Inversion of Source Model of the 2011 off the Pacific Coast of Tohoku Earthquake Using Empirical Green's Function Method

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SUMMARY:
Source model composed of four strong motion generation areas (SMGAs) of the 2011 off the Pacific coast of Tohoku earthquake (Mw9.0) is estimated using the empirical Green's function method. We also estimate the short period spectral level $A$ of interplate earthquakes (Mw6.0 to 7.8) including the aftershocks and foreshocks using the spectral inversion method. It is found that the $A$ of the main shock calculated from the estimated source model is consistent with the empirical scaling estimated in our previous study and this study for interplate earthquakes with Mw6.6 to 8.2. The SMGAs are located at deeper positions and are different from large slip areas. The total area of SMGAs $S_A$ of the main shock is consistent with the empirical scaling by our previous study for interplate earthquakes with Mw7.1 to 8.2. The empirical $S_A$ is 1/5 of empirical total area of asperities derived by Murotani et al..

Keywords: The 2011 Tohoku earthquake, Source model, Empirical Green's function method, Scaling law

1. OBJECTIVES

The severe damage from tsunami and ground motions was caused during the 2011 off the Pacific coast of the Tohoku earthquake with Mw9.0. In this study, toward the advancement of the strong motion prediction for interplate earthquakes, we estimate the source model composed of strong motion generation areas (SMGAs) using empirical Green's function method and calculate the short period spectral level from the source model. We also estimate the short-period spectral level of the foreshock, aftershock, and the other interplate earthquakes with Mw6.0 to 7.8 on the Pacific plate in Japan using the spectral inversion method. The short-period spectral level is flat level of acceleration source spectrum (Dan et al., 2001) and is one of important parameters to strong motion prediction using fault models (e.g., Irikura and Miyake, 2011). Therefore we discuss the scaling law of the short-period spectral level with respect to seismic moment for the interplate earthquakes with Mw6.0 to 9.0. In addition we examine whether the scaling law of the total area of SMGAs with respect to seismic moment derived from the interplate earthquakes with Mw7.1 to 8.2 in our previous study (Satoh, 2010a) could apply to the main shock.

2. DATA AND METHOD

2.1. The Source Model of the Main Shock

Figure 2.1 shows the locations of epicenters by JMA and F-net CMT solutions by NIED of the main shock and two earthquakes used as empirical Green's functions together with 15 KiK-net strong motion stations by NIED used in the empirical Green's function method. To avoid the influence of nonlinearity of soil, borehole records at KiK-net stations are used. Locations of rupture starting points and ground motion generation areas (SMGAs) of the main shock estimated in this study are also shown in Fig. 2.1. We assume four SMGAs from analysis of the observed records. The 12/5/2005
earthquake (EQ4) is used as the empirical Green's function for SMGA1 and SMGA2. The 5/8/2008 earthquake (EQ6) is used for SMGA3 and SMGA4. Element fault is defined as to be 15 x 15 km square based on the short-period spectral level of EQ4 and EQ6 shown in Table 2.1. The strike of the fault plane is assumed to be 200° based on F-net and the dip angle is assumed to be 15° as the subducting angle of the Pacific plate near the Japan arc.

We estimate the source model by the grid search method by Satoh (2010b) based on Miyake et al. (2003) using the empirical Green's function method by Dan and Sato (1998). We estimate the rupture starting point and the starting time for each SMGA by the method by Takenaka et al. (2006) and Suzuki and Iwata (2007) at the first step. Then we estimate the optimal values searching around them and parameters of four SMGAs using the grid search method. The optimal values are estimated to minimize the summation of normalized L2 norm between observed and synthetic seismograms. Here the envelope of 1 to 10 Hz acceleration records, 0.05 to 1 Hz velocity records, and 0.05 to 1 Hz displacement records are used to calculate the L2 norm.

2.2. The Short-period Spectral Level

Short-period spectral level $A$ of the main shock is calculated from the estimated SMGAs using the equation (2.1) by Dan and Sato (1998).

$$A = 4\pi\beta^2 \left[ \sum_{i=1}^{N} \left( \Delta\sigma_i r_i \right)^2 \right]^{1/2}$$  \hspace{1cm} (2.1)

Here $\beta$ is the S-wave velocity of the source (4.0 km/s), $\Delta\sigma_i$ is the stress drop of $i$th asperity, $r_i$ is the equivalent radius of the $i$th asperity, $N$ is the number of the asperities. We regard SMGAs as asperities.
Short-period spectral level of the other interplate earthquakes shown in Table 2.1. are estimated using empirical site amplification factors and $Q$ values for path estimated using the spectral inversion method (e.g., Iwata and Irikura, 1988) by Satoh and Tatsumi (2002). The detailed method was shown in Satoh (2011). In Fig. 2.2. the locations of K-NET strong motion stations by NIED used to estimate the short-period spectral level are shown together with the epicenters by JMA and F-net CMT solutions by NIED. We select interplate earthquakes within the source region of the main shock with $M_w \geq 6.0$ and the focal depth of less than 60 km from earthquakes whose short-period spectral levels have not been estimated in previous studies.

Figure 2.3. shows the observed acceleration source spectra and $\omega^2$ model of EQ4 and EQ6 used as empirical Green's function method.

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Figure 2.3. shows the observed acceleration source spectra and $\omega^2$ models of EQ4 and EQ6 used as the empirical Green's functions. The agreement between observed and model spectra is reasonably well. The flat level of the acceleration source spectra is the short period spectral level.
Table 3.1. Source Parameters of the Tohoku Earthquake

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SMGA1</th>
<th>SMGA2</th>
<th>SMGA3</th>
<th>SMGA4</th>
<th>Total SMGA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length [km]</td>
<td>45.0</td>
<td>90.0</td>
<td>30.0</td>
<td>15.0</td>
<td>—</td>
</tr>
<tr>
<td>Width [km]</td>
<td>45.0</td>
<td>90.0</td>
<td>30.0</td>
<td>15.0</td>
<td>—</td>
</tr>
<tr>
<td>Area [km^2]</td>
<td>2025.0</td>
<td>8100.0</td>
<td>900.0</td>
<td>450.0</td>
<td>11475.0</td>
</tr>
<tr>
<td>Seismic Moment [dyne \cdot cm]</td>
<td>1.49E+28</td>
<td>7.73E+28</td>
<td>3.23E+27</td>
<td>8.06E+26</td>
<td>9.63E+28</td>
</tr>
<tr>
<td>Stress Drop [bar]</td>
<td>397.7</td>
<td>258.5</td>
<td>291.0</td>
<td>205.7</td>
<td>—</td>
</tr>
<tr>
<td>Slip [cm]</td>
<td>1530.3</td>
<td>1989.5</td>
<td>746.6</td>
<td>373.2</td>
<td>—</td>
</tr>
<tr>
<td>Short-period Spectral Level [dyne \cdot cm/s^2]</td>
<td>2.03E+27</td>
<td>2.64E+27</td>
<td>9.90E+26</td>
<td>4.95E+26</td>
<td>3.51E+27</td>
</tr>
<tr>
<td>Rupture Starting Time from Origin Time [s]</td>
<td>28.0</td>
<td>58.0</td>
<td>103.4</td>
<td>107.9</td>
<td>—</td>
</tr>
<tr>
<td>Rupture Velocity [km/s]</td>
<td>3.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>—</td>
</tr>
</tbody>
</table>

Table 3.1. Source Parameters of the Tohoku Earthquake

<table>
<thead>
<tr>
<th>Rupture Starting Point</th>
<th>Longitude [°]</th>
<th>Latitude [°]</th>
<th>Depth [°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMGA1</td>
<td>141.729</td>
<td>38.036</td>
<td>48.0</td>
</tr>
<tr>
<td>SMGA2</td>
<td>142.168</td>
<td>37.863</td>
<td>36.6</td>
</tr>
<tr>
<td>SMGA3</td>
<td>141.093</td>
<td>36.892</td>
<td>50.9</td>
</tr>
<tr>
<td>SMGA4</td>
<td>140.941</td>
<td>36.937</td>
<td>54.8</td>
</tr>
<tr>
<td>Total SMGA</td>
<td>140.941</td>
<td>36.937</td>
<td>54.8</td>
</tr>
</tbody>
</table>

Figure 3.1. Comparison between observed (black lines) and the synthetic (red lines) seismograms.
3. RESULTS

3.1. The Source Model of the Main Shock

Table 3.1 shows the estimated source parameters of the main shock. The stress drop of the SMGA1 is largest among four SMGAs. All SMGAs are located west of the epicenter as shown in Figure 1. This location at deeper positions is different from large slip areas estimated from long-period strong motion records or teleseismic records (e.g., Yoshida et al., 2011a; Yoshida et al., 2011b). Large slip areas in these studies are mainly located east of the epicenter. Large slip areas estimated through tsunami data by Koketsu et al. (2011) are mainly located east of the epicenter similar to Yoshida et al. (2011a) and Yoshida et al. (2011b). However, large slip areas estimated through joint inversion of teleseismic, strong motion, and geodetic datasets by Koketsu et al. (2011) are overlapped to SMGA1 and SMGA2. These results suggest frequency-dependent rupture process as pointed out by several studies (e.g., Koper et al., 2011).

Figure 3.1 shows the observed and synthetic waves at KiK-net stations during the main shock. Number at the tip of each seismogram shows peak ground motion. The synthetic waves reasonably agree well with observed ones. Figure 3.2 shows synthetic acceleration wave calculated from each SMGA and the observed waves at FKSH17, FKSH14, and IBRH14. At IBRH14 synthetic waves from SMGA2, SMGA3, and SMGA4 are overlapped and so the duration with large acceleration are shorter than that at the other sites.

The SMGAs estimated by other researchers (Kamae and Kawabe, 2011; Asano and Iwata, 2011; Irikura and Kurahashi, 2012) using the empirical Green's function method are also located west of the epicenter. However, there is a SMGA located in Fukushima-ken oki in their source models, but not in our source model. In addition, area of SMGA2 in our model is larger than that of the SMGAs in Miyagi-ken oki in their models. In order to interpret the cause of the differences we divide SMGA2 into forward and backward side for FKSH17 and FKSH14 as shown in Fig. 3.3.(c) and calculate synthetic waves from both side. Figure 3.3. (a) and (b) show the acceleration seismograms generated from forward and backward side. It is found that the duration becomes longer by the backward waves at FKSH17 and FKSH14. The length of backward-side fault is long and the rupture velocity with 2.0 km/s is slow compared with those by the other researchers. Therefore the synthetic waves generated from the SMGA in Fukushima-ken oki in the other source models are interpreted to be mainly generated from backward side of large SMGA2 in our model.

![Figure 3.2. Comparison between observed (black lines) and the synthetic (red lines) acceleration waves (1 to 10 Hz) from all SMGAs and each SMGA.](image1)

![Figure 3.3. Comparison between the synthetic acceleration waves (1 to 10 Hz) from forward and backward potions of SMGA2 (a) and the location of the forward and backward potions of SMGA2 for two sites (b).](image2)
3.2. Scaling Law

Figure 3.4. shows the relations between the seismic moment $M_0$ and the short period spectral level $A$ for interplate earthquakes on the Pacific plate in Japan. The $A$ inverted in this study is consistent with the Satoh's (2010a) empirical relation for interplate earthquakes on the Pacific plate in Japan. The Satoh's (2010a) $M_0-A$ relation is

$$A = 4.02 \times 10^{17} M_0^{1/3},$$

(3.1)

which is about 1.6 times of Dan et al.'s relation (2001) for crustal earthquakes. It is also found that the $A$ of big earthquakes ($M_w > 7$) is different among regions. Especially, the $A$ of earthquakes in Miyagi-ken oki tend to be large. The $A$ of the 1978 Miyagi-ken oki earthquake, the 2005 Miyagi-ken oki earthquake and the foreshock EQ11 have similar $M_0-A$ scaling which is slightly larger than the average + standard deviation of Satoh's (2010a) relation. The $M_0-A$ relation of the main shock is consistent with extrapolation of average of Satoh's (2010a) relation. Here $M_0$ of the main shock is $4.0 \times 10^{29}$ [dyne cm] by Yoshida et al. (2011a) and Yoshida et al. (2011b).

Figure 3.5. shows the relations between $M_0$ and total area of SMGAs $S_a$ for interplate earthquakes on the Pacific plate in Japan. The $M_0-S_a$ relation for the main shock estimated in this study is consistent with extrapolation of Satoh's (2010a) empirical relation for interplate earthquakes on the Pacific plate in Japan. The Satoh's (2010a) $M_0-S_a$ relation is

$$S_a = 1.27 \times 10^{-16} M_0^{2/3},$$

(3.2)

which is about 1/5 times of Murotani et al.’s (2008) $M_0-S_{asp}$ relation for interplate earthquakes on the Pacific plate and the Philippine Sea plate in Japan. Here $S_{asp}$ is the total area of asperities. The definition of asperities by Murotani et al. (2008) are the zones of slips that are 1.5 times larger than the average slip estimated by waveform inversion. In the waveform inversion, data with period of longer than 2 to 5 seconds are mainly used. SMGAs are estimated by empirical Green's function method.
using broadband strong motion records in the period range from about 0.1 to 10 (or 20) seconds. Therefore the difference between $S_{asp}$ and $S_a$ is caused by the difference of main period range of strong motions. These results also support frequency-dependent rupture process as pointed out by several studies (e.g., Koper et al., 2011).

4. CONCLUSIONS

Source model composed of four strong motion generation areas (SMGAs) of the 2011 off the Pacific coast of Tohoku earthquake ($M_{w}9.0$) is estimated by the empirical Green's function method. We also estimate the short period spectral level $A$ of interplate earthquakes ($M_{w}6.0$ to 7.8) on the Pacific plate including the aftershocks and foreshocks by the spectral inversion method. The results are summarized as follows:

1) The short period spectral level of the main shock calculated from the estimated source model is consistent with the empirical scaling estimated in our previous study and this study for interplate earthquakes with $M_{w}6.6$ to 8.2 on the Pacific plate in Japan.

2) The SMGAs of the main shock are located west of the epicenter. This feature is similar to SMGAs estimated using the empirical Green's function method by three groups (Kame and Kawabe, 2011; Asano and Iwata, 2011; Irikura and Kurahashi, 2012) and are tend to be different from large slip areas estimated by waveform inversion using long-period waves or tsunami data.

3) The short period spectral level of big earthquakes ($> M_{w}7$) occurred in Miyagi-ken oki tend to be large among the other interplate earthquakes on the Pacific plate in Japan.
4) The total area SMGAs $S_a$ of the main shock is consistent with the empirical scaling in our previous study (Satoh, 2010a) for interplate earthquakes with $M_w$7.1 to 8.2 on the Pacific plate in Japan. The total area SMGAs by Satoh (2010a) is 1/5 of the total area of asperities $S_{asp}$ for interplate earthquakes in Japan by Murotani et al. (2008). The difference between $S_{asp}$ and $S_a$ is caused by the difference of main period range of strong motions generated from SMGAs and asperities.

5) The results of 2) and 4) support frequency-dependent rupture process as pointed out by previous several studies (e.g., Koper et al., 2011).

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REFERENCES


Satoh, T. (2006). High-stress drop interplate and intraplate earthquakes occurred off shore of Miyagi prefecture, Japan, Third International Symposium on the Effects of Surface Geology on Seismic Motion, Grenoble,


Satoh, T. (2011). Scaling of short-period spectral level of acceleration source spectra for aftershocks and foreshocks of the 2011 off the Pacific coast of Tohoku Earthquake, Fourth IASPEI / IAEE International Symposium on the Effects of Surface Geology on Seismic Motion, Santa-Barbara, California, 1.3_Satoh.pdf


