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Broadband ground motion simulations of mega-thrust subduction earthquakes based on multi-scale heterogeneous-source model

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Abstract

Six segments for the region off the coast of Tohoku from Middle Sanriku-Oki to Ibaragi-Oki were indicated with seismic activities of past 400 years by the Headquarter of Earthquake Research Promotion, Japan (HERP) before the 2011 Mw 9 Tohoku earthquake. Long-term forecasts for individual segments in this region were done so that Mw 7–8.4 earthquakes would occur within those segments, having different recurrence times from one to the other. The information about the source process and ground motions of this earthquake was obtained by dense networks of geophysical instruments including strong-motion, teleseismic, tsunami, and geodetic sensors. Most of slip distribution inverted from long-period records such as geodetic and tsunami data are placed at depths shallower than the hypocenter toward the trench. On the other hand, short-period seismic energy obtained by the back-projection method was generated mainly from the down-dip areas near the coasts of Pacific coast. We also estimate a short-period source model for generating strong ground motions from this earthquake by comparing the observed records from the mainshock with synthetic motions based on an asperity source model and the empirical Green's function method. We find the segmentation controls the characteristics of ground motions from the rupture process inversion of near-field strong motion records as well as earthquake occurrence in the source region of this event. The period-dependent source behavior of this earthquake can be interpreted by a multi-scale heterogeneous earthquake model. Recent other Mw 9.0 class subduction earthquakes such as the 2004 Mw 9.1 Sumatra earthquake and the 2010 Mw 8.8 Maule earthquake are known to have almost the same period-dependent source model mentioned above. Then, we propose an improved idea for recipe of predicting strong ground motions for mega-thrust subduction earthquakes based on the multi-scale heterogeneous-source model.

Keywords: the 2011 Tohoku earthquake, segmentation, subduction earthquake, strong ground motion, strong motion generation area

1. Introduction

Before the 2011 Mw 9 Tohoku earthquake, there are considered six segments for the region off the coast of Tohoku from Middle Sanriku-Oki to Ibaragi-Oki with seismic activities of past 400 years by the Headquarter of Earthquake Research Promotion, Japan (HERP) (ERC, 2009[1]). Then, they made a long-term forecast that Mw 7–8.4 earthquakes would occur within those segments, having different recurrence times from one to the other. Prior to the Mw 9 event, the possibility of a megathrust earthquake of magnitude larger than 8.5 was never expected from a scientific point of view.

The along-dip segmentation for the Tohoku subduction zone was pointed out by Yomogida et al. (2011[2]) due to apparent absence of eathquakes historically in the trench-ward segments, in contrast to rather large earthquakes (up to Mw 7.5) that repeatedly break the deeper, Japan Island-ward segments. Repeated occurrences of earthquakes and characteristics of ground motions during the earthquakes might be controlled by the segmentation.

The 2011 Mw 9.0 Tohoku earthquake was observed by dense networks of geophysical instruments including strong-motion, teleseismic, tsunami, and geodetic sensors. Long-period (more than 20 s) source models have been constructed from individual and joint inversions of long-period data including long-period strong motion data (e.g., Fujii et al., 2011[3]; Ozawa et al., 2011[4]; Yagi and Fukahata, 2011[5], Yokota et al., 2011[6]). Short-period source models have been estimated from the back-projection method using short-period teleseismic data (Ishii, 2011[7]; Honda et al., 2011[8]; Koper et al, 2011[9]) and the empirical Green's function method using strong motion data (Asano and Iwata, 2012[10]; Kawabe, et al., 2012[11]; Satoh, 2012[12]; Kurahashi and Irikura, 2013[13]).

We find that five small-asperities in the down-dip areas generate short-period motions of engineering interest. We call such small asperity strong-motion generation area (SMGA). Another problem is that the short-period source models with such SMGAs cannot simulate impulsive waves with high acceleration and velocity seen at onsets of the wave-packets in strong motion records observed near the source fault. To generate the impulsive waves, more heterogeneities are needed with e.g. variation of slip velocity time function at subfaults inside the SMGAs.

Recent other Mw 9.0-class subduction earthquakes such as the 2004 Mw 9.1 Sumatra earthquake and the 2010 Mw 8.8 Maule earthquake are known to have almost the same period-dependent source model mentioned above (Lay et al., 2012[14]). Then, we propose an improved idea for recipe of predicting strong ground motions based on a multi-scale heterogeneous model as a recipe of predicting strong ground motions for mega-thrust subduction earthquakes. This model provides broadband ground motions from 0.1 s to 10 s of engineering interest for aseismic design and base-isolation.

2. Segmentation of mega-thrust earthquakes

The segmentation in the subduction zone along the Japan Trench off the East-Tohoku has been done for the probabilistic evaluation of earthquake occurrence based on the seismic activity in this region by the HERP(ERC, 2002[1]) as shown in Fig 1a. The 2011 Mw 9.0 Tohoku earthquake mainly ruptured the area within the solid ellipse. The historically largest earthquake in each segment is indicated in the left upper of Fig. 1 (a). The segments were divided based on background seismicity, virtually no seismicity in shallow segments but active with large events repeating in deep segments. The probability of a future *M*w 7.5 earthquake (or a slightly larger event) in Segment C in Fig. 1(a), within the next 30 years, had been estimated to be as high as 99%. The 2011 earthquake ruptured Segment C initially and extended further east towards the Japan trench and the northern and southern segments all together.

Yomogida et al. (2011[2]) pointed out that the above pattern of the seismic activity in the Pacific coast of Tohoku, Japan is termed to be the along-dip double segmentation (ADDS). A map indicating a series of segments with many earthquakes along the island arc of Japan was made by Koyama et al. (2012[15]) as shown in Fig. 1(b). The 1707 Houei great earthquake along the Nankai trough are shown with a multiple-segment rupture of Segments F, G and H in Fig. 1(a). The best-known typical megathrust earthquake in Japan is the 1707 Houei great earthquake along the Nankai trough (multiple-segment rupture of Segments F, G and H of Fig. 1(a)). The epicenters of earthquakes with magnitudes larger than 6.0 and focal depths shallower than 60 km from 1950 to 2010 are shown in Fig. 1 (b) with yellow symbols classified by magnitude on their epicenters given by Japan Meteorological Agency. The 1707 earthquake occurred where little seismicity was observed, neither in the land-ward nor the trench-ward areas (Koyama et al., 2012[15]). The inactive seismicity in this region not only applies to the period analyzed in Fig. 1(b), but also to the period from 1924 to the present, according to the Japan Meteorological Agency data except for the activity following the 1944 Tonankai earthquake in Segment G and the 1946 Nankai earthquake in Segment H in Fig. 1(a). This type of multiple-segment great earthquake is referred as an earthquake of along-strike single segmentation (ASSS) in contrast to ADDS of the 2011 Tohoku-oki megathrust event.

The difference between these two types of segmentations is that strongly-coupled areas of trench-ward segments give rise to ADDS, whereas almost 100% coupled areas of shallow parts of the subduction zone give rise to ASSS. The 1960 Chile (*M*w 9.5) had the seismic activity characterized by the along-strike single segmentation (ASSS), where there is weak seismicity before the main event all over the plate interfaces of the subduction zone as at the Nankai trough in Fig. 1(b) (Koyama et al., 2012[15]).

Concerning the matter of strong motion generation from the 2011 Tohoku earthquake associated with the ADDS, the high frequency radiation is dominated from SMGAs in segments located in a down-dip region closer to Japan coast similar to high-frequency back projection studies using teleseismic short-period P waves data as described in later sections. The low frequency radiation from the asperity inverted from long-period strong-motions (more than 20 s) data tends to dominate in the shallow segment closer to the trench. Similarly, apparent along-dip rupture differences were observed for several other large megathrust events such as the 2010 Mw 8.8 Maule earthquake in Chile, the 2005 Mw 8.6 Sumatra earthquake, and the 2004 Mw 9.2 Sumatra earthquake by comparing the slip distribution with HF radiation observations (Lay et al. 2012[14]; Yao et al., 2015[16]).

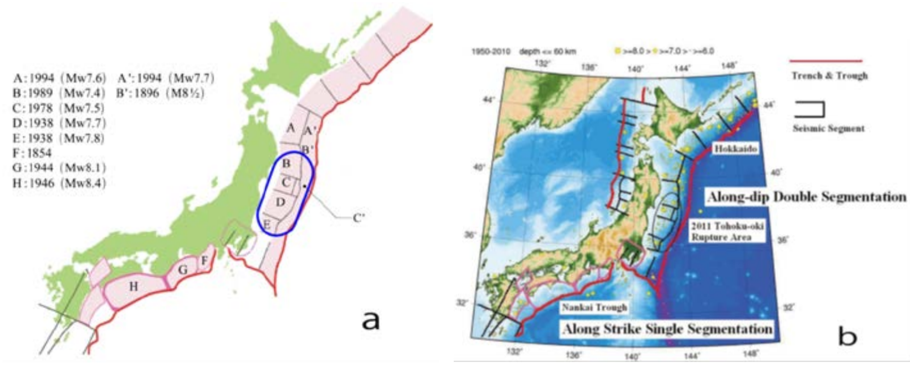

Fig. 1 – Seismic segmentation of Japan and its vicinity (Koyama et al., 2012[15]). **a**:Seismic segments in the subduction zone along the Pacific coast lines from the East Tohoku to the South Kyushu made by the Headquarter for Earthquake Research Promotion (HERP). **b**: Epicenters of earthquakes (yellow symbols classified by magnitudes) from 1950 to 2010 with magnitudes given by Japan Meteorological Agency equal to or larger than 6.0 and focal depths equal to or shallower than 60 km.

3. Period-dependent rupture process

The rupture process of the 2011 Tohoku earthquake was studied based on dense-networks' data of geophysical instruments including teleseismic, strong-motion, tsunami, and geodetic instruments. Tsunami data indicate that the source of the largest tsunami was located near the axis of the Japan Trench (Fujii et al., 2011[3]). Large amounts of slip on the plate interface in the southern Sanriku-oki (~ 30 m) and Miyagi-Oki (~ 17 m) areas surrounding the epicenter have been estimated from tsunami data. The coseismic slip areas estimated using GPS data extend for ~ 100 km eastward of the hypocenter and for 150 km along the Japan Trench (Ozawa et al., 2011[4]). The source process inverted from long-period teleseismic P-wave data is characterized by asymmetric bilateral rupture propagation, showing continuous slips up-dip from the hypocenter to a large maximum slip (50m), long slip duration, and a large stress drop (20 MPa) (Yagi and Fukahata, 2011[5]). A quadruple joint inversion of strong motion, teleseismic, geodetic, and tsunami dataset for the rupture process was performed by Yokota et al. (2011[6]), demontrating the maximum coseismic slip approximate 35 m east of the hypocenter toward the trench. The rupture propagated not only in the strike direction but also in the dip direction including both the deep area called the Miyagi-oki region and the compact shallow area near the Japan trench.

Kubo et al. (2014[17]) obtained source models of the 2011 Tohoku earthquake using multi period-bands waveform data by a common inversion method and discussed its period-dependent source characteristics. They introduce a new fault surface model having finer sub-fault size and estimate the source models in multi period-bands using a Bayesian inversion method combined with a multi-time-window method using strong motion data at K-NET and Kik-net stations and broad-band data at F-net. The strong motion data are divided into three period bands (10-25 s, 25-50 s, and 50-100 s) to estimate a kinematic source model in each period band using a Bayesian inversion method. The estimated source models in multi period-bands are shown in Fig. 2. The long-period (50 – 100 s) motions are radiated from up-dip regions shallow off Miyagi, while relatively short period (10 – 25 s) motions are radiated from down-dip regions deep off Miyagi and off Fukushima. Further, they find longer period motions are also radiated from down-dip deep off Miyagi.

The short-period energy source region can be constrained by the back-projection method (Ishii et al., 2005[18]) using regional network observations of teleseismic P waves, such as the North American (e.g. Ishii 2011[7]; Koper et al., 2011[9]), EU, and Tokyo Metropolitan arrays (e.g., Honda et al., 2011[8]). Subsidiary source regions extend to areas of rupture farther north and south than the regions mainly from the down-dip areas near the coasts of Pacific coast, which have been identified by those back-projection studies.

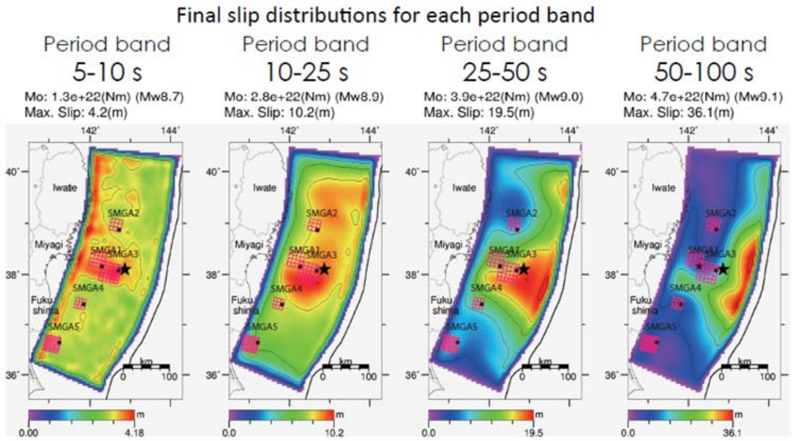

Fig. 2 – Period-dependent source rupture behavior of the 2011 Tohoku earthquake in multi successive period-bands using Bayesian waveform inversion strong-motion data (Kubo et al., 2014[17]).

The strong-motion stations that recorded the 2011 Tohoku earthquake and the acceleration records at the stations are shown in Fig. 3a and 3b. The observed acceleration seismographs show five distinctive-wavepackets that correspond to ground motions from respective small asperities. The origins of the wavepackets were retrieved from data arrays consisting of the strong motion stations using a semblance analysis (Kurahashi and Irikura, 2013[13]). Then, we estimate a short-period source model for generating strong ground motions from this earthquake by comparing the observed records from the mainshock with synthetic motions using an asperity source model and the empirical Green's function method as shown in Fig. 4. We find that five small-asperities in the down-dip areas generate short-period motions of engineering interest, while a large asperity with large slip exists in the shallower area east of the hypocenter and close to the trench (Suzuki et al., 2011[19]). Comparisons between the observed and synthetic ground motions are shown in Fig. 5 in the form of acceleration. The synthetic motions at most of stations fit the observations well except impulsive waves seen at the onsets of the wavepackets at some stations near the source fault. The impulsive waves will be discussed in later section.

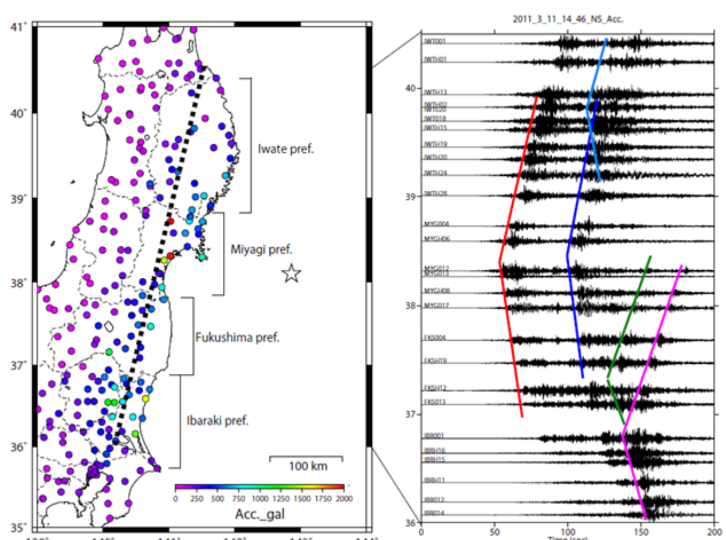

Fig. 3. - (a) Map showing the location of observation stations. (b) Acceleration seismograms at stations plotted in order from north to south. The colored lines indicate the travel times of S waves generated from five strong-motion generation areas (SMGAs). Red, sky-blue, blue, green, and pink represent S waves propagating from SMGA1, SMGA2, SMGA3, SMGA4, and SMGA5 to the stations, respectively.

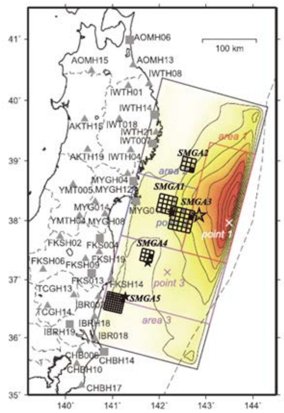

Fig. 4. - Comparison between the short-period source model obtained Kurahashi and Irikura (2013) and the slip distributions obtained by Suzuki et al. (2011[19]) via the waveform inversion using band-pass-filtered (10–100 s) strong-motion data.

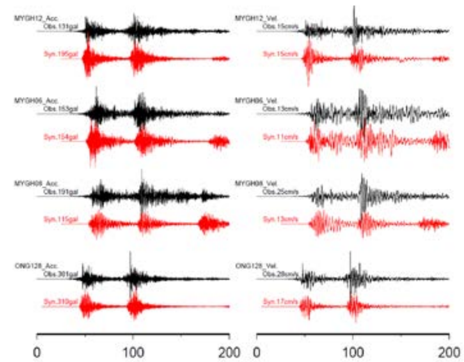

Fig. 5 - Comparison of the observed and synthetic seismograms (north–south component) obtained using the empirical Green's function (EGF) method at underground KiK-net and Onagawa Nuclear Power Plant (NPP) stations.

Other authors also estimate the short-period source models composed of several SMGAs using the characterized source model and the empirical Green's function method (Asano and Iwata, 2012[10]; Kawabe et al., 2012[11]; Satoh, 2012[12]). The SMGA models by them are compared in Fig. 6 together with the slip distribution obtained by Yoshida et al. (2011[20]). The locations of the SMGAs are almost consistent to one another, although they are not exactly the same. Those SMGAs are overwrited on the segmentation map made by the HERP in Fig. 6. One SMGA is allocated in each segment done for the long-term forcast by the HERP except for the near-trench zone, which has mostly generated tsunami earthquakes and large tsunami in historic times but only relatively small short-period motions.

To first order, the short-period energy release areas obtained by Ishii (2011[7]) and other authors are consistent with the locations of the SMGAs identified in our study.

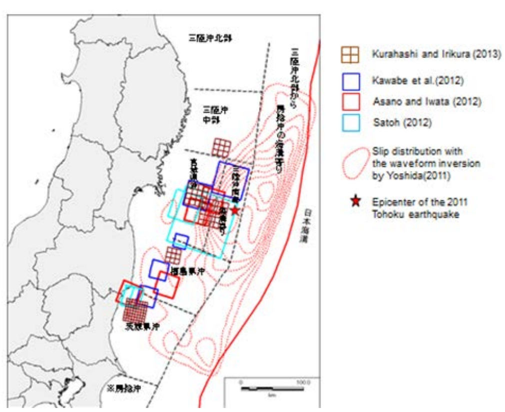

Fig. 6 - The locations of the SMGAs by different authors are compared one another (Asano and Iwata, 2012[10]; Kawabe et al., 2012[11]; Satoh, 2012[12]; Kurahashi and Irikura,2013[13]). The SMGAs in their models are estimated using the characterized source model and the empirical Green's function method. The slip distribution obtained by Yoshida et al. (2011[20]) is shown in the map together with the short-period source models.

4. Multiscale heterogeneity source model

4.1 Dynamic source model with a multi-scale heterogeneity

Multi-scale heterogeneity conception is introduced to explain the scaling issues of earthquakes of different sizes, e.g. asperity size and fracture energy (Ide and Aochi, 2005[21]). Aochi and Ide (2014[22]) have carried out numerical simulations of seismic ground motion radiating from a mega-earthquake whose rupture process is governed by a multi-scale heterogeneous distribution of fracture energy for an earthquake model as shown in Fig. 7. The observed complexity of the Mw 9.0 2011 Tohoku-Oki earthquake such as period-dependent source rupture behavior may be explained by such heterogeneities with fractal patches (size and number), even without introducing any heterogeneity in the stress state. They indicate that wave radiation is generally governed by the largest patch at each moment and that the contribution from small patches is minor based on their simulations.

Then, they made parametric studies on the frictional parameters of peak (τ_p) and residual (τ_r) friction to produce the case where the effect of the small patches is evident during the progress of the main rupture. Results are shown for three cases in the upper of Fig, 8. Ground motions and their Fourier spectra for the three cases are compared in the middle and lower of Fig. 8. They found that heterogeneity in τ_r has a greater influence on the ground motions than does heterogeneity in τ_p. Local heterogeneity in the static stress drop ($\Delta\tau$) influences the rupture process more than that in the stress excess ($\Delta\tau^{excess}$). It mean the residual friction (τ_r) is directly related to the static stress drop ($\Delta\tau$). The effect of small patches is particularly evident when these are almost geometrically isolated and not simultaneously involved in the rupture of larger patches. The results mentioned above are applied to the differences in the spatial distributions of sources which generate ground motions with different periods.

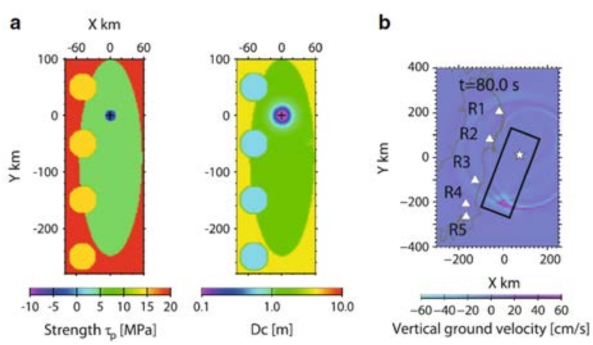

Fig. 7 – Multiscale heterogeneity model (Aochi and Ide, 2014[22]). (a) Fault heterogeneity was defined by one large ellipse with high fracture energy and four small circles with low fracture energy. The hypocenter was set at (0, 0) on the figure. Strength τ_p and D_c are shown in the left and right panel. (b) Wave propagation was calculated for the source model of the 2011 Tohoku earthquake model. The panel shows a snapshot of the simulation corresponding to case (a).

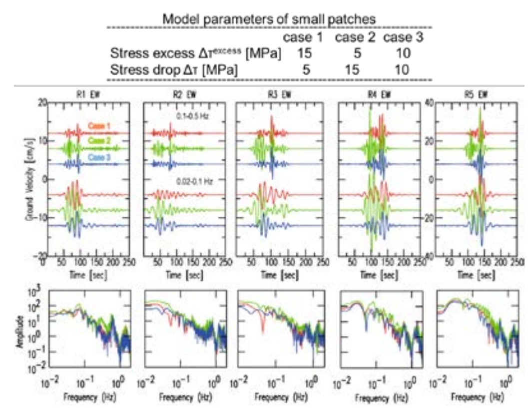

Fig. 8 - Ground motion comparison for the three cases presented in the upper table. The five stations as R1 to R5 are shown in Figure 7b. At the bottom of the figure, the Fourier spectra are also shown for a frequency band of 0.01 and 2 Hz. Local heterogeneity in the static stress drop influences ground motions more than those in the stress excess as seen in case 2.

4.2 Kinematic source model with a multi-scale heterogeneity

Sekiguchi (2008[23]) and Sekiguchi and Yoshimi (2010[24]) have proposed a method to simulate broadband ground motions using a characteristic asperity model with a multi-scale heterogeneity as a kinematic approach. The method modifies a so-called characteristic asperity model with very long-wavelength heterogeneity by adding adequate amount of shorter wavelength heterogeneity so that the model can generate a broadband ground motions. They reconstruct ground motions in Kanto Basin during the 2003 Tokachi-oki earthquake. However, it is not so easy to validate their method by comparing simulated and observed motions because too many parameters are necessary for calculating ground motions at specific sites.

Simpler kinematic approaches to simulate tsunami and strong-motion generation have been proposed by the Committee for Technical Investigation on Long-period Ground Motions from the Nankai-trough Mega-thrust earthquakes under Cabinet Office, Japan. They summarized many source models including short-period source models for estimating seismic intensities in period-range from 0.1 to 2 s and long-period source models for simulating long-period strong ground motions and tsunami generations collecting many references on the 2011 Tohoku earthquake. Then, they made a combined source model with a multiscale heterogeneity as illustratively described in Fig. 9. In the model, short-period sources typically identified as several small isolated regions referred to as strong motion generation areas (SMGAs), while large slip areas are located in shallow regions. In particular, super-large slip areas are put in shallowest place very near the trench.

They validated the tsunami generation models with the large and super-large slip and the JMA intensity models with the SMGAs for the 2011 Tohoku earthquake. However, the source models for estimating long-period (2 – 10 s) motions has not been calibrated from a comparison between observation and synthetics before the 2011 Tohoku earthquake. There has been a general consensus of whether the source of the long-period motions is identical to the large slip areas in the tsunami models, or the same as the SMGAs, or something in between them.

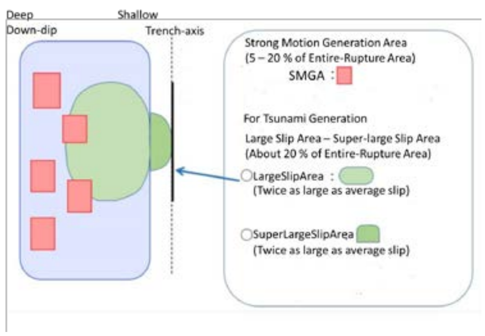

Fig. 9 – An illustrative source model with multiscale heterogeneity combining tsunami and strong motion generation proposed by the Long-Period Motion Evaluation Committee of Cabinet Office, Japan.

Long-period (2 – 10 s) ground motions become an important issue because of recent rapid increase of large scale structures such as high-rise buildings, oil storage tanks, and long-span bridges. Mega-thrust subduction-zone earthquakes and large crustal earthquakes can generate long-period ground motions amplified by sedimentary basins and secondarily-generated on the basin-edges in propagation path from source to site. Such long-period strong motions were observed widely in the Tokyo metropolitan area during the 2011 Tohoku earthquake. More than a little damage of elevators and non-structural elements in high-rise buildings have been reported in the Tokyo metropolitan region. Even in in the Osaka Bay area, despite being about 770 km from the epicenter, high-rise buildings were damaged resonating at 6 - 7-seconds due to the long-period ground motions (Building Research Institute, 2011[25]). Then, the Cabinet office established a committee to make long-period ground motion hazard maps for the Nankai-trough earthquakes and the Tokyo metropolitan earthquakes after the 2011 Tohoku earthquake.

The problem about the source of the long-period motions are solved by Kawabe et al. (2012)[11]. They examined whether the short-period source models obtained using the empirical Green's function method are available for long-period motions from 3 to 10 s of engineering interest. They calculate the Green's functions using a finite difference method with non-uniform spacing for a 3D velocity structure model. They found that the synthetic long-period (3 to 10 s) ground motions from the SMGAs fit the observed ones at most of stations reasonably well. It means the short-period source models consisting of plural SMGAs provide broadband ground motions including long-period motions from 3 s to 10 s that are engineering interest for aseismic design and base-isolation.

The committee for Technical Investigation on Long-period Ground Motions of the Cabinet Office extends the method to be applicable to broader period band from 2 to 10 s (Cabinet Office, 2015[26]). First, they have been trying to construct a nation-wide velocity structure models to be usable in a national project long-period ground motion hazard map, combining velocity structures constructed by various institutions. They successfully construct the velocity structure over Tohoku and Kanto regions comparing observed and synthetic motions from the aftershocks of the 2011 Tohoku earthquake.

Next, they examined the two scaling relations, rupture area S versus seismic moment M_o and combined area of asperities S_s versus M_o for subduction earthquakes (Murotani et al., 2008[27]) as shown in Fig. 10 and 11. They reestimate the SMGA model to fit best the observe long-period (2 to 10 s) motions of the 2011 Tohoku earthquake velocity using the 3-D FDM for reconstructed 3-D structure models in the Tohoku and Kanto regions. Comparisons between the observed and synthetic ground motions are shown in Fig. 12 at two selected sites (Shinjuku, Tokyo and Ohmiya, Saitama) in the 3 components of velocity. The synthetic motions at most of stations fit the observations at most of sites widely distributed from Tohoku to Kanto.

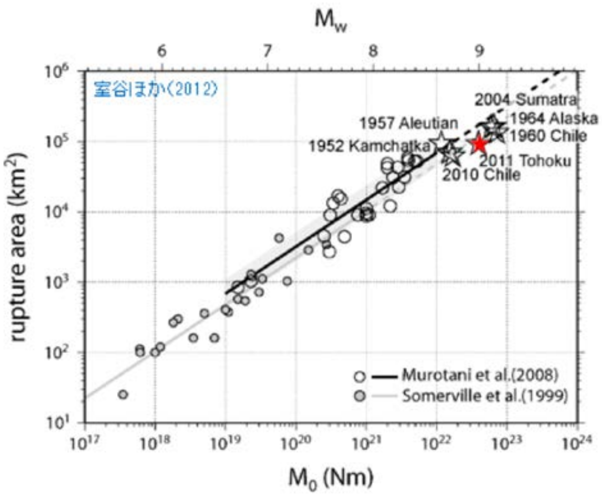

Fig. 10 – Empirical relationships between seismic moment M_o and rupture area S for subduction earthquakes summarized by Murotani et al. (2008[27]). The 2011 Tohoku earthquake is added a red star.

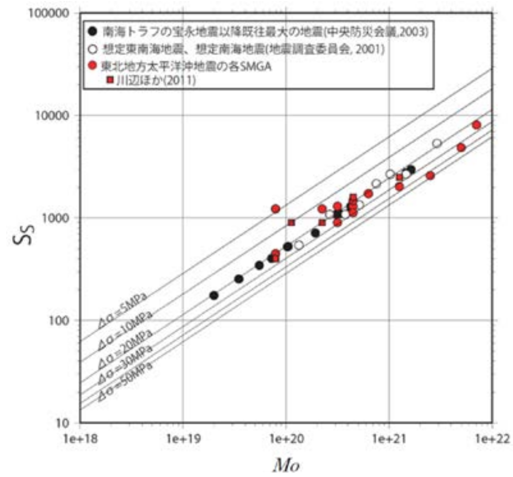

Fig. 11 – Empirical relationships between seismic moment M_o and combined area of asperities S_s for subduction earthquakes. Red circles are for SMGAs obtained by different authors

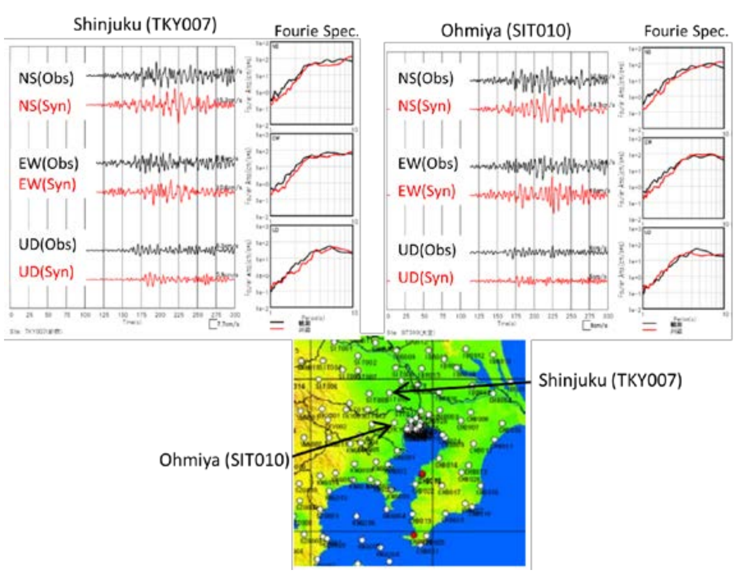

Fig. 12 - Comparison between observed (black) and synthetic (red) ground velocities for the Cabinet Office model combining Kawabe et al. (2012[11]) with Kurahashi and Irikura (2013[13]). Left: Shinjuku (TKY007). Right: Ohmiya (SIT010). The locations of those two sites are shown in a map of Kanto region.

5. Heterogeneity inside 'strong motion generation areas' (SMGAs)

The common features of the short-period source models by different authors (Asano and Iwata, 2011; Kawabe et al., 2012; Satoh, 2012; Kurahashi and Irikura, 2013) for the 2011 Tohoku earthquake are the three to five SMGAs with a uniform-stress parameter. Not only the locations of the SMGAs are close to each other as shown in Fig.6, but also the waveform shapes of the synthetic motions by different authors are very similar. In detail, however, the synthetic motions do not precisely fit the observed motions with distinctive pulses.

There are two considerable points in simulating the ground motions from the SMGAs. One is that the wavepackets have transient waveforms consisting of distinctive pulses with a certain duration. The other is that the waveforms at sites near the source have a remarkably impulsive wave in the initial portions.

The first is a point indicated by Nozu (2014[28]). He showed that the distinctive pulse waves from SMGA3 are not clearly seen in the waveforms by Asano and Iwata (2011), Kawabe et al. (2012), and Satoh (2012) except Kurahashi and Irikura (2013). There is a notable difference in procedure for simulating ground motions from the mainshock between Kurahashi and Irikura (2013) and the other authors. It is the selection of the empirical Green's function (EGF). Kurahashi and Irikura (2013) made a simulation using the second wavepackets of the 2005 Mw 7.2 Miyagi-oki earthquake as EGF, while the other authors use the records of the Mw 6.0 earthquake. One of the reasons why the synthetic motions are different depending on the EGF is that the earthquakes whose records are used as the EGF have their own rupture processes. We successfully simulate the ground motions from the Mw 7.2 earthquake using the records of the Mw 6.0 earthquake as the EGF. We find the rupture during the Mw 7.2 propagated from east to west, creating forward directivity for inland sites in the Tohoku region.

The second point is not solved even using the records of the Mw 7.2 earthquake. For example, the observed ground motions at ONG128, one of the stations closest to the source fault, exhibit remarkably impulsive waves in the initial portions of WP1 and WP3, while the synthetic motions do not have such features as shown in Fig. 5. The impulsive waves mentioned above are also observed at some other stations near the source fault, propagating from near-source to far-source stations. It means the impulsive waves seem to be created from the source. A different approach of simulating ground motions during the 2011 Tohoku earthquake was conducted by Nozu (2012[29]). He showed that the strong ground motions from the 2011 Tohoku earthquake were well simulated using nine pseudo-point sources. The pseudo-point source can generate the impulsive waves whose amplitudes concentrate in the initial portions of the wavepackets, but can not yield pulse durations attributed to the rupture propagation inside the SMGAs.

Kurahashi and Irikura (2013[13]) proposed a heterogeneous model is needed with higher stress parameters at one of subfaults inside the SMGAs, showing the synthetic motions which have an remarkable impulse and pulsive motions with a certain duration. Their results concerning heterogeneous SMGAs qualitatively agree well with those of Nozu (2012[29]).

We need to keep the seismic moments of the SMGAs constant to follow the empirical scaling relationships, seismic moment (M_o) versus combined area of asperities (S_s). Then, we examined another model with heterogeneity inside SMGAs, varying rise-times of slip velocity time functions at subfaults inside the SMGAs. Smaller rise-time at one of the subfaults is given as shown in Fig. 13, while the same rise-time is assumed at the other subfaults. Synthetic motions for the SMGA model with different rise-times at the one subfault are compared with the observed motions at ONG128 in Fig.14. The impulsive waves of WP1 and WP3 are well simulated using a heterogeneous model containing a subfault whose rise time is smaller than that at the rest of the subfaults.

Similar ground motions containing impulsive waves were reported at Kaihoku Bridge during the 1978 Mw 7.4 Miyagi-ken-Oki earthquake by Matsushima and Kawase (2006[30]) and at TKCH07 (Toyokoro) during the 2003 Tokachi-Oki earthquake by Nozu and Sugano (2006[31]). Those authors showed that such impulsive ground motions could be explained by modeling a small subarea with higher stress parameters inside an asperity, which is called a super asperity.

We find the impulsive waves are well simulated using the heterogeneous model with varying rise-time of the slip velocity time functions inside the SMGAs without considering higher stress parameters inside an asperity.

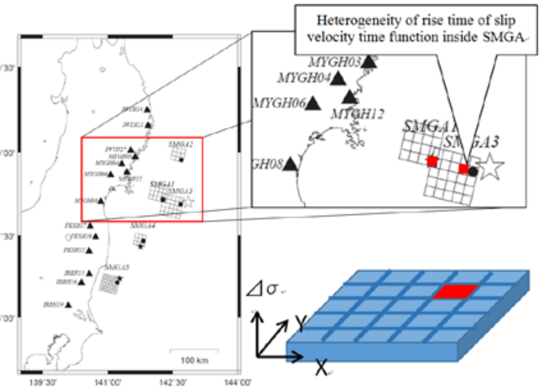

Fig. 13 – (Left) The short-period source model used in this study. (Upper right) Close-up illustration of SMGA1 and SMGA3. Rise-time of slip velocity time function varies at each subfault. (Lower right) Heterogeneous SMGA model incorporating spatially varying rise-time of slip velocity time function.

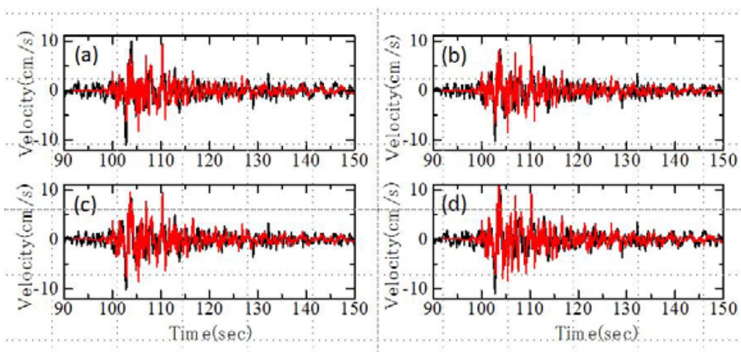

Fig. 14 - Comparison of observed and synthetic seismograms (NS component) from SMGA3. Rise time of slip velocity function varies at one of the subfaults. (a) Uniform model. Rise time is 3.7 s in all subfaults. (b) Heterogeneous model. Rise time is 2.5 s in one of the subfaults and 3.7 s in the other subfaults. (c) Heterogeneous model. Rise time is 1.0 s in one of the subfaults and 3.7 s in the other subfaults. (d) Heterogeneous model. Rise time is 0.25 s in one of the subfaults and 3.7 s in the other subfaults.

6. Conclusion

1. Six segments for the region off the coast of Tohoku from Middle Sanriku-Oki to Ibaragi-Oki have been indicated before the 2011 0ff the Pacific coast of Tohoku Earthquake, based on seismic activities of past 400 years by the Headquarter of Earthquake Research Promotion, Japan (HERP). The pattern of the segments is termed to be the along-dip double segmentation (ADDS). We find the segmentation control the characteristics of ground motions from the rupture process inversion of near-field strong motion records as well as earthquake occurrence in the source region of this event.

2. The low frequency radiation tends to dominate in the shallow segment closer to the trench based on the slip distributions inverted from long-period (more than 20 s) strong-motions data and extremely long-period motion data such as tsunami and geodetic data. On the other hand, the high frequency motions on the observed acceleration seismographs become superior in five wavepackets that correspond to ground motions from respective small asperities, i.e. SMGAs in the down-dip areas closer to the Pacific coast. Similar results are obtained from high-frequency back projection studies using teleseismic short-period P waves data.

3. The observed complexity of the Mw 9.0 2011 Tohoku-Oki earthquake such as period-dependent source rupture behavior may be explained by such heterogeneities with fractal patches (size and number) by Aochi and Ide (2014[22]). Similarly, apparent along-dip rupture differences were observed for several other large megathrust events such as the 2010 Mw 8.8 Maule earthquake in Chile, the 2005 Mw 8.6 Sumatra earthquake, and the 2004 Mw 9.2 Sumatra earthquake by comparing the slip distribution with HF radiation observations (Lay et al. 2012[14]; Yao et al., 2015[16]). Simpler kinematic approach to simulate the tsunami and strong-motion generation has been proposed by the Committee for Technical Investigation on Long-period Ground Motions from the Nankai-trough Mega-thrust earthquakes under the Cabinet Office, Japan. They find that the synthetic long-period (2 to 10 s) ground motions from the SMGAs fit the observed ones at most of stations reasonably well. Long-period (2 to 10 s) ground motions become an important issue because of recent rapid increase of large scale structures such as high-rise buildings, oil storage tanks, and long-span bridges.

4. High acceleration and velocity ground motions with impulsive waves whose amplitudes are large at onsets of the wave-packets are observed near the source fault of the 2011 Tohoku earthquake. To generate such impulsive waves, more heterogeneous model is needed to have varying slip velocity time functions at subfaults inside the SMGAs. Then we propose a multi-scale heterogeneous model as a recipe of predicting strong ground motions for mega-thrust subduction earthquakes. This model provides broadband ground motions from 0.1 s to 10 s that are engineering interest for aseismic design and base-isolation.

7. Achnowledgment

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