Source modeling of the 2005 off-shore Miyagi prefecture, Japan, earthquake ($M_{JMA}=7.2$) using the empirical Green's function method

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A preliminary source model composed of asperities for the 2005 off-shore Miyagi prefecture, Japan, earthquake ($M_{JMA}=7.2$) was estimated by the empirical Green's function method. The source parameters for two asperities located on the fault plane were determined by comparing synthesized broad-band ground motions with observed ones at several stations. We concluded that the stress parameters of the asperities are very high (90 MPa for Asp-1, 300 MPa for Asp-2) and that these values are nearly equal to those (73 MPa and 29 MPa) calculated by the Earthquake Research Committee (2005) in Japan for the off-shore Miyagi prefecture earthquake that is expected in the near future. However, the location of the asperities is not completely consistent with the expected event.

Key words: 2005 Off-shore Miyagi prefecture earthquake, source model, asperity, forward modeling, empirical Green's function method.

1. Introduction

On 16 August 2005, an earthquake with a JMA magnitude (M_{JMA}) of 7.2 occurred off-shore of Miyagi prefecture (38.1507°N, 142.2795°E, 41.6 km depth; Japan Meteorological Agency (JMA)). This event (the 2005 event) had a maximum instrumental seismic intensity of 6, as measured by the JMA, and caused some damage as well as a small tsunami on the Pacific coast in the Tohoku region. It is thought that this event occurred at the boundary between the Pacific and the continental plates. The Earthquake Research Committee (2005) in Japan had estimated that there is a high potential for an earthquake of $M_{JMA}=7.4$ to occur in this area, similar to the 1978 off-shore Miyagi prefecture earthquake (the 1978 event), or for an even greater earthquake to occur. However, this 2005 event is not thought to be the expected event because of its smaller magnitude and different extension of aftershock distribution. On the other hand, it has been reported that a part of the source area of the expected event has been ruptured (Okada *et al.*, 2005) and that the extension of the seismic intensity is similar to those measured as a result of past off-shore of Miyagi prefecture earthquakes that have occurred many times. It is very important to understand the source process when discussing the relation between this event and the expected event in the near future. This paper provides a preliminary source model for the 2005 event based on estimates using the empirical Green's function method (Irikura, 1986). The advantage of this method is that it includes the propagation path and local site effects and estimates basically broad-band ground motions as long as the empirical Green's function recordings are accurate enough in broad-frequency band. In our simu-

lation, we determine a source model composed of asperities which is capable of reproducing broad-band strong ground motions using a forward modeling approach. This procedure is the same as that used by Kamae and Irikura (1998), Kamae and Kawabe (2004) and Kamae *et al.* (2005). We then attempt to compare the estimated source model with that for the 1978 event ($M_{JMA}=7.4$).

2. Strong Ground Motion Data

We used broad-band acceleration bore-hole data at six stations (MYGH11, MYGH12, IWTH23, MYGH03, MYGH01, MYGH08) of the KiK-net of the National Research Institute for Earth Science and Disaster Prevention. The locations of these stations are shown in Fig. 1 together with the epicenters of the mainshock and the event studied here as the empirical Green's function (we call this event the "EGF-event"). We decided to use this event based assessment of the location, magnitude, mechanism and longer period limitation, although there were some aftershocks with magnitudes smaller than 5. Tables 1 and 2 provide detailed information on the mainshock and the EGF-event, respectively. The source parameters (seismic moment, fault area and stress drop) of the EGF-event were estimated roughly from the displacement source spectra calculated by the borehole data of KiK-net, which are not affected strongly by the reflected wave from the surface. We used the EGF-event bandpass-filtered data (0.2–10.0 Hz) at all stations from the quality of waveform data.

3. Source Modeling

Several inverted source models have already been estimated from teleseismic data or/and strong ground motion data (e.g. Asano *et al.*, 2005; Wu and Koketsu, 2005). These models include the two regions with a relatively large slip - in the part near the hypocenter and in the deeper part of

Fig. 1. Map showing the Kik-net observation station locations and epicenters of the mainshock (a red star) and the EGF-event (a black star) used as the empirical Green's functions.

Table 1. Information of the mainshock.	
Origin Time (JST)	2005/10/16 11:46
Latitude (deg)	38.1507
Longitude (deg)	142.2795
Depth (km)	41.6
M _{JMA}	7.2
Seismic moment (Nm)*	5.43×10^{19}
Focal Mechanism Solution*	194/76/22
(Strike/Rake/Dip)	29/96/69

*F-net

Table 2. EGF-event and source parameters.	
Origin Time (JST)	2002/5/6 17:12
Latitude (deg)	38.462
Longitude (deg)	142.153
Depth (km)	40.0
M _{JMA}	5.2
Seismic moment (Nm)**	9.98×10^{15}
Fault area (km ²)**	4.0
Stress drop (MPa)**	3.0
Focal Mechanism Solution*	21/93/73
(Strike/Rake/Dip)	192/81/18

*F-net **This study

the west direction of the hypocenter. The results, as shown in Fig. 2, demonstrate that the first asperity (Asp-1) is located near the rupture nucleation point (hypocenter) and that the second (Asp-2) is located in the deeper part of the west direction of the hypocenter. Our objective was to determine a source model capable of explaining broad-band motions containing low- and high-frequency components. To accomplish this, we assumed a simplified source model

Fig. 2. Source model composed of two asperities. Two blue rectangles show the asperities for the 2005 event. Two pink rectangles show the asperities for the 1978 event. Blue dotted line does not mean the exact rupture area.

Table 3. Source parameters for each asperity.				
2005 EVENT (M _{JMA} 7.2)				
	M ₀ (Nm)	L (km) × W (km)	Δσ (MPa)	τ (sec)
Asp-1	2.40×10^{18}	4.0 × 4.0	90.0	0.4
Asp-2	6.39×10^{18}	8.0 × 8.0	30.0	0.6
1978 EVENT (M _{JMA} 7.4)				
	M ₀ (Nm)	L (km) × W (km)	Δσ (MPa)	τ (sec)
Asp-1	6.22×10^{18}	6.0 × 6.0	70.0	0.6
Asp-2	9.62×10^{18}	10.0 × 6.0	50.0	0.8

composed of asperities located on the two regions shown in Fig. 2. We assumed that the ground motions should be generated only from the two sub-events that correspond to Asp-1 and Asp-2. We adjusted the locations, sizes and stress parameters of those two sub-events to fit the simulated motions to the observed ones using a forward modeling approach. The dimensions of these asperities were basically determined from the reproduction of the typical velocity pulse duration that appeared at some stations. We were therefore able to determine the stress parameters from the levels of the synthetic high- and low-frequency ground motions specified by the number of divisions and the area of the EGF-event used as the empirical Green's function. We searched the parameters to obtain a better fit in broad-band frequency between synthetics and observed ground

Fig. 3. Comparison between the synthesized and observed motions at six stations from north to south (IWITH23, MYGH03, MYGH12, MYGH11, MYGH01, and MYGH08).

Fig. 3. (continued).

motions at MYGH11 and MYGH12 where typical velocity pulse waveforms were observed. We assumed an S -wave velocity of 4.0 km/s along the wave propagation path and a rupture velocity of 3.1 km/s (about 80% of S -wave velocity) on the fault plane. Furthermore, we assumed that the rupture should start from the south-east side inside Asp-1 and propagate radially. The rupture of Asp-2 should restart from the south-east side after the rupture reaches that point and then propagate radially.

After several trials, we obtained the best source model, which is shown in Fig. 2. The source parameters for each asperity are summarized in Table 3. The stress parameters (stress drop) of the asperities are close to those (70 MPa) calculated for the expected off-shore of Miyagi prefecture earthquake by the Earthquake Research Committee (2005) in Japan. The synthesized motions at six stations are compared with the observed ones in Fig. 3. Figure 4 shows the comparison between the synthetic and observed pseudo-velocity response spectra (PVRs) with a damping factor of 0.05.

4. Discussion

Figures 3 and 4 clearly reveal that the synthetics at MYGH11 and MYGH12 are in agreement with the observed ones and that, the separate contributions due to Asp-1 and Asp-2 are successfully reproduced at these stations. At IWTH23 and MYGH03, located to the north of the source area, it seems that the synthetics are strongly affected by the rupture directivity. At these stations, the effect

of the rupture directivity of the EGF-event itself, as seen in the recordings shown in Fig. 5, may be one reason why the synthetics were overestimated. Another reason may be that we did not consider the differences in the radiation patterns between the Asp-1, Asp-2 and the EGF-event in this study. On the other hand, at MYGH01 and MYGH08, located to the south of the source area, the synthetic high-frequency ground motions are conspicuously overestimated. We currently are unable to explain this discrepancy with any certainty. One possibility is that of a non-linear effect in the reflective waves included in the borehole data due to both of these stations having thick soft sediments that distinguish them from the other stations. We need to investigate the reason for these overestimations in the high-frequency range in order to increase the accuracy of this source model. Finally, we attempted to compare the source model with that of the 1978 event ($M_{JMA}=7.4$) proposed by Kamae *et al.* (2002). The modified source model composed of two asperities for the 1978 event is depicted in Fig. 2 together with that of the 2005 event ($M_{JMA}=7.2$). The stress parameters of two asperities for the 1978 event are also summarized in Table 3. This source model for the 1978 event is similar to the expected off-shore Miyagi prefecture earthquake calculated by the Earthquake Research Committee (2005) in Japan. When we focus on the location of the asperities in both events, we can see that the location of Asp-2 in both events is different, even though Asp-1 is located in almost the same region near the hypocenters. This result is basically consistent with the suggestion by Okada *et al.* (2005) that the

Fig. 4. Comparison of the pseudo-velocity response spectra (PVRs) with damping factor of 0.05 of the synthesized motions and those of the observed motions at six stations. Bold dotted line shows the PVRs of the synthesized motions. Solid thin line shows the PVRs of the observed motions.

Fig. 5. Integrated velocity waveforms for the EGF-event (M5.2) at six stations (EW Component).

2005 event possibly ruptured a part of the source area of the 1978 event. In order to confirm the difference in the locations of Asp-2 in both source models, some simulations using the stochastic Green's function method (Kamiae *et al.*, 1991) have been conducted. Figure 6 shows the comparison of the observed acceleration at KHB (Kaihoku-bashi) in Fig. 2 by the Public Works Research Institute (PWRI) during the 1978 event and the synthetics using the source models composed of two asperities for the 1978 event and the 2005 event. It is clear that the observed acceleration during the 1978 event can not completely be reproduced by the source model for the 2005 event. These results provide us with important information to further discussions on the occurrence of repeated subduction earthquakes.

5. Conclusions

We have attempted to estimate the source model composed of two asperities by forward modeling using the empirical Green's function method. We determined the source parameters for two asperities located on the fault plane from comparisons between the broad-band strong ground motions synthesized and the observed ones. Based on our comparison of the source model for the 2005 event and the 1978

Fig. 6. Comparison of the observed acceleration waveforms at KHB during the 1978 event with the synthetics (red line) by the stochastic Green's function method. (a) Synthetics using the source model for the 1978 event by Kamae *et al.* (2002) (b) Synthetics using the source model for the 2005 event in this study.

event, we have shown that both events have two asperities and that these stress parameters are almost same; however, the location of the asperity in the landside is different. We need to revise the estimates of the source parameters for asperities and to further our discussion on the relation of these asperities to the large earthquake expected in the near future by the Earthquake Research Committee (2005).

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