High Acceleration Motions generated from the 2011 Pacific coast off Tohoku, Japan Earthquake

K. Irikura
Disaster Prevention Research Center, Aichi Institute of Technology, Japan

S. Kurahashi
Disaster Prevention Research Center, Aichi Institute of Technology, Japan

SUMMARY: (10 pt)
Strong motion records in near-source area from the 2011 Tohoku earthquake show several isolated wave-packets arriving from different origins on the source fault. The source model is estimated from the forward modeling, comparing short-period ground motions simulated using the empirical Green's functions with those observed. The final model has five strong motion generation areas (SMGAs) located west of the hypocenter and along the down-dip edge of the source fault. Impulsive waves with high acceleration are seen on observed seismograms near the source fault. The impulsive waves are well simulated using a heterogeneous models with higher stress parameter in a small subarea inside the SMGA. Attenuation-distance relationship of peak ground velocity (PGV) from this earthquake was virtually equivalent to a conventional empirical-equation with Mw 8.0 class. Another cause of ground motions with extremely high-accelerations can be explained by nonlinear site responses due to surface geology with decreased S wave velocities.

Keywords: Strong ground motion prediction, the 2011 Pacific coast off Tohoku Earthquake, high acceleration

1. INSTRODUCTION

The 11 March 2011 Tohoku earthquake with Mw 9.0 was a mega-thrust earthquake, occurring on the boundary between the Pacific and the continental plates off the Pacific coast of Tohoku, Japan. Huge tsunami from this earthquake caused tremendous disasters near the Pacific coast of Tohoku, Japan. In addition, strong ground motions affected building damage and ground failures, then causing liquefaction, subsequently infrastructure including inland area as well as the Pacific coast areas.

Strong ground motions from this earthquake have some remarkable features. The acceleration and velocity records at stations show several isolated wave-packets arriving from different origins on the source fault. Such origins are considered to be the strong motion generation areas (SGMAs) on the source fault. Attenuation-distance relationship of peak ground velocity (PGV) from this earthquake was virtually equivalent to the empirical one from Mw 8.0 determined by Si and Modorikawa (1999). On the other hand, peak ground acceleration (PGA) was also virtually equivalent to the empirical one from Mw 8.0 in the distance over 100 km, but clearly larger than that from Mw 8.0 near the source fault.

In this study, we estimate a source model for generating strong ground motions from this earthquake by comparing the observed records from the mainshock with synthesized motions based on a characterized source model and the empirical Green's function method. Further, in order to obtain better fit to impulsive waves seen on observed seismograms at some stations very near the source fault, we introduce a heterogeneous source model improving the conventional uniform SMGA model, .

One of features of this earthquake is relatively small damage caused by ground motions. To clarify the reasons of less damage are discussed about the characteristics of attenuation-distance relationships such as PGV and PGA in relation of the long period and short period source models. Then we propose an improved idea for recipe of predicting strong ground motions for mega-thrust earthquakes.

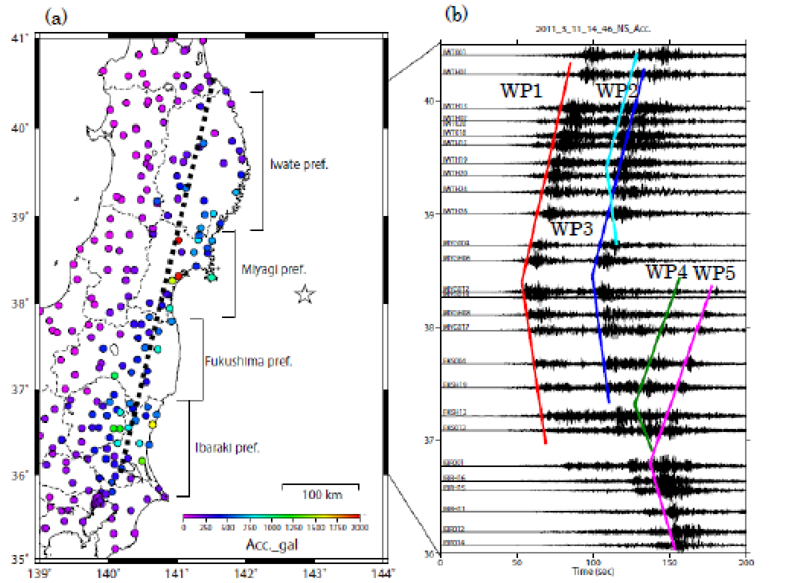

Figure 1. (a): Map showing the location of observed stations. (b): Acceleration seismograms at stations along a line from north to south. The colored thin solid lines indicate five wavepackets, WP1(red), WP2(sky-blue), WP3(blue), WP4(green), and WP5(pink) which correspond to the S waves propagating from SMGA 1, SMGA 2, SMGA 3, SMGA 4 and SMGA 5 to the stations, respectively.

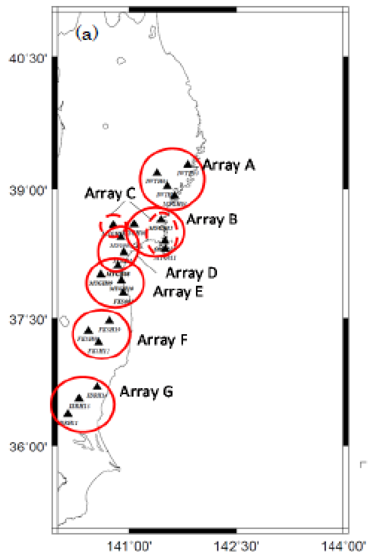

Figure 2. Map showing Array A to G for semblance analysis. The closed triangles indicate the KiK-net and K-NET stations used for analysis.

2. SHORT-PERIOD SOURCE MODEL FOR SIMULATING STRONG GROUND MOTIONS

The source models of this earthquake have been studied by many authors using variety of data-sets from very long-period data such as GPS and Tsunami to short-period data such as teleseismic short period P waves and strong ground motion data. The common features of the models are summarized as follows: The main slip distributions from the long-period data were located east of the hypocenter toward the Japan Trench zone (GSJ, 2011; Fujii, 2011), while short-period generation areas were located west of the hypocenter from the back-projection methods to the first P waves data in the US, Euro, and Tokyo Metropolitan arrays (Ishii, 2011; Honda et al, 2011).

Strong motion data in the near-source region provide more detailed information about the shorter period rupture process during the earthquakes. In our study, we estimate a source model for generating strong ground motions from this earthquake by comparing the observed records from the mainshock with synthesized motions based on a characterized source model (Irikura and Miyake, 2010) and the empirical Green’s function method.

2.1. Locating Strong Motion Generation Areas

Strong motion stations recording ground motions from the 2011 Tohoku earthquake were shown in Figure 1(a). The acceleration records at stations along a line from north to south are arranged with the same time and amplitude scale in Figure 1 (b). Five isolated wave-packets, WP1, WP2, WP3, WP4, and WP5 in the aligned records are found, arriving from different origins on the source fault. Such origins are considered to be the strong motion generation areas (SGMAs).

The source fault plane is defined as 450 km long and 200 km wide with strike of 193° and dip 10°, based on the aftershock distribution in the first 24 hours and the CMT solution by Japan Meteorological Agency (JMA). The hypocenter is at 38.1033 N, 142.86 E, and 23.7 km deep by JMA. Assuming the SMGAs were located on the source fault plane, Kurahashi and Irikura (2011) determined the locations of the SMGAs and the optimum S waves- and rupture- velocities between the mainshock hypocenter and the SMGAs, picking up the onset times of those wave-packets on the strong motion seismograms obtained at the underground sites of the KiK-net stations. The result showed that WP1, WP2, WP3, WP4, and WP5 were arriving from SMGA 1, SMGA2, SMGA3, SMGA4, and SMGA5 located near the down-dip edge of the mainshock source fault ranging from offshore Miyagi to offshore Ibaraki prefectures.

However, the locations of the SMGAs were not well constrained from those onset times. The onset times picked from the records have a certain range of uncertainty because the onsets of the wave-packets are not always sharp. The precision of the locations of the SMGAs is controlled by the uncertainty of picking the onset times. It is very difficult to identify direct S waves at many stations from an identical source from only the onset times as long as the number of stations are limited. Then, in order to determine the short-period source model more accurately, we attempt to retrieve the origins of the wavepackets using the semblance analysis. The wavepackets of WP1, WP3, and WP5 among them are easily extracted from the observed seismograms because they are making isolated wavelets in the observed seismograms as shown in Figure 1 (b). Then, for the semblance analysis we group the strong motion stations near the source fault into 7 arrays, Array A to G, each of which consists of three or four neighboring stations as shown in Figure 2.

The arrival azimuth and apparent velocities of the wavepackets in each array are estimated by the semblance analysis (Honda et al, 2008). First, the waveforms of each wavepacket are confirmed as a wavepacket consisting of S waves from a strong motion generation area, examining the particle motion diagrams of the waveforms. Next, we choose the waveforms with a time window of 3 sec to avoid contamination of other waves, e.g. secondary-generated waves in propagation-paths from source to station. Semblance values were projected onto an assumed source area on the mainshock fault plane using seismic ray tracing in uniform velocity structures. We calculate the semblance values considering travel time from assumed origins on the assumed source area to stations in the arrays. The analysis for a wavepacket can be made independently of the other wavepackets because those wavepackets on the seismograms are isolated each other.

The assumed source area including the origin of each wavepacket is put on the fault plane as shown in Figure 3. The location and area size are assumed after some preliminary analysis such as rough estimation of the origin from the onset times of the wavepackets at plural stations. The assumed areas for WP1, WP3, and WP5 are set to be 110 x 110 km^2 divided into 11 x 11 elements. The velocity waveforms of those wavepackets are extracted for 3 seconds as a time window after bandpass-filtered between 0.1 and 10 Hz. At first, the travel times Tr between the reference site and the assumed origin and T_i’ between the i-th site and the assumed origin in each array are calculated assuming average S wave velocity, then the travel time differences Ti between the reference site and ith site is calculated to be Ti = Tr – T_i’. The slowness as inverse of S waves are taken range from 1/2 to 1/4 s/km.

We confirmed that the semblance values were maximized for S wave velocity of 3.8 km/s for the wavepackets. Figure 3 shows the semblance value distributions for WP1 using Array A, B, E in the upper and for WP3 using Array C, D, and E in the lower. Assuming a certain distance between the origin of each wavepacket and the array centroid drawn as a circle in each panel of Figure 3 and S wave velocity of 3.8 km/s, the semblance values are calculated as a function of incident azimuth. The azimuths with the maximum semblance values indicate the propagating direction from the origins of the wavepackets to the arrays. Each array shows a different azimuth from the origin to the array centroid.

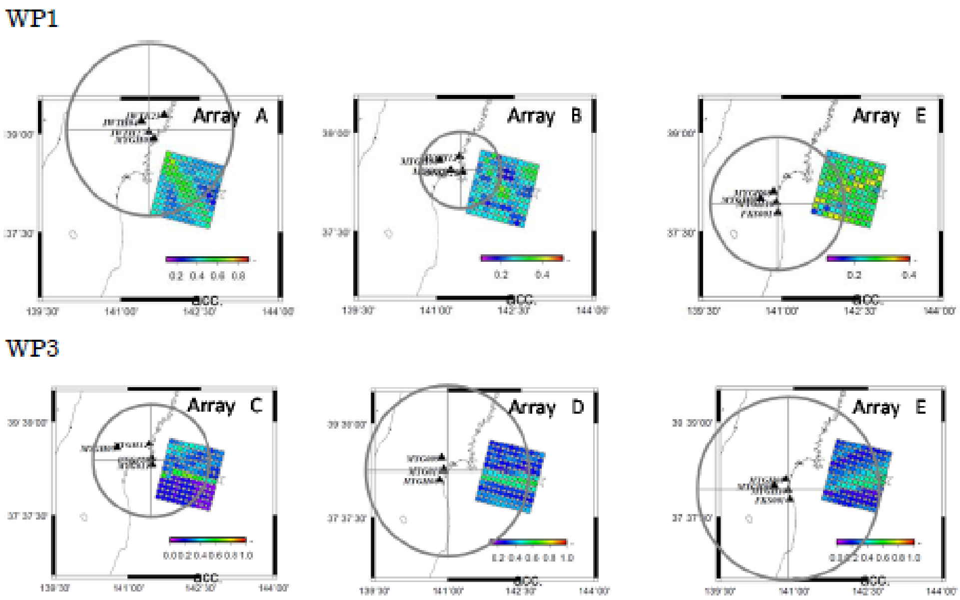

Figure 3. Semblance-value distribution obtained by Array A to G. Upper three panels show the semblance values on the assumed source area for WP1, and lower three show those for WP3.

We find that those propagating azimuths for the arrays make a focus as shown in Figure 4, indicating solutions of the wavepacket origins, that is, the locations of the SMGAs. The results of the semblance analysis shows that the locations of SMGA 1 and SMGA 5 obtained from WP1 and WP5 are almost the same as those by Kurahashi and Irikura (2011) obtained by the back-propagation method (Kurahashi and Irikura, 2010), while the location of SMGA 3 is changed shifting to east of SMGA 1.

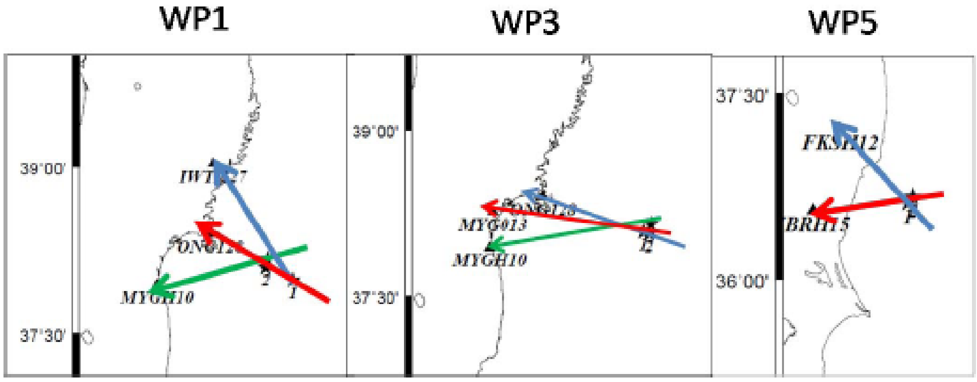

Figure 4. Origins of WP1, WP3, and WP5 determined from the arrivel azimuths optimized by the semblance analysis shown in Figure 3.

2.2. Simulation of Strong Ground Motions Using the Empirical Green's Function Method

The source fault is divided into N x N subfaults, the areas of which are taken to be equal to the fault area of the subevent. The ground motions from the SMGAs are expressed as a superposition of the subevents used as EGFs. Irikura and Kamae (1994) indicated that the simulated spectra using the empirical Green's function method have deeper sags in the intermediate frequency range, as long as the number of superposing the subevents increases. This means the subevents for EGF with a suitable size should be selected. In this study, the subevents with magnitude of more than 6 are required to satisfy the condition by Irikura and Kamae (1994).

The subevents occurring near each SMGA are adopted as the EGFs to share the propagation-path effects with ground motions from the SMGA. The 2005 Miyagi-oki earthquake with magnitude of 7.2 occurred very near the SMGA1 and SMGA3. We use the records of this earthquake as EGFs for SMGA1 and SMGA3, called Event A in Table 1. The records of this earthquake also for SMGA 2 are adopted as EGFs because there are no appropriate subevents near SMGA2. An earthquake with magnitude of 6 occurred near the SMGA4 and SMGA5. We adopt the records from this earthquake called Event B as EGFs for SMGA4 and SMGA5 in Table 1.

Figure 5 shows observed records of the 2005 Miyagi-oki earthquake at ONG128 and MYGH04. This earthquake has two SMGAs from the observed seismograms because the S-wave portions of these records consist mainly of two wave-packets (Suzuki and Iwata, 2008). In this study, we used the second wave-packet of the observed records as EGFs. The second ones have not only S-waves main motions but also coda parts of S-waves, while the first ones have no coda part. .

The displacement source spectra of Event A and Event B were estimated using ground motion records at stations on rock. The source spectra were obtained by removing propagation-path and site effects from the observed spectra at the stations. The Q values for estimating propagation-path effects are used by Matsuo and Kawase (2004). We adopt the seismic moment of Event A reported by Suzuki and Iwata (2008) and that of Event B from NIED seismic moment tensor catalogue. The corner frequencies of these spectra are determined by fitting the omega-squared model. Source areas and stress parameters are estimated from the seismic moments and corner frequencies based on Brune's (1970; 1971) formula. The source parameters of the event used as EGFs are listed in Table 2.

We simulated the ground motions for the characterized source model using the EGF method (Irikura, 1986). Since the details of the EGF method were explained by several papers (e.g. Kamae and Irikura, 1998; Kurahashi and Irikura, 2010), we omit the description about this method in this paper. The rise time and rupture velocity inside each SMGA are given to be Ws/4Vr (Ws: width of the SMGA and Vr: rupture velocity), following empirical relations by et al. (2003). The average S wave velocity is given to be 3.8 km/s from Ts-p time versus arrival time at observed stations. The total ground motions at each station are calculated by summing the contributions from all of the SMGAs with the arrival times from the initiation points of the SMGAs to the station.

The locations of the SGMAs contributing to generation of WP1, WP3 and WP5 were determined based on the semblance analysis. SMGA2 and SMGA4 were estimated from the back-propagation method (Kurahashi and Irikura, 2010), because the waveforms of WP2 and WP4 are not isolated on the observe seismograms. Figure 6 presents the comparison between the observed and synthetic waveforms in the form of acceleration and velocity. Agreement between the observed and synthetic ones is satisfactory at all of stations. The best-fit short-period source model consisting of five SMGAs is obtained by minimizing the fitting function defined by Miyake et al. (2003). Thee area and initiation of each SMGA are shown in left of Figuer 8 by a rectangle and closed circle mark, respectively.

Table 1 The source parameters of the 2011 Tohoku earthquake and two subevents (Event A and Event B) used as empirical Green's functions.

	2005/8/16 11:46	2007/11/26 22:51
name	Event A	Event B
M	7.2	6
dx, dw (km)	8.5	7.7
Stress parameter (MPa)	20	4.2
Mo (Nm)	5.23E+18	7.66E+17

** Suzuki and Iwata (2007) only SMGA2

Table 2 The source parameters of strong motion generation areas (SMGAs) consisiting of the source model in this study.

	L (km)	W (km)	Mo (Nm)	stress parameter (MPa)
SMGA1	34	34	2.68E+20	16.0
SMGA2	23.1	23.1	1.41E+20	20.0
SMGA3	42.5	42.5	6.54E+20	20.0
SMGA4	25.5	25.5	1.24E+20	25.2
SMGA5	38.5	38.5	5.75E+20	25.2

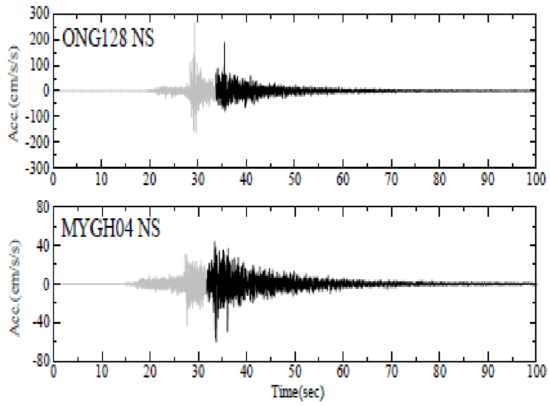

Figure 5. Observed seismograms at ONG128 and MYGH04 from the 2005 Miyagi-oki earthquake as Event A. The waveforms shown as the second wavepacket are used as EGFs at observed stations.

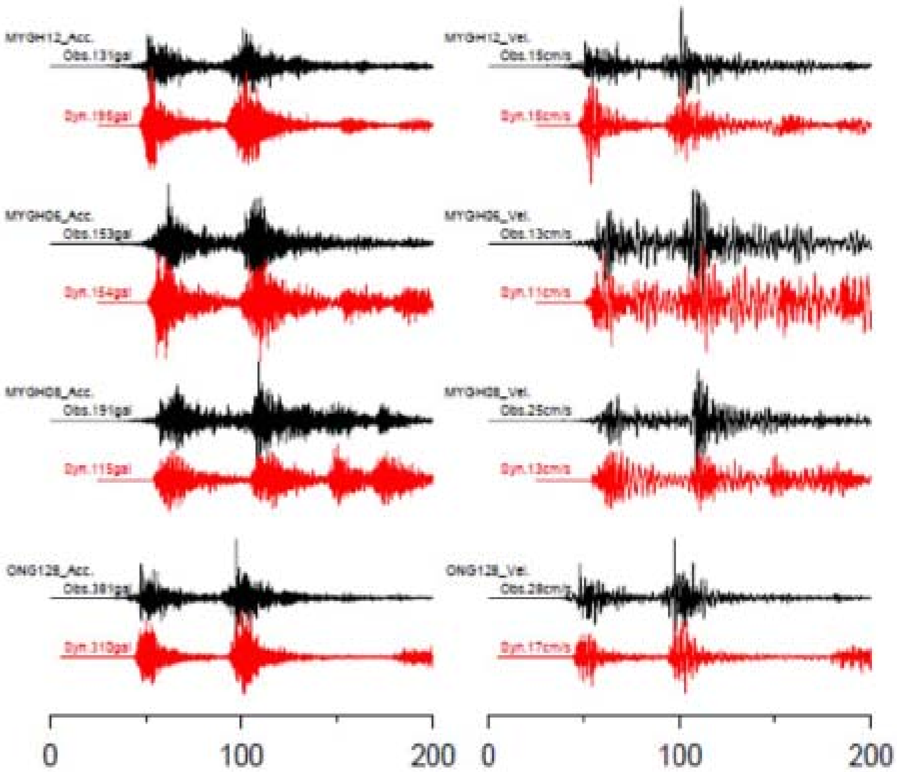

Figure 6. Comparison of the observed and synthetic seismograms using the empirical Green's function method at underground stations of Kik-net and Onagawa NPP.

The source parameters of the final source model, such as length, width, seismic moment, stress parameter and delay time from the origin time of each SMGA are listed in Table 2. Locations of SMGAs in this study coincide with those by Asano and Iwata (2011) and Satoh (2012).

2.3. Heterogeneity inside the Strong Motion Generation Area

Global features of the short-period ground motions, acceleration as well as velocity seismograms are almost simulated using five strong-motion-generation-areas (SMGAs) with a uniform stress parameter. However, in details, observed ground motions with impulsive waves with high-acceleration at some stations near the source fault are not always simulated using the source model mentioned above. For example, observed ground motions at ONG128 (Onagawa NPP), one of the closest station to the source fault, have remarkably impulsive waves at the initial parts of WP1 and WP3, but simulated

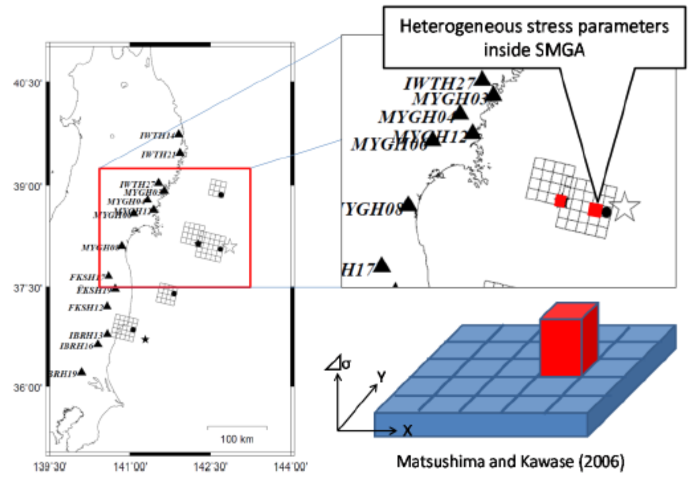

Figure 7. Left: the short-period source model in this study. Right upper: close-up of SMGA 1 and SMGA 2. A higher stress parameter is given on a mesh with red color. Right lower: heterogeneous SMGA model. There are heterogeneous stress parameters inside SMGA taken into consideration.

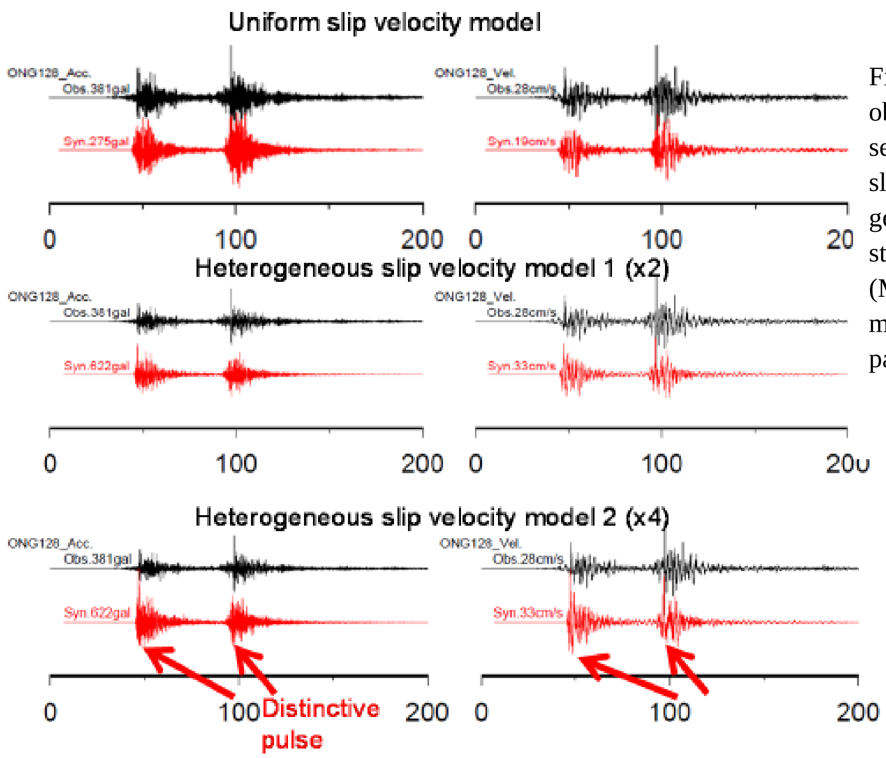

Figure 8. comparison between observed and synthetic seismograms using a uniform slip model (Top), a heterogeneous model with twice stress parameter in a mesh (Middle), and a heterogeneous model with four time stress parameter in a mesh (Bottom).

ground motions do not have such impulsive waves there, although the simulated ground motions agree roughly well with the observed ones.

Those impulsive waves were observed at other stations, propagating from near-source to far-source stations. We attempt to simulate the observed ground motions at ONG128 on the assumption that the SMGAs related to WP1 and WP3 have heterogeneous stress parameters. That is, each SMGA has a small subarea with a higher stress parameter inside the area with a uniform stress parameter as shown in Figure 7. Comparison between observed and synthetic acceleration- and velocity-ground-motions at ONG128 using the heterogeneous model are made in Figure 8. In the top the observed motions are compared with the synthetic motions for an uniform model, in the middle the observed ones are compared with the synthetic ones for a heterogeneous model with a subarea of twice as high as stress parameter, and in the bottom the observed ones are compared with the synthetic ones with a subarea with four times stress parameters.

The impulsive waves of WP1 are well simulated using the heterogeneous model with a subarea of twice stress parameter shown in the middle, while those of WP3 are well simulated using the heterogeneous model in a subarea with four times stress parameter shown in the bottom. Other wavepackets such as WP2, WP4, and WP5 have no remarkable impulsive waves, showing that the synthetic ground motions using the uniform stress parameter model for SMGA 2, SMGA 4, and SMGA 5 agree well with the observed ones in Figure 6.

3. ATTENUATION-DIATANCE RELATIONSHIPS OF STRONG GROUND MOTIONS

The horizontal components of peak ground acceleration (PGA) and those of peak ground velocity (PGV) observed during this earthquake were compared with the empirical attenuation relationships (i.e. strong motion prediction equation) for Mw 7 to Mw 9 by Si and Midorikawa (1999) as shown in Fig. 9. We found that the attenuation-distance relationship of the peak ground velocity (PGV) from this earthquake was virtually equivalent to the empirical one from an earthquake of Mw 8.0. On the other hand, peak ground acceleration (PGA) was also virtually equivalent to the empirical one from Mw 8.0 in the distance over 100 km, but clearly larger than that from Mw 8.0 near the source fault.

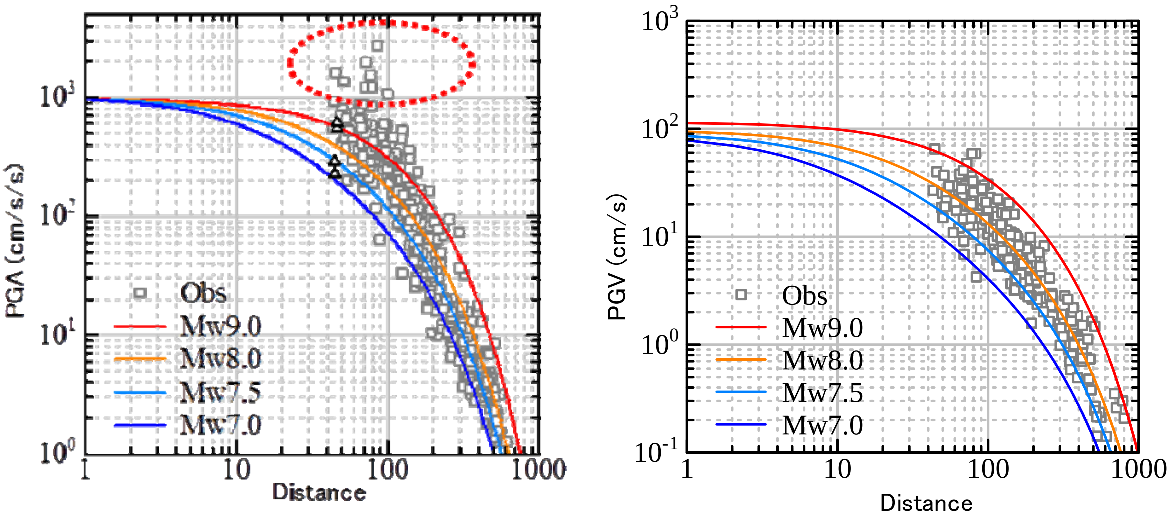

Fig. 9 . Comparison of observed data of PGA and PGV from the 2011 Tohoku earthquake (Mw 9.0) with and the empirical attenuation-distance relationships for Mw 7.0 to Mw 9.0 by Si and Midorikawa (1999). Right is for PGA and left is for PGV. Extremely high accelerations (marked by a red dotted line) were observed deviating from the attenuation-distance relationship.

High accelerations were mainly caused by two different mechanisms comparing observed data with ground motion simulations. One is that ground motions with relatively high acceleration caused by source characteristics, such as rupture directivity effects, heterogeneous slip velocity inside the strong motion generation areas and so on. This case was discussed in 2.3. High acceleration motions were successfully simulated taking heterogeneous model into account. The other is that strong ground motions of more than 1000 gals were recorded at soft grounds formed by the Quaternary deposits. Such ground motions were generated by large amplifications due to surface geology with reduction of S wave velocities in soil layers (nonlinear soil behavior). Then, their waveforms present clear cyclic mobility as shown in Figure 10.

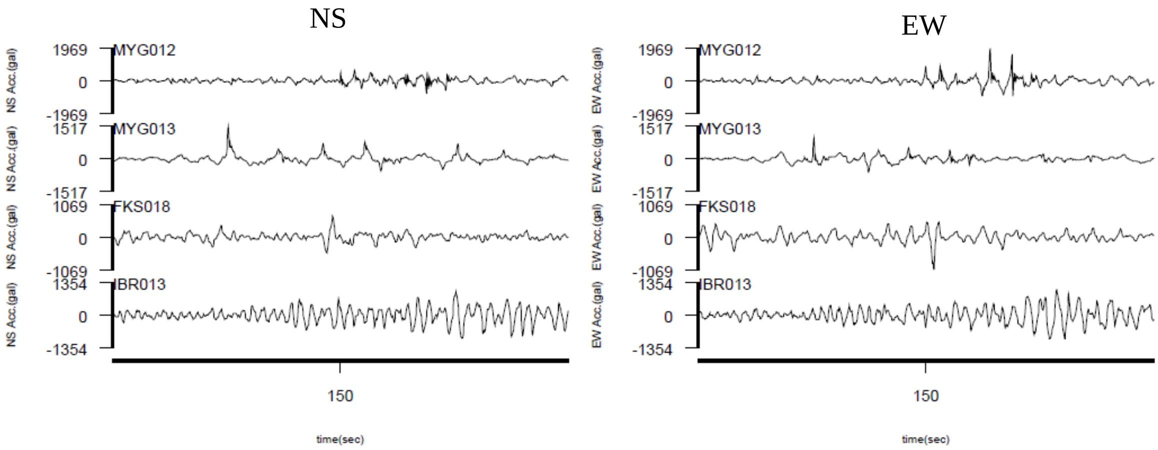

Figure 10. Closeup of acceleration waveforms for ground motion records with more than 1000 gals.

4. CONCLUSION

The short-period source model of the 2011 Tohoku earthquake (Mw 9.0) was constructed using forward modeling by comparing the observed records with synthesized motions based on a characterized source model and the empirical Green's function method. The observed strong motions have five remarkable wavepackets which correspond to the strong motion generation areas (SMGAs). The locations of the origins of the wavepackets were retrieved using the semblance analysis in order to determine the short-period source model more accurately. Acceleration as well as velocity motions from this earthquake are well simulated using a characterized source model consisting of five SMGAs. SMGA 1 is located in the source region of the Miyagi-oki and SMGA 2 in that of the Middle Sanriku-oki north of the hypocenter. SMGA3 is located in the source region of Southern Sanriku-oki west of the hypocenter, SMGA 4 is located in that of Fukushima-oki and SMGA 5 is located in that of Ibaraki-oki. The probabilities of earthquake occurrence in these source regions including the five SMGAs have been estimated by the ERC at less than 7 % to 99 % with magnitude about 6.9 to 7.5, separately.

Attenuation-distance relationship of peak ground velocity (PGV) from this earthquake was virtually equivalent to the empirical one from Mw 8.0 determined by Si and Modorikawa (1999). On the other hand, peak ground acceleration (PGA) was also virtually equivalent to the empirical one from Mw 8.0 in the distance over 100 km, but clearly larger than that from Mw 8.0 near the source fault. High accelerations were mainly caused by two different mechanisms comparing observed data with ground motion simulations. One is that ground motions with relatively high acceleration caused by source characteristics, such as rupture directivity effects, heterogeneous slip velocity inside the strong motion generation areas and so on. High acceleration motions were successfully simulated taking heterogeneous model into account. The other is that strong ground motions of more than 1000 gals were recorded at soft grounds formed by the Quaternary deposits. Such ground motions were generated by large amplifications due to surface geology with reduction of S wave velocities in soil layers (nonlinear soil behavior).

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