Broadband Strong Ground Motion Simulation of the 2011 Tohoku, Japan, Earthquake

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SUMMARY:
Strong ground motions simulation of the 2011 Tohoku earthquake (M_W 9.0) is studied. The record section of acceleration waveforms along the Pacific coast of east Japan exhibits four isolated wave packets propagating from different locations to north and south. A source model that consists of four strong motion generation areas (SMGA) is constructed. Each isolated wave packet is assumed to be contributed by the corresponding SMGA. Firstly the rupture starting points of each SMGA are identified by picking up the onset of individual wave packets. Then the model parameters of these four SMGAs are determined by strong motion simulations using the empirical Green's function method (Irikura, 1986). The obtained source model explains the acceleration, velocity, and displacement time histories in the period range from 0.1 to 10 s at most stations well. SMGA should be appropriately considered in source modelling for strong motion prediction of future great plate-boundary earthquakes.

Keywords: the 2011 Tohoku earthquake, strong motion simulation, strong motion generation area, source model

1. INTRODUCTION

The strong ground motions excited by the 2011 Off the Pacific Coast of Tohoku earthquake (M_{JMA} 9.0, hereafter the 2011 Tohoku earthquake), which occurred at 14:46 on 11 March 2011 (JST=UT+9), were widely observed all over Japan. It was the largest event in Japan since the instrumental observation had started in the late 19th century. This event is characterized as a mega-thrust earthquake rupturing the plate boundary between the North American Plate and subducting Pacific Plate. The seismic intensity of 7 in the intensity scale of the Japan Meteorological Agency (JMA) was observed at Tsukidate, Kurihara city 175 km west of the epicentre and the seismic intensity of 6+ was observed at a lot of sites in Tohoku and Kanto districts (e.g. Hoshiba *et al.*, 2011).

In this paper, we present broadband strong ground motion simulation in the frequency range from 0.1 Hz to 10 Hz for the 2011 Tohoku earthquake using the empirical Green's function (EGF) method (Irikura, 1986). The source model is represented by superposition of the plural strong motion generation areas (SMGAs). The SMGA is defined as a source patch characterized by a large uniform slip velocity within the total rupture area, which reproduces near-source strong ground motions up to about 10 Hz (Miyake *et al.*, 2003). Miyake *et al.* (2003) concluded that the near-source strong ground motions were controlled mainly by the size of the SMGA and rise time there. The SMGA source model and the empirical Green's function method have been successfully applied to strong motion simulations of past subduction-zone plate-boundary earthquakes (e.g., Kamae and Kawabe, 2004; Miyahara and Sasatani, 2004; Suzuki and Iwata, 2007; Takiguchi *et al.*, 2011).

Finally, we will discuss on the scaling relationship of SMGA to seismic moment to obtain a hint for improving the source modelling in strong motion prediction of great subduction-zone plate-boundary earthquakes.

2. CHARACTERISTICS OF OBSERVED STRONG GROUND MOTIONS

Figure 2.1 shows the record section of the north-south components of observed original acceleration and filtered velocity waveforms along the Pacific coast ordered by the latitude of stations. These records were observed by the nation-wide dense strong motion observation networks K-NET and KiK-net both operated by the National Research Institute for Earth Science and Disaster Prevention (NIED) (Aoi *et al.*, 2011).

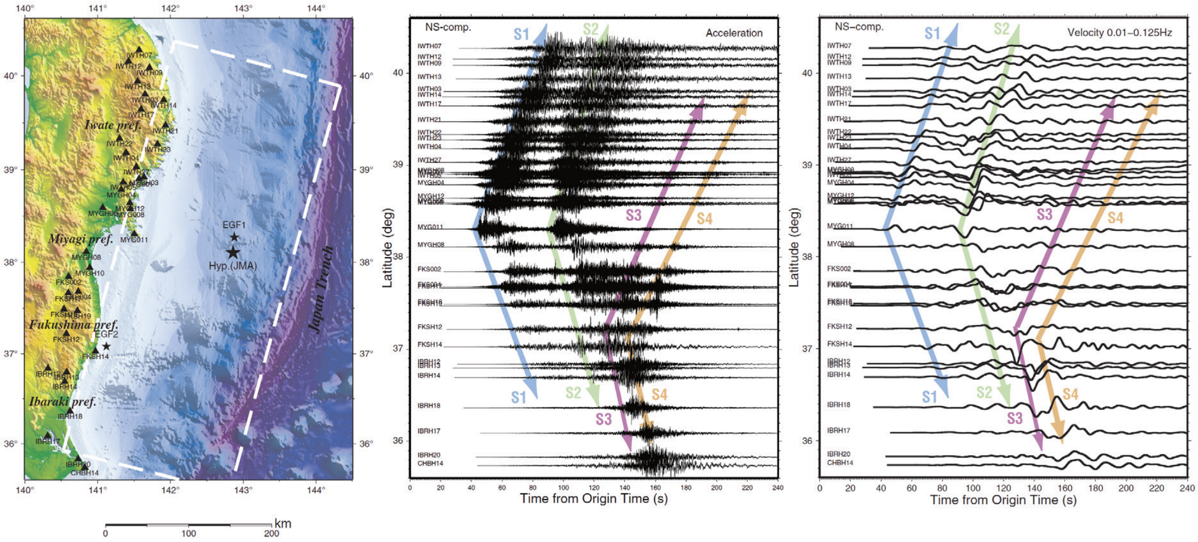

Figure 2.1. NS components of observed acceleration and velocity waveform ordered by the latitude

Four distinctive wave packets propagating northward and southward are recognized from the record section of acceleration waveforms in Fig.2.1. Both the first (S1) and second wave packets (S2) are originated from the neighbourhood of the hypocentre (38.1035°N, 142.8610°E, 23.74 km depth, by JMA), but S1 and S2 are separated by approximately 40s. The third wave packet (S3) propagates from off Fukushima prefecture, and the forth wave packet (S4) propagates from neighbourhood of the border between Fukushima and Ibaraki prefectures. Those observed characteristics of strong ground motions give a brief image of the source process related to strong ground motion generation during the 2011 Tohoku earthquake.

3. SOURCE MODEL AND STRONG MOTION SIMULATION

3.1. Locating SMGAs on the Plate Interface

Firstly, we objectively determined the location and rupture time of each SMGA corresponding to the distinctive wave packets S1~S4 seen in Fig.2.1. The hypocentre is fixed at the location determined routinely by JMA, and each SMGA is assumed to be located on the interface of the subducting Pacific plate. Its depth was determined by Nakajima and Hasegawa (2006) and Nakajima *et al.* (2009), whose contour is indicated by the broken lines with an interval of 10 km in Fig.3.1.

We carefully read the onset of S1~S4 in the observed waveforms at K-NET and KiK-net stations along the coast. The best set of parameters was determined to minimize the RMS of difference between the observed and theoretical travel times by a grid search. The one dimensional velocity structure model, which is assumed by approximating the regional integrated velocity structure model by Koketsu *et al.* (2008), is used to calculate the theoretical travel time. The difference between the observed and theoretical travel times is corrected by using an M_W 6.0 foreshock (EGF1 in Fig.3.1) occurring at 03:16 on 10 March 2011 (JST) as a reference event, whose location was fixed at the hypocentre determined by JMA. The search intervals in the grid search are 0.005° for latitude and longitude and 0.1 s for rupture time (Asano and Iwata, 2012).

The estimated rupture starting points of four SMGAs are indicated by the open stars in Fig.3.1. The rupture delay times from the origin time are 24.1 s, 65.4 s, 106.5 s, and 133.0 s, respectively. The broken rectangle in Fig.2.1 is the source fault plane by Suzuki *et al.* (2011). The locations of SMGA1 and SMGA2 are close to each other as expected from the record section in Fig.2.1.

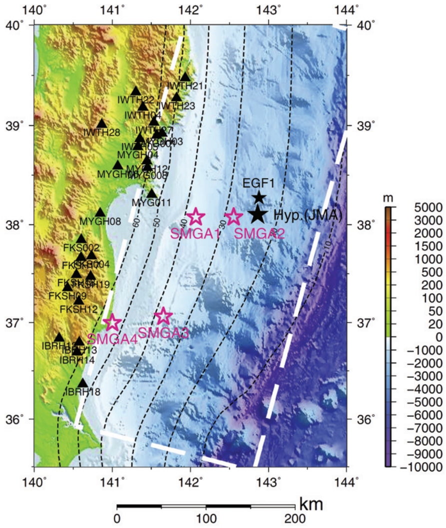

Figure 3.1. The locations of rupture starting points of SMGAs

3.2. SMGA Source Model for Broadband Strong Ground Motion Simulation

We constructed the source model composed of four SMGAs based on broadband strong motion simulation in 0.1-10 Hz using the empirical Green's function method developed by Irikura (1986). In this method, the ground motion for a target event is synthesized by summing up the records of small events with a filtering function which corrects the difference in the slip velocity time function between the large and small events following the source scaling laws and the ω^{-2} source spectral model (Irikura, 1986; Miyake *et al.*, 2003). The source scaling relationships are controlled by two parameters N, which corresponds to the ratio of spatial dimension and slip amount between the large and small events, and C, which corrects the difference in the stress drop between the large and small events.

The scaling parameters N and C are determined for each SMGA by a source spectral fitting method (Miyake *et al.*, 1999; 2003). This method derives these parameters by fitting the observed source spectral ratio between the large and small events to the theoretical source spectral ratio following the ω^{-2} source spectral model. The moment ratio and the corner frequency of the target and small events are estimated by the grid search algorithm. In this analysis, only records in which individual wave packets corresponding to each SMGA are isolated sufficiently to have the time windows for calculating Fourier amplitude spectra are used. The propagation path effects are corrected for geometrical spreading for body waves and an attenuation factor. The frequency-dependent quality factor, $Q(f) = 110f^{0.69}$ obtained by Satoh *et al.* (1997) in this region and the S wave velocity of 4.46 km/s are used to correct the attenuation factor.

The records of an M_W 6.0 event, which occurred at 03:16 on 10 March 2011 (JST) is used as EGF for SMGA1 and SMGA2 (EGF1), and those of an M_W 5.5 event, which occurred at 22:12 on 22 October 2005 (JST) is used as EGF for SMGA3 and SMGA4 (EGF2). The epicentres of two EGF events are shown in Fig.3.2. Derivation of the scaling parameters N and C from the obtained moment ratios and corner frequencies is straightforward (e.g., Miyake *et al.*, 2003). N are 3, 3, 5, and 5 for SMGA1, SMGA2, SMGA3, and SMGA4, respectively. C values are estimated to be 10.6 and 4.6 for SMGA3 and SMGA4, respectively. Since C values for SMGA1 and SMGA2 seem not to be constrained well because of small N, C values for these SMGAs are searched together with other unknown parameters in the following strong motion simulations.

Then, the source parameters of four SMGAs are estimated based on broadband strong motion simulations using the empirical Green's function method. The best set of parameters is estimated by minimizing the residuals of acceleration envelopes and displacement waveforms through a grid search (Miyake *et al.*, 1999; 2003). The parameters to be estimated by the grid search are the spatial dimensions, rise times of the EGF events, the stress drops and rupture starting subfaults of each SMGA, and the rupture propagation velocities within the SMGAs. The length L, width W, and rise time T of the SMGA are given by Nl, Nw, $N\tau$ from the length l, width w, and rise time τ of the EGF event. The search range and its grid interval of the model parameters in the grid search are referred to Asano and Iwata (2012). The stress drops of the EGF events are calculated assuming the circular crack source model (Eshelby, 1957). The strike and dip angles of each SMGA are determined based on the local geometry of the plate interface (Nakajima and Hasegawa, 2006; Nakajima *et al.*, 2009). The deeper SMGA has slightly steeper dip angle because of the bending of the subducting Pacific slab. The strong motion stations used in this modelling are indicated by the solid triangles in Fig.3.2.

Figure 3.2 shows the estimated source model on the map. The parameters of each SMGA are listed in Table 3.1. All SMGAs are located at deeper portion of the source fault plane. The rupture within SMGA1 propagates towards the up-dip direction whereas that within SMGA2 propagates towards the down-dip directions. The ruptures of SMGA3 and SMGA4 located southwest of the hypocentre mainly propagate in southwest direction. SMGA1 and SMGA2 are included in the source region of the past repeating off Miyagi subduction-zone events, and SMGA3 is located in the source region of the past off Fukushima events in 1938 (Asano and Iwata, 2012). The stress drops of four SMGAs range from 6.6 to 27.8 MPa.

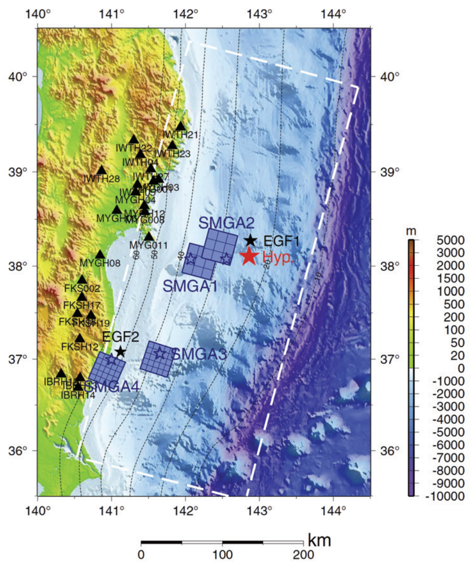

Figure 3.2. Map view of SMGA source model of the 2011 Tohoku earthquake

Table 3.1. Estimated parameters of SMGAs. L, W, S, T, M_0, $\Delta\sigma$, and D denote the length, width, area, rise time, seismic moment, stress drop, and slip, respectively.

	N	C	Strike (deg.)	Dip (deg.)	L (km)	W (km)	S (km^2)	T (s)	M_0 (Nm)	$\Delta\sigma$ (MPa)	D (m)
SMGA1	3	12.0	195	13	36	36	1296	6.90	4.57×10^{20}	23.9	5.2
SMGA2	3	14.0	195	13	36	36	1296	6.90	5.33×10^{20}	27.8	6.1
SMGA3	5	10.6	198	17	35	35	1225	1.70	3.07×10^{20}	17.5	3.7
SMGA4	5	4.0	203	20	35	35	1225	1.70	1.16×10^{20}	6.6	1.4
Total							5042		1.41×10^{21}		

3.3. Result of Broadband Strong Ground Motion Simulations in 0.1-10 Hz

Figure 3.3 shows the comparison between the observed and synthetic acceleration, velocity, and displacement waveforms in the frequency range from 0.1 to 10 Hz at 23 strong motion stations. Two horizontal components are shown in this figure. The characteristics of propagating wave packets are reproduced well.

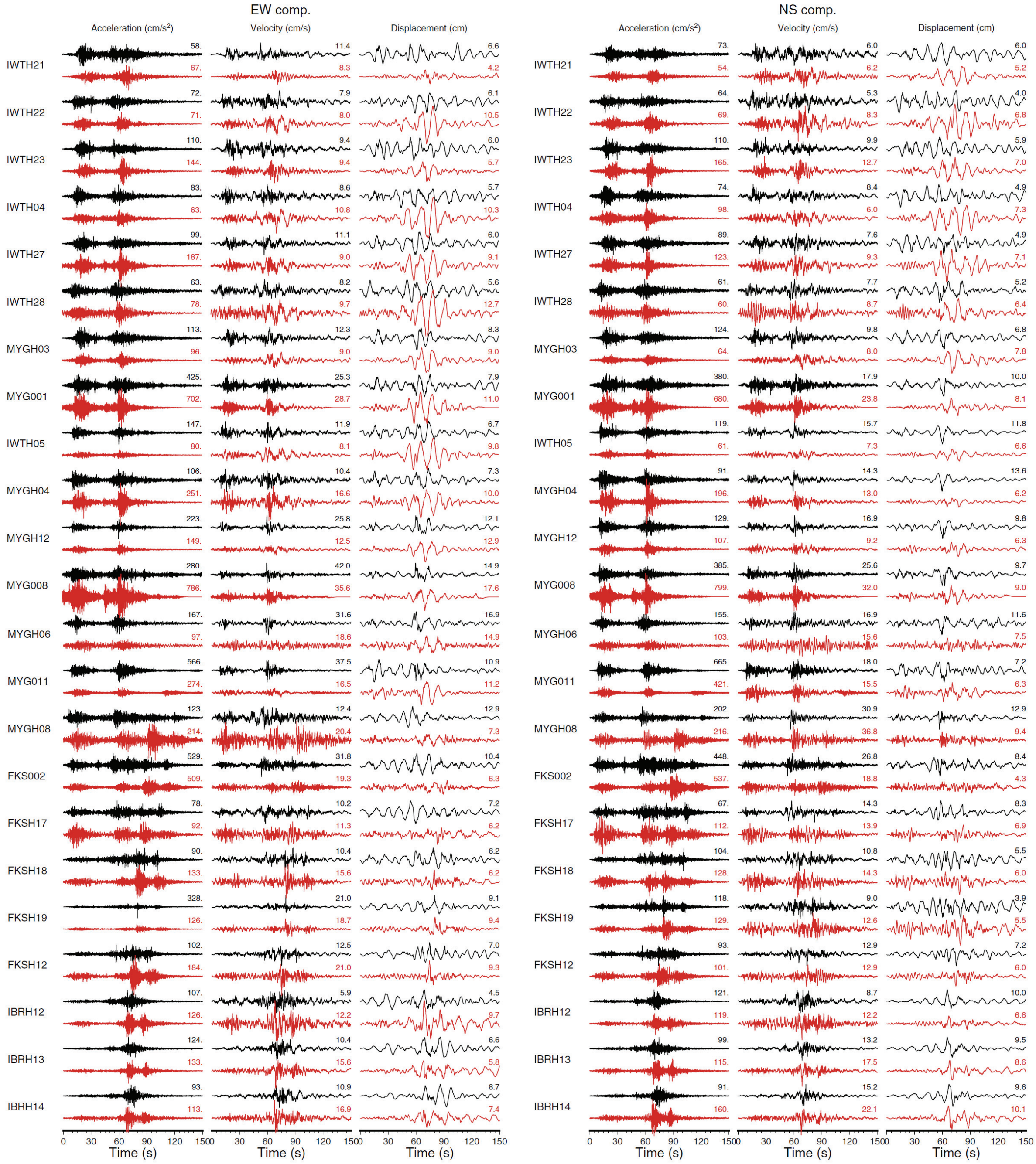

Figure 3.3. The observed (black) and synthetic (red) acceleration, velocity, and displacement waveforms

Pseudo velocity response spectra (h = 0.05) at selected stations are shown in Fig.3.4. The synthetic response spectra match well the observation.

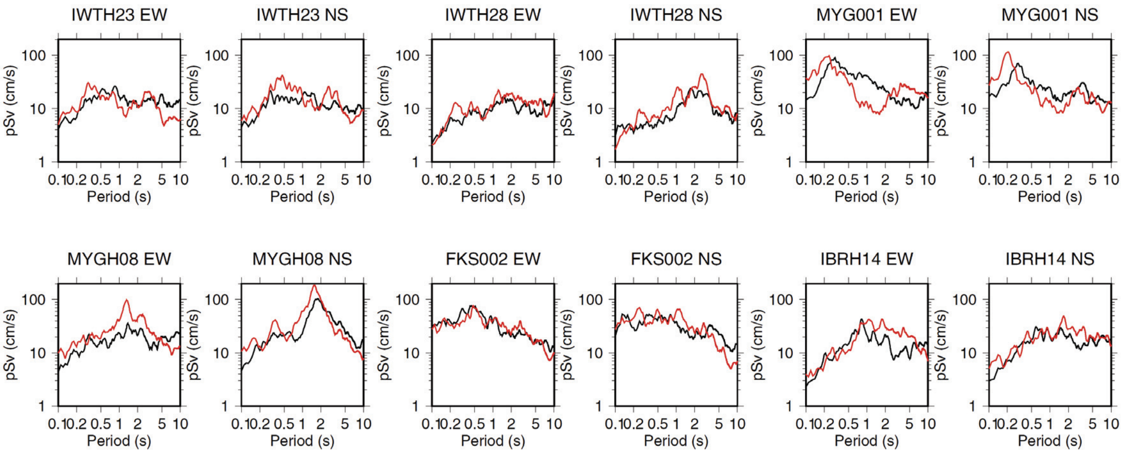

Figure 3.3. The observed (black) and synthetic (red) pseudo velocity response spectra (h = 0.05)

4. DISCUSSIONS

SMGA source models for past plate-boundary earthquakes in northeast Japan have been obtained based on broadband strong motion simulations using the empirical Green's function methods. The 1994 far off Sanriku earthquake (M_W 7.7) (Miyahara and Sasatani, 2004), the 2005 off Tokachi earthquake (M_W 8.3) (Kamae and Kawabe, 2004), the 2005 off Miyagi earthquake (M_W 7.2) (Suzuki and Iwata, 2007), and the 1982 and 2008 off Ibaraki earthquakes (M_W 7.0 and 6.8) (Takiguchi *et al.*, 2011) were studied in the previous studies. Suzuki and Iwata (2005) analysed other moderate and large events of M_W 6.0–7.0 in northeast Japan. The scaling relationship between the size of SMGA and its seismic moment are summarized together with the 2011 Tohoku earthquake in Fig.4.1. SMGA for inland crustal events analysed by Miyake *et al.* (2003) are also plotted for comparison.

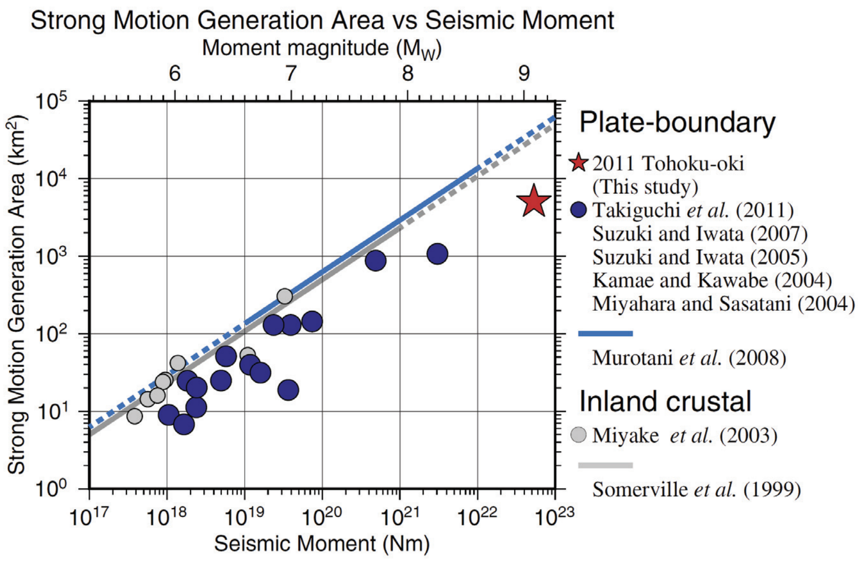

Figure 4.1. Scaling relationship between size of SMGA and seismic moment

As for inland crustal earthquakes, Miyake *et al.* (2003) concluded that the location and size of SMGA correspond to the asperity or large slip area on the source fault. That is, SMGA for inland crustal earthquakes follows the empirical scaling relationship for asperity and seismic moment proposed by Somerville *et al.* (1999). On the other hand, the size of SMGA of plate-boundary earthquakes in northeast Japan is smaller than that of inland crustal earthquakes of the same seismic moment. This fact indicates that the stress drop of SMGA for subduction-zone plate-boundary earthquakes is larger than that of inland crustal earthquakes (Suzuki and Iwata, 2007). It is also smaller than the empirical scaling relationship for asperity of subduction-zone plate-boundary events by Murotani *et al.* (2008), which is represented by the blue line in Fig.4.1. Unlike inland crustal earthquakes, the size of SMGA does not correspond to that of asperity for subduction-zone plate-boundary earthquakes. The 2011 Tohoku earthquake also has similar tendency with previous subduction-zone plate-boundary earthquakes. The strong ground motions of the 2011 Tohoku earthquake and other subduction-zone plate-boundary earthquakes are controlled by small isolated patches within the ruptured source fault.

An appropriate setting of SMGA source model is necessary for precise strong motion prediction for large and huge subduction-zone plate-boundary earthquakes. The size of SMGAs for future events in northeast Japan may be given by an empirical scaling relationship as shown in Fig.4.1.

5. CONCLUSIONS

Strong ground motions from the 2011 Tohoku earthquake (M_w 9.0) in 0.1–10 Hz were simulated well by a source model that consists of four strong motion generation area (SMGA) by using the empirical Green's function method. Two SMGAs are found in the off Miyagi region, west of the hypocentre, and the other two SMGAs are found in the off Fukushima and Ibaraki region, southwest of the hypocentre. All SMGAs exists in the deeper portion of the source fault. The 2011 Tohoku earthquake follow the empirical scaling relationship for size of SMGA to seismic moment from past subduction-zone plate-boundary events in northeast Japan, and these SMGA are isolated and much smaller than asperity or large slip area. The SMGA should be appropriately considered in the source modelling for strong motion prediction for great plate-boundary earthquakes.

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