Source modeling of the off Miyagi Intraslab Earthquake (M_{JMA} = 7.1) occurred on April 7, 2011

Satoshi Harada
Chubu Electric Power Co., Inc, Japan

Katsuhiro Kamae, Hidenori Kawabe & Hirotoshi Uebayashi
Research Reactor Institute, Kyoto University, Japan

15 WCEE
LISBOA 2012

SUMMARY:
The 7 April 2011 intraslab earthquake with M_{JMA} 7.1 occurred in the east of Oshika peninsula, Miyagi prefecture, Japan. In this earthquake, high-frequency-rich ground motions were observed comparing with those observed during the crustal earthquakes. In this study, we firstly constructed the characterized source model using the empirical Green's function method. The final source model has a couple of SMGAs (strong motion generation area) according to the existing empirical scaling law for intraslab earthquakes. Furthermore, we pointed out the possibility that the areas with relatively strong ground motion extended in the northwest of the source area by the forward rupture directivity effect. Finally, we concluded the strong ground motions with rich high-frequency component observed at the stations located in the northwest of the epicenter have been generated by not only a high stress drop on the fault but also a directivity effect on the rupture process.

Keywords: Intra-slab earthquake, Source modeling, Strong ground motion, Empirical Green's function method

1. INTRODUCTION

The 7 April 2011 intraslab earthquake with M_{JMA} 7.1 occurred in the east of Oshika peninsula, Miyagi prefecture, Japan. This earthquake occurred in aftershock activity of the 11 March 2011 Tohoku giant earthquake with M_w9.0. The earthquake was registered as 6 upper based on Japanese Seismic Intensity scale in a part of Miyagi prefecture. The strong ground motions from this earthquake struck the Onagawa nuclear power plant located in the Oshika peninsula operated by Tohoku Electric Power Company, and the observed response spectra (h=0.05) in a high-frequency range partially exceeded those estimated from the design basis earthquake ground motion Ss which is based on the regulatory guide for seismic design of nuclear power reactor facilities in Japan. Generally, high-frequency-rich ground motions are observed for intraslab earthquakes. The source models of the several large-scale intraslab earthquakes have been proposed by the forward modeling approach using the empirical Green's function method (EGFM). Also, the empirical scaling laws of the source parameters for intraslab earthquakes are proposed by Dan *et al*. (2006), Sasatani *et al*. (2006) and Iwata and Asano (2011). However, because of a few data, the validity of such empirical scaling laws should be verified with much more data.

Here, we firstly conduct the source modeling of this intraslab earthquake by the forward modeling approach using the EGFM. The source modeling in this study means estimating the strong motion generation areas (SMGA) with large slip velocity or high stress drop on the fault plane. Through such simulations, we investigate the effect of the source process to the generation of strong ground motion and the scaling law of the source parameters.

2. ESTIMATION OF SMGA

2.1. Ground Motion Data

We used the broadband acceleration borehole data at the KiK-net stations (IWTH23, MYGH04, MYGH08, FKSH19) by the National Research Institute for Earth Science and Disaster Prevention (NIED). The locations of these stations are shown later. Firstly, we used the records of the earthquake with M_{JMA} 5.0 occurred on June 2, 2008, as the empirical Green's function (EGF) considering the location and the focal mechanism (Case 1). Furthermore, in order to investigate the effect of the EGFs to the simulations, we conducted the additional simulations using the different records as the EGFs (Case 2 and Case 3). The source parameters of these earthquakes are listed in Table 1. We referred to Japan Meteorological Agency (JMA) for the hypocenter and F-net moment tensor solution catalog by NIED for the focal mechanisms and seismic moments. The stress drops were estimated roughly from the seismic moment and the fault size obtained from the corner frequency on the displacement source spectra calculated by the borehole data of KiK-net which are not affected strongly by the reflected wave from the ground surface. We use the data bandpass-filtered 0.1 to 10.0 Hz depending on the quality of the data.

Table 1. Source parameters of three EGF-events

		Case1	Case2	Case3
Origin Time	(JST)	2008/6/2 0:58	2011/4/21 1:33	2011/4/9 18:42
Latitude	(deg.)	38.304	38.147	38.247
Longitude	(deg.)	141.885	141.741	141.815
Depth	(km)	46.1	54.9	58.2
M_{JMA}		5.0	4.5	5.4
Seismic Moment	(Nm)	1.46×10^{16}	7.9×10^{15}	1.2×10^{17}
Stress Drop	(MPa)	7.1	10.1	21.9
fc	(Hz)	1.5	2.1	1.1
Focal mechanism (strike/dip/rake)	(deg.)	20/75/87 212/16/101	32/37/106 192/55/78	162/71/39 57/53/156

2.2. Source Modeling

Several source models have been estimated based on the waveform inversion using the long-period ground motion records. We referred to the fault plane as well as the slip distribution on the fault by Yamanaka (2011) for setting the initial model. The source model of the 2011 off-Miyagi intraslab earthquake composed of SMGAs, which can reproduce the broadband ground motions, is proposed by the forward modeling approach using EGFM proposed by Irikura (1986). We assumed an S-wave velocity of 3.9 km/s along the wave propagation path and a rupture velocity of 2.75 km/s (about 70% of the S-wave velocity) on the fault plane. The rupture starting point was set at the hypocenter by JMA. The pulsive waveforms are observed in the velocity records at the stations located in the northwest of the epicenter. Therefore, we firstly adjusted the location, size and stress parameter of SMGA1 which reproduce the large velocity pulse due to forward rupture directivity at these stations. Next, SMGA2 was additionally set in order to reproduce the entire recorded ground motion characteristics (duration and envelope etc).

After several trials, we obtained the best source model consisting of a couple of SMGAs on the north and south sides of the hypocenter. The source parameters for each SMGA are summarized in Table 2. Figure 1 shows the estimated source model. Figure 2 shows the locations of the source model, the epicenters of the target and three EGF-events, and KiK-net stations used in this study. Figure 3 shows the comparison of the observed and synthesized horizontal waveforms (acceleration, integrated velocity and displacement) in Case 1. Figure 4 shows the comparison between the synthetic and observed pseudo-velocity response spectra (PVRS) for a damping factor of 0.05 in Case 1. By the bilateral rupture process, observed strong motions at every stations are reproduced well. In particular, pulsive waveforms observed in northwest direction of the epicenter are reproduced well by forward rupture directivity effect. We confirm that the synthetics in Case 2 and 3 show good agreement with the observed motions at every stations. These results mean that this source model is appropriate as

Table 2. Estimated source parameters of the SMGAs for the mainshock

		SMGA1	SMGA2
Strike	(deg.)	15	15
Dip	(deg.)	37	37
Area	(km^2)	10.2 × 10.2	10.2 × 10.2
Seismic moment	(Nm)	3.2×10^{19}	3.2×10^{19}
Stress drop	(MPa)	71	71
Rise time	(s)	0.6	0.6
Rupture time	(s)	0	0

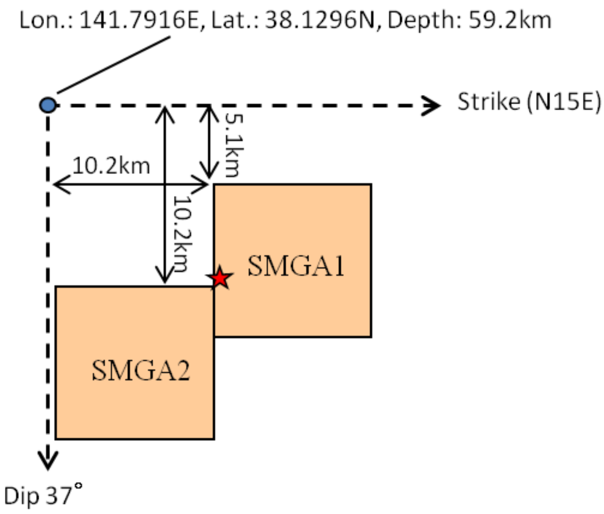

Figure 1. Simplified source model composed of a couple of SMGAs for the off Miyagi Intra-slab Earthquake. The red star indicates the location of the hypocenter (the rupture start point). We assumed the rupture propagates radially from the hypocenter.

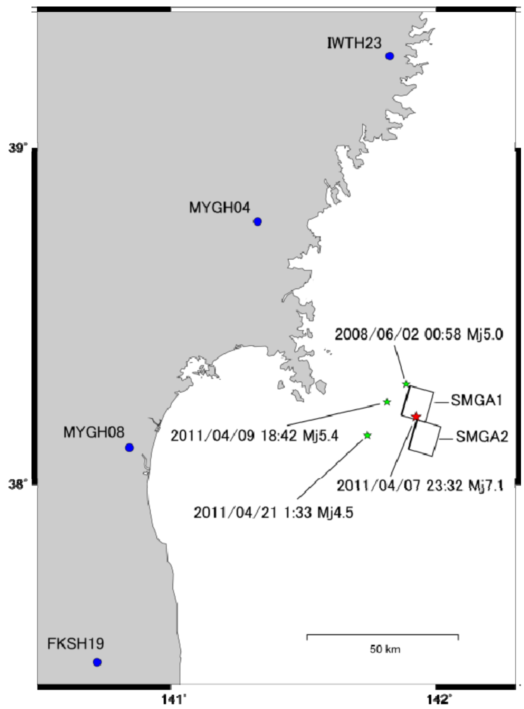

Figure 2. The locations of estimated SMGAs, the epicenters of the mainshock and EGF-events, and KiK-net stations used in this study

well as acceptable. The static stress drop of SMGAs is 71 MPa. This value consists with those shown in the past studies for the intraslab earthquakes.

3. DISCUSSION ON THE FORWARD RUPTURE DIRECTIVITY EFFECT

In the previous chapter, we estimated the source model to reproduce the large velocity pulse at the stations located in the northwest of the epicenter by the forward rupture directivity effect. Here, in order to verify the effect on forward rupture directivity, we investigated the spatial distribution of the PGV (peak ground motion velocity) of the horizontal components simulated using the obtained source model. On the other hand, we collected borehole data at KiK-net stations and examined the spatial distribution of the observed PGV. The simulations were performed using the stochastic Green's function method (SGFM) proposed by Kamae *et al.* (1991). Before conducting the spatial simulations, we confirmed that such simulations are useful as shown in the comparison between the synthetic and

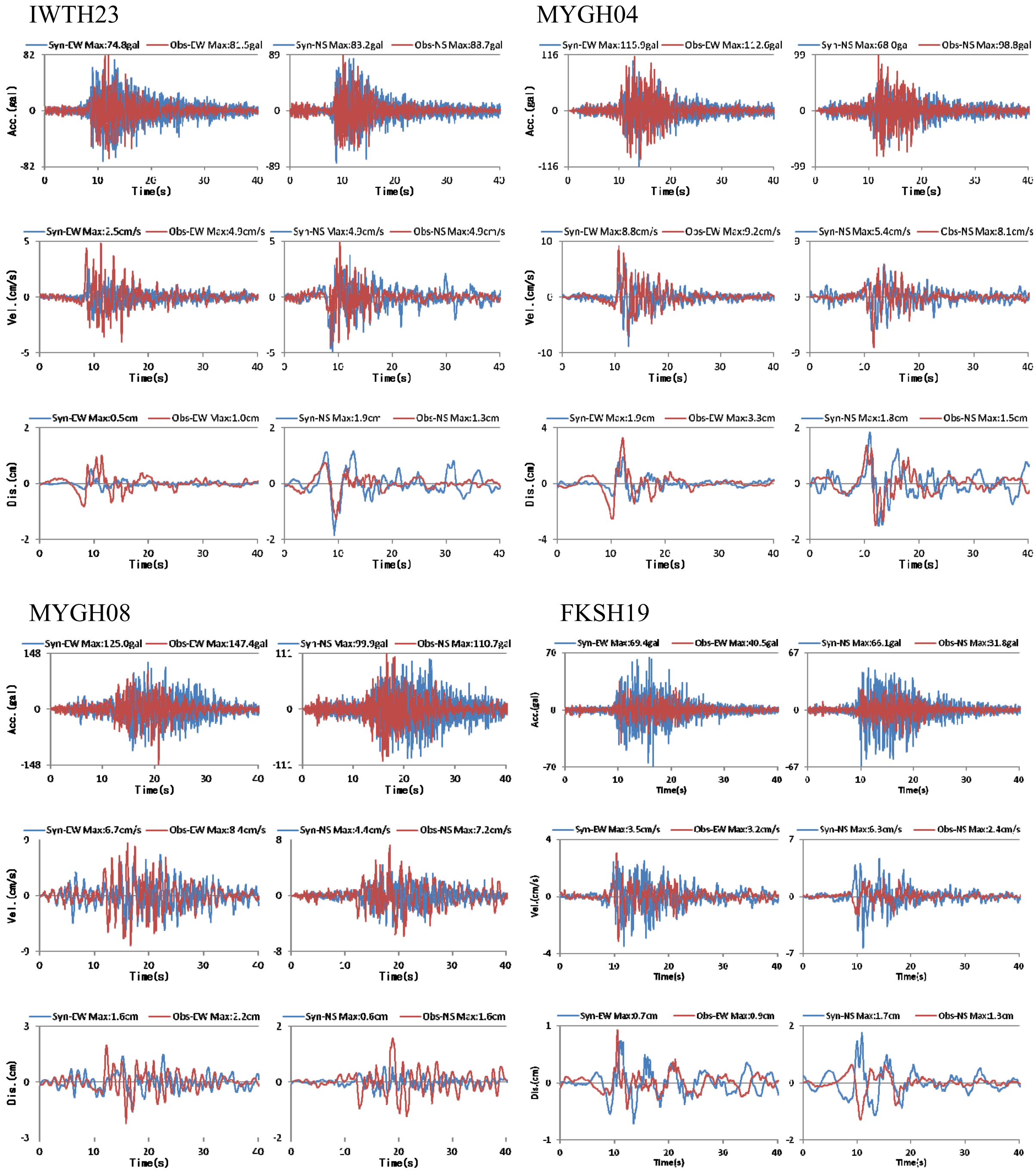

Figure 3. Comparison of the observed (red trace) and synthetic (blue trace) waveforms at IWTH23, MYGH04,MYGH08 and FKSH19 in Case 1

the observed ground motions at MYGH04 in Figure 5. We performed the ground motion simulations using SGFM at 11,700 points (2 km×2 km meshes) in the area of 260 km×180 km. The PGV was calculated as the vector sum of the two horizontal components. The objective of this simulation is to investigate the effect of the source process to the PGV distribution. So, we carried out the simulations on seismic bedrock not considering the surface geologies. Therefore, we can strictly not discuss the differences between the synthetic and the observed PGVs. We focus on the tendency of spatial distribution of the PGVs. Figure 6 shows the spatial distribution of the synthetic and the observed PGVs, together with the locations of the KiK-net stations used in the previous simulations and the source model. We can see that the relatively large PGV area in simulation spread northwest direction of the epicenter. We confirmed this result is based on the forward rupture directivity effect from some simulations changing the rupture starting point. On the other hand, the observed large PGV also appeared clearly in the northwest direction of the epicenter. From this investigation, we preliminarily conclude the extension of the relatively large PVGs in the northwest side of the epicenter comes from the source process (forward rupture directivity).

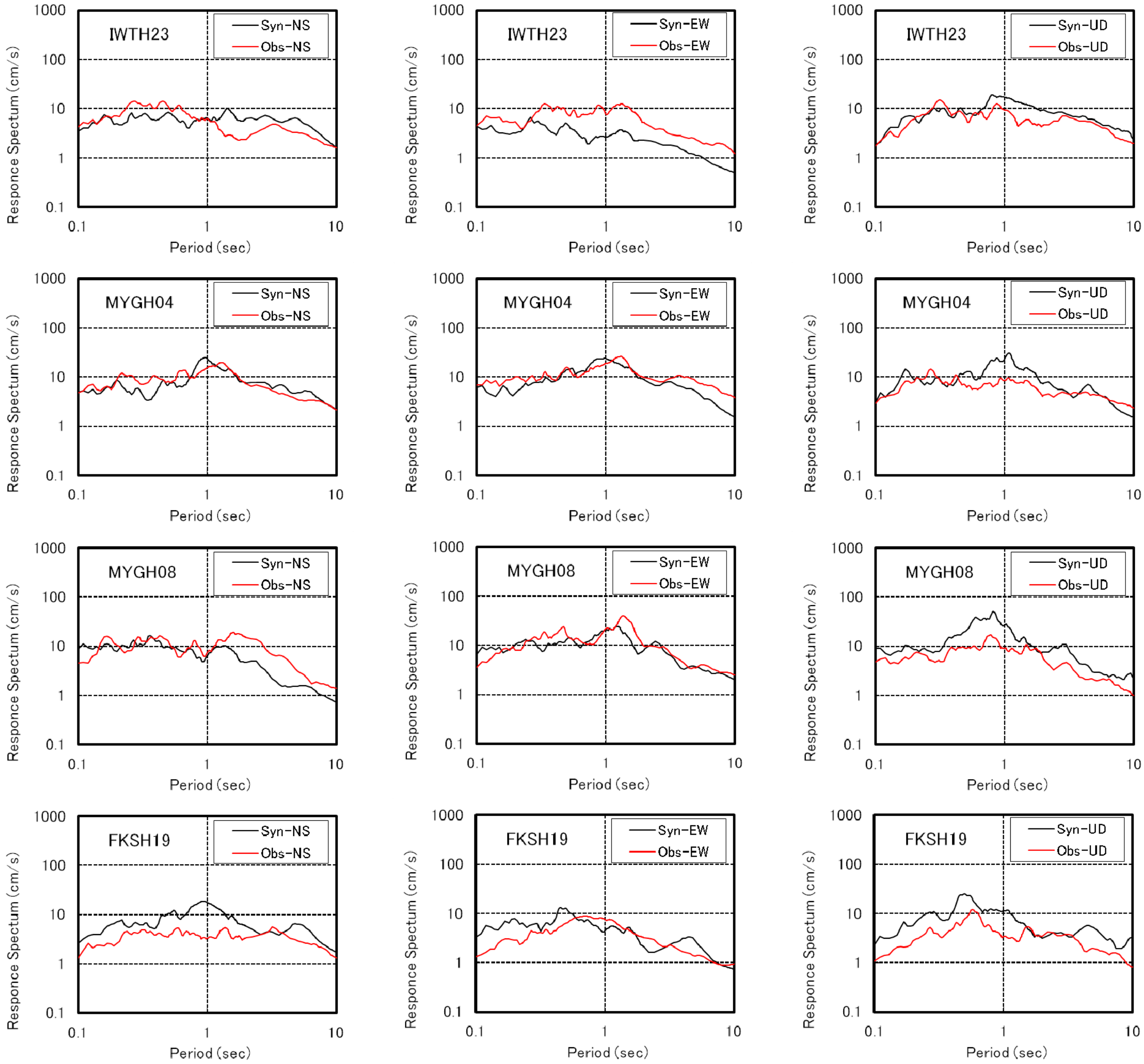

Figure 4. Comparison of the pseudo-velocity response spectra with damping factor of 0.05 of the observed (red) and the synthetic (black) motions in Case 1 at four stations

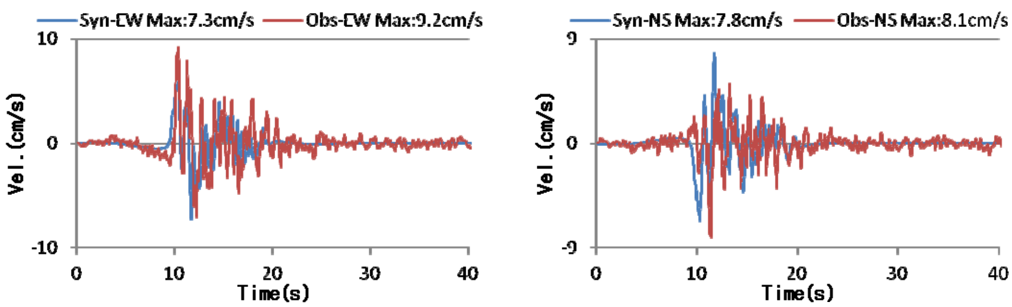

Figure 5. Comparison of observed (red trace) and synthetic (blue trace) horizontal velocity waveforms using the SGF method at MYGH04

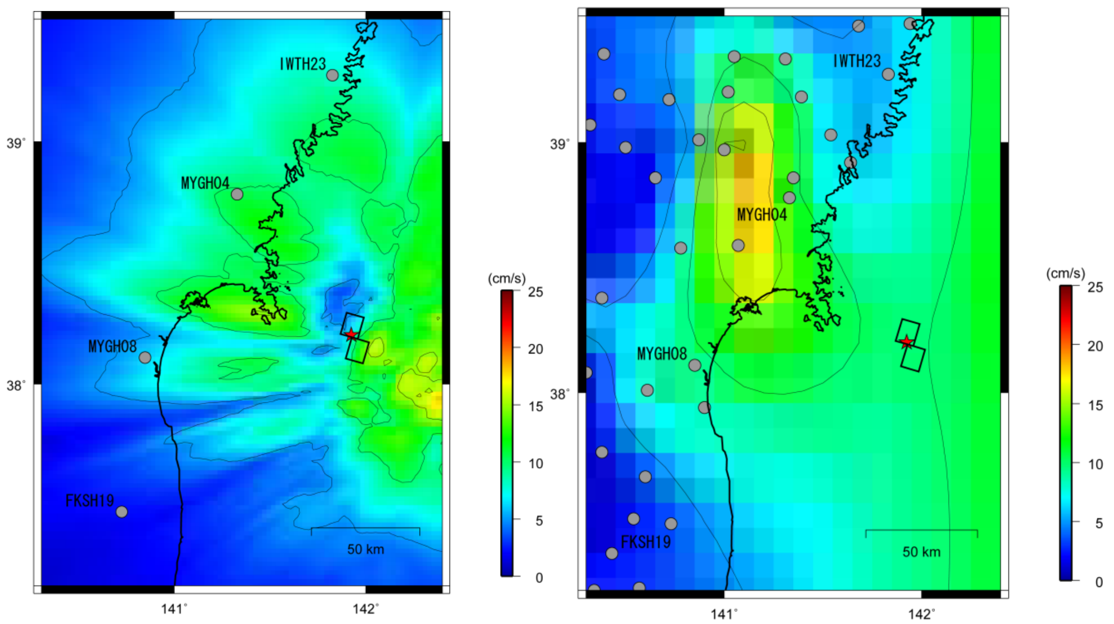

Figure 6. Comparison of the spatial distribution of synthetic (left) and observed (right) peak horizontal velocity (PGV)

4. SCALING LAW OF SOURCE PARAMETERS

The empirical scaling laws of source parameters for intraslab earthquakes are proposed by Dan *et al.* (2006), Sasatani *et al.* (2006) and Iwata and Asano (2011). Dan *et al.* (2006) obtained it from the estimation of SMGA by the forward modeling approach using the EGF method for earthquakes with magnitude smaller than M_w 7. Sasatani *et al.* (2006) considered the earthquakes with magnitude larger than M_w 7.5. On the other hand, Iwata and Asano (2011) estimated it using the source slip model derived from the waveform inversions. Figure 7 shows the empirical relationships between the seismic moment and the combined area of SMGA, including the estimate in this study. This figure shows the difference between these three scaling laws is not so significant. And the combined area of SMGAs for the intra-slab earthquake in this study is slightly larger than that calculated by these three scaling laws. Such a difference is not significant considering the variation in data used in order to estimate the scaling laws. Figure 8 shows the empirical relationships between the seismic moment and the acceleration spectral level (short-period spectral level), including the estimate (estimated from the stress drop and the fault size) in this study. The acceleration spectral level is also slightly larger than that calculated by the existing empirical scaling laws. From these results, we can conclude that the size and acceleration spectral level on SMGAs follow the empirical scaling laws for intraslab earthquakes.

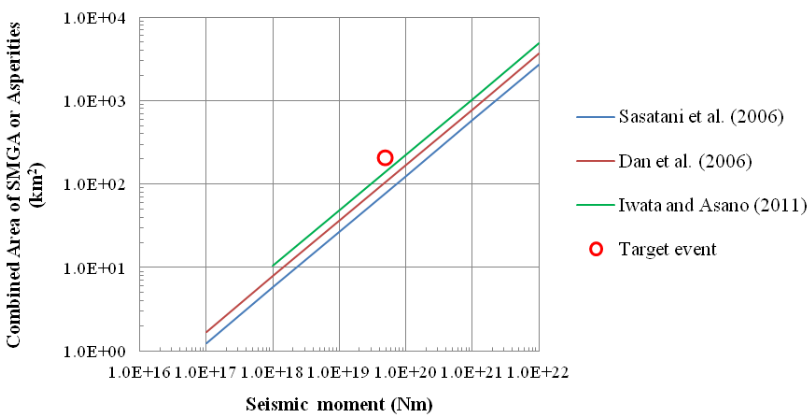

Figure 7. Comparison of the combined SMGA area (○) estimated in this study and the existing three empirical scaling laws

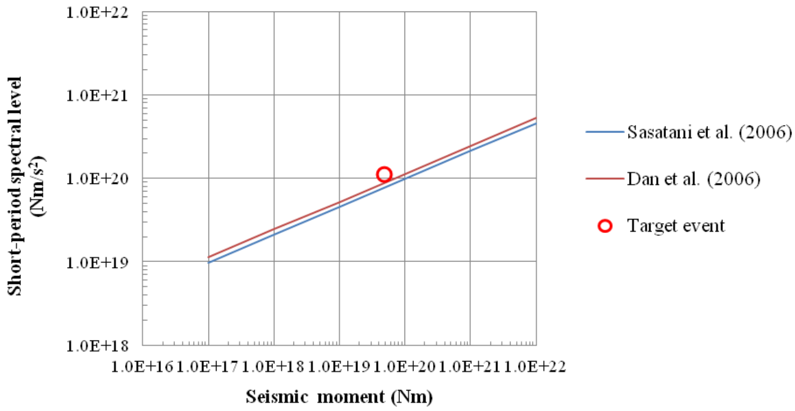

Figure 8. Comparison of the short-period spectral level (○) estimated in this study and the existing a couple of empirical scaling laws

5. CONCLUSIONS

A large intraslab earthquake (M_{JMA} 7.1) with the focal depth of about 66km occurred in the Pacific slab in the east of Oshika peninsula, Miyagi Prefecture, northeastern Japan on April 7, 2011. The strong high-frequency ground motions struck the near-source region during this earthquake. Here, we tried to estimate a source model by the forward modeling approach using the EGFM. Four borehole station data of KiK-net are used in the strong ground motion simulations. A simple source model having a couple of rectangular SMGAs was proposed. The source parameters for the SMGAs are consistent with the existing empirical scaling laws. Next, strong ground motion simulation was conducted at many points using the estimated source model to investigate the forward rupture directivity effect. The spatial distribution of the simulated PGV was consistent with the observed one. This is an evidence showing the principal characteristics of the actual source process of this earthquake. However, synthetic peak horizontal accelerations are much larger than observed ones at several stations, which may be caused by nonlinear effect in some surface layers during the mainshock.

AKCNOWLEDGEMENT

We appreciate the National Research Institute for Earth Science and Disaster Prevention (NIED) for providing us with KiK-net and F-net data. This study was partially supported by a Grant-In-Aide for scientific Research, Number 21241044.

REFERENCES

Dan *et al*. (2006). Charavterized fault model for prediction of strong ground motions from intra-slab earthquakes, *J. Struct. Constr. Eng., AIJ*, **600**, 35-42.

Irikura, K. (1986). Prediction of strong acceleration motion using empirical Green's function, *Proceeding of 7th Japan Society of Civil Engineering Earthquake Engineering Symposium*, 151-156.

Iwata, T. and K. Asano (2011). Characterization of the Heterogeneous Source Model of Intra-slab Earthquakes toward Strong Ground Motion Prediction. *Pure Appl. Geophys.*, **168**, 117-124.

Kamae *et al*. (1991). Prediction of strong motion based on scaling law of earthquake by stochastic synthesis method, *J. Struct. Constr. Eng., AIJ*, **430**, 1-9.

Sasatani *et al*. (2006). Source Characteristics of Intra-slab Earthquakes. *Geophys. Bull. of Hokkaido University*, **69**, 123-134.

Yamanaka (2011). NYG seismological Note, Nagoya University.