distribution of strong motion generation area is close to the large slip area from the kinematic waveform inversion [7]. The large star in Fig.3 is the starting point of the whole rupture fixed at the hypocenter determined by the JMA, and the small star is the rupture starting point for the strong motion generation area. The ruptures of the strong motion generation area B and C started at 0.36 s and 3.28 s after the rupture of the strong motion generation area A, respectively.

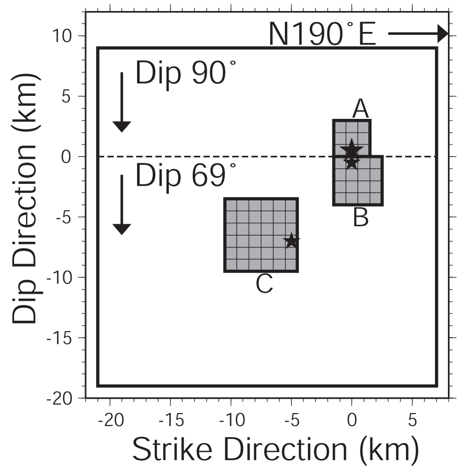

Figure 6: Obtained source model of the 2003 Off-Miyagi earthquake

Observed and synthetic acceleration, velocity, and displacement waveforms of each component are shown in Fig. 7. These records are band-pass filtered between 0.3 and 10 Hz. The number between observed and synthetic waveforms of each component is the maximum amplitude of the observed records. Observed waveforms are well reproduced by synthetic waveforms.

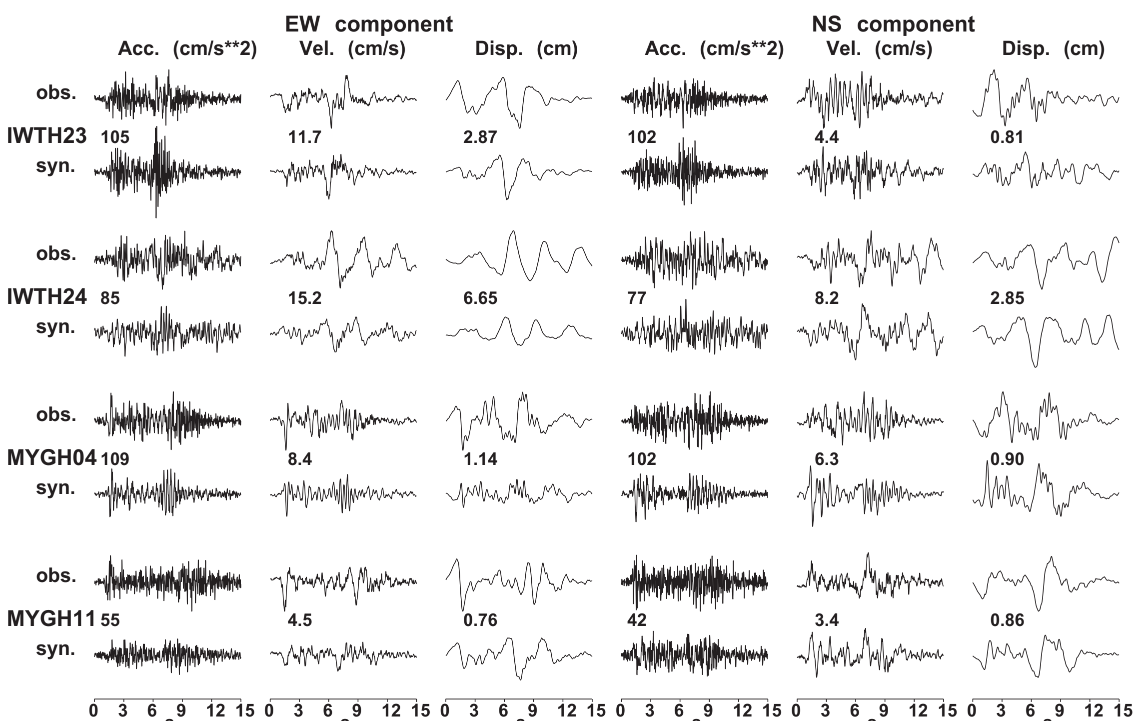

Figure 7: Comparison of observed and synthetic waveforms for the 2003 Off-Miyagi earthquake

Summary of all events

Source parameters of all events analyzed here are listed in Table 2.

Table 2: Source parameters of Strong Motion Generation Areas obtained in this study

No.	Length (km)	Width (km)	Area (km^2)	Rise time (sec)	V_r (km/s)	$\Delta\sigma$ (MPa)
1m	1.5	1.8	2.7	0.09	3.05	N.A.
2m	1.2	1.2	1.44	0.04	4.2	314
3m	4.4	5.6	24.64	0.12	3.7	261
4m	7.2 and 5.4	4.6 and 4.6	57.96	0.28 and 0.21	2.7	47 and 41
5m	1.8	2.2	3.96	0.04	3.1	23
6m	2.2	3.4	7.48	0.12	3.4	19
7m	3.0, 4.0, and 6.0	3.0, 4.0, and 6.0	61.0	0.18, 0.24, and 0.36	2.75	105, 105, and 105

Event 4m and 7m has two and three strong motion generation areas, respectively.
V_r is the rupture propagation velocity inside the strong motion generation area.
$\Delta\sigma$ is the stress drop on the strong motion generation area calculated assuming a circular crack [18, 19].

DISCUSSION

Scaling relationship between strong motion generation area and seismic moment

Strong motion generation area obtained here is plotted against the seismic moment in Fig.8. Strong motion generation areas for two great intraslab earthquakes in Hokkaido derived by Morikawa *et al.* [15] are also plotted in the same figure. For comparison, strong motion generation areas of inland crustal earthquakes estimated by the forward waveform modeling using the empirical Green's function method [11-14] are plotted by squares in Fig.8. The solid line in Fig.8 is the empirical relationship between combined area of asperities and seismic moment proposed by Somerville *et al.* [20]. Miyake *et al.* [14] has concluded that strong motion generation area of inland crustal earthquakes follow the empirical relationship by Somerville *et al.* [20]. However, shallow intraslab earthquakes studied in this study show smaller strong motion generation area than that predicted from the empirical relationship by Somerville *et al.* [20]. Since their empirical relationship is a self-similar relationship with constant stress drop on asperities, it means the stress drop on strong motion generation area or asperities of shallow intraslab earthquakes are larger than that of inland crustal earthquake. That is a quite important characteristic for the source modeling of shallow intraslab earthquakes.

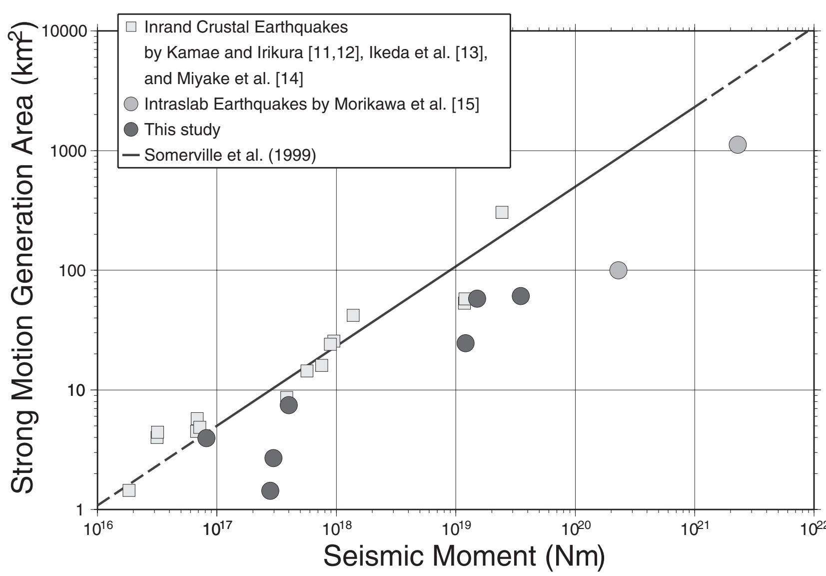

Figure 8: Relationship between strong motion generation area and seismic moment

Depth dependence of stress drop on strong motion generation area

Fig.9 shows the relationship between the stress drop on strong motion generation area and the depth of the center of strong motion generation area. Solid circles indicate normal-fault intraslab events in the Philippine Sea slab, respectively. Open squares indicate reverse-fault events in Pacific slab. Horizontal bars accompanying with these symbols correspond to the spatial extent of strong motion generation area in the depth direction. The relation shows the depth dependence of stress drops, in which the deeper event has larger stress drop. In addition, the reverse fault intraslab events seem to have relatively larger stress drop than the normal fault events. Another possible controlling factor for the difference in stress drop is the regional difference between the Pacific slab and Philippine Sea slab.

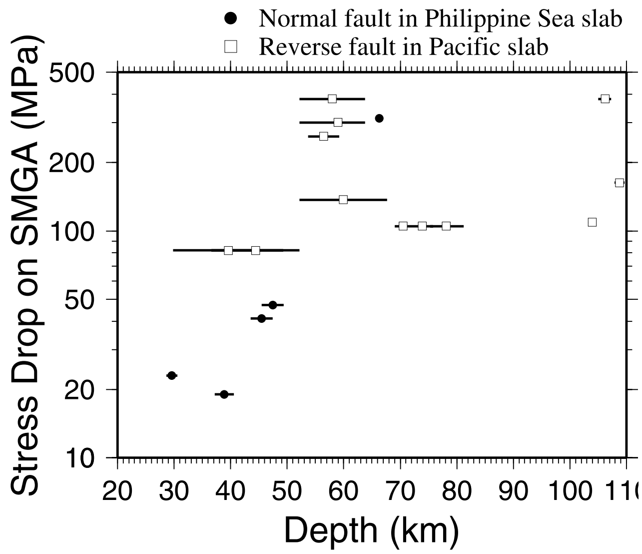

Figure 9: Relationship between the stress drop on strong motion generation area and the depth

CONCLUSIONS

Source modeling of seven shallow intraslab earthquakes occurred in Japan were studied via the forward modeling using the empirical Green's function method. Obtained result indicate that strong motion generation area of shallow intraslab earthquakes are smaller then the predicted values from the empirical relationship between seismic moment and combined area of asperities for inland crustal earthquakes. And, the stress drop on the strong motion generation area seems to depend on its depth, which should be one of important source characteristics for shallow intraslab earthquakes. These results suggests that we need to consider the depth dependence of the stress drop on the strong motion generation area or the asperity in case of the source modeling for the strong motion prediction for shallow intraslab earthquakes.

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