Short-Period Source Characteristics of a Great Earthquake Doublet in the Central Kurile Islands

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SUMMARY
We examine short-period source characteristics of the doublet events based on strong motion records observed at four stations in Hokkaido, Japan; the doublet events are the 15 November 2006 great underthrusting event (Mw8.3) and the 13 January 2007 great outer rise event (Mw8.1). The peak accelerations from the 2007 event are about ten times larger than those from the 2006 event. The S-wave acceleration spectral ratios of the 2007 event to the 2006 event are about 10 around 10Hz. We make source modelling of the doublet events by using the Empirical Green's Function method to understand the factor in these peculiar observations. The stress drops on the strong motion generation areas for the 2007 outer rise earthquake are about four times larger than those for the 2006 underthrusting earthquake. We confirm that the great outer rise earthquake generates strong short-period seismic waves compared with the great underthrusting earthquake.

Keywords: Great earthquake doublet, Underthrusting earthquake, Outer rise earthquake, Sort-period source characteristics

1. INSTRUCTION

A great earthquake doublet occurred in the central Kurile Islands on November 15, 2006 and January 13, 2007; the former is a large interplate (underthrusting) event (Mw8.3) and the latter is a large intraplate (normal faulting) event (Mw8.1) in the outer rise region seaward of the Kurile trench. Detailed their rupture processes were studied using far-field records by hundreds of global broadband seismographs. Seismic waves from the Kurile Islands doublet were recorded by strong-motion seismographs at four statioins (epicentral distances: 700~1200km) in Hokkaido, Japan, southwest of the doublet source region. These records provide a good opportunity to study short-period source characteristics of the great earthquake doublet, two great earthquakes with different categories.

First we examine the strong ground motions observed at four stations in Hokkaido from the doublet events. The seismic intensity distributions, the peak ground accelerations and the S-wave spectral ratios are compared for the doublet events. Next we make source modeling of the doublet events to understand the factor in the peculiar observations. The source models are estimated by using the EGF (Empirical Green's Function) method. Finally we discuss the short-period source characteristics for the doublet events.

2. A GREAT EARTHQUAKE DOUBLET IN THE CENTRAL KURILE ISLANDS

In late September 2006, a swarm of thrust faulting foreshocks ruptured the plate boundary east of the central Kurile islands. Subsequently, the great thrust event occurred on November 15, 2006. Thrust-faulting aftershocks of this event were distributed 250 km along the arc. A parallel band of aftershock activity in the outer rise, eventually extending more than 200 km along the arc, initiated within minutes and continued for two months. On January 13, 2007, the great earthquake ruptured a normal fault in the outer rise roughly parallel to the rupture zone of the thrust event. The aftershock sequence following the great outer rise event was less intense than that for the earlier thrust, but also extended several hundred kilometres along the trench. The sequence resulted in an extraordinary double band of seismic activity.

The source parameters of the doublet events by GCMT (Global CMT solutions) are shown in Table 1. The epicentres and focal mechanisms for the doublet events are shown in Fig. 1. Ground motions from the doublet events were felt on the Japan islands. Figure 2 shows seismic intensity distribution in the northern Japan islands during the double events by JMA (Japan Meteorological Agency). We can see that the maximum seismic intensity and felt area for the 2007 normal faulting event are considerably larger than those for the 2006 thrust faulting event despite the smaller seismic moment of the former one. This evidence motivated us to study short-period source characteristics of the great earthquake doublet based on the observed strong motion records.

Table 1. Source parameters of earthquakes used in this study.

Doublet Events	Year/Month /Day	Epicenter Lat. Long.	Depth km	Seismic Moment Nm	Remarks / References
Underthrusting	2006/09/30	46.29 153.45	12.8	8.81x10**18	GCMT, Element Event
Earthquakes	2006/11/15	46.71 154.33	13.5	3.51x10**21	GCMT, Target Event
Outer Rise	2006/12/07	46.24 154.44	15.4	4.42x10**18	GCMT, Element Event
Earthquakes.	2007/01/13	46.17 154.80	12.0	1.78x10**21	GCMT, Target Event

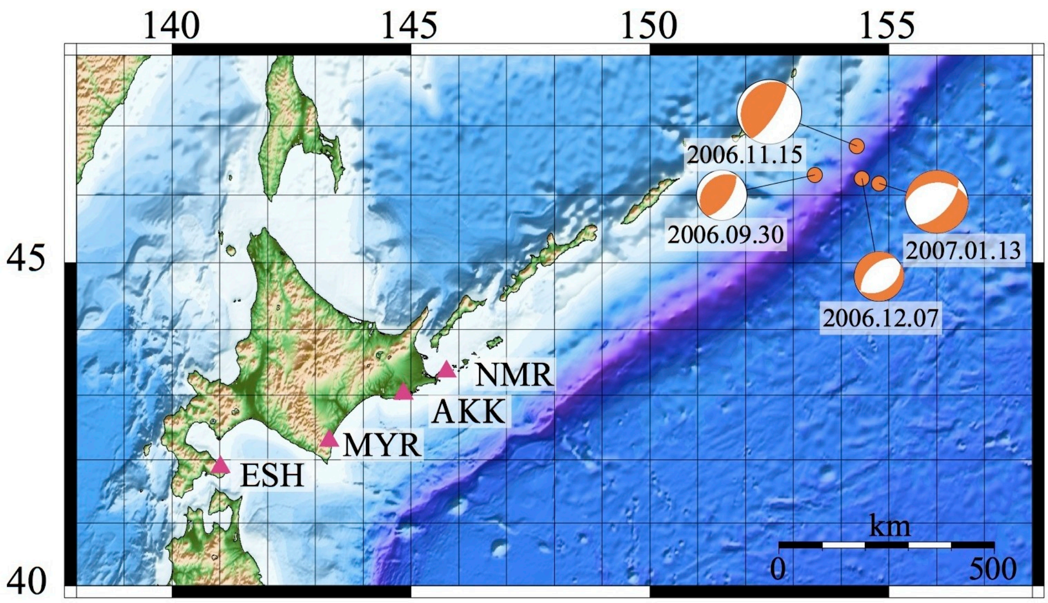

Figure 1. Location map showing strongmotion stations
and the epicentres and focal mechanisms for the doublet events by GCMT.

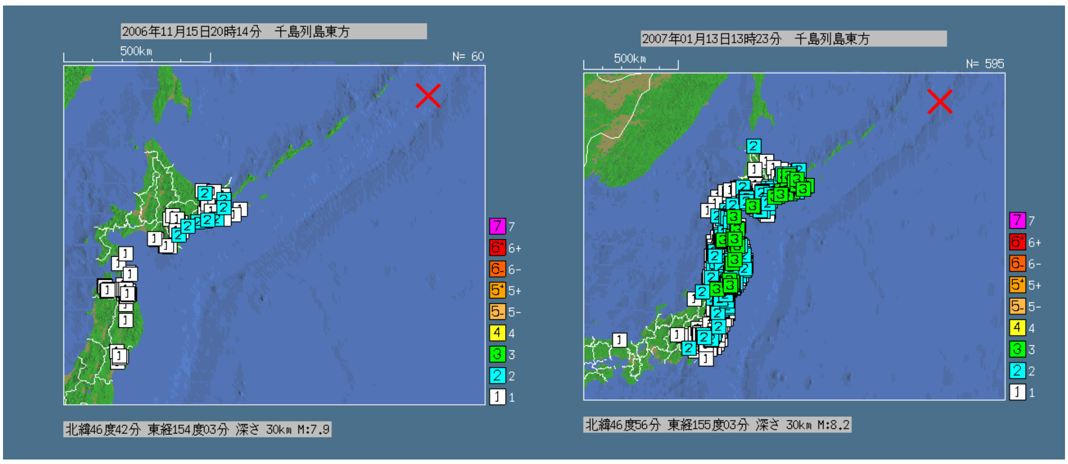

Figure 2. Seismic intensity distribution in the northern Japan islands during the double events by JMA .

3. STRONG GROUND MOTIONS FROM THE GREAT DOUBLET EARTHQUAKES

First we examine the strong ground motions observed at four stations in Hokkaido from the doublet events; the station locations are shown in Fig. 1. Wide-band velocity type strong motion instruments are installed at these stations. Figure 3 shows the observed seismograms at NMR. The acceleration and displacement waveforms are obtained by differentiating and integrating the velocity waveforms, respectively. The peak ground acceleration from the 2007 event is about ten times larger than that from the 2006 event despite the smaller seismic moment of the 2007 event. This is directly related to difference in the seismic intensity distributions for the doublet events as shown in Fig. 2. However, the peak ground velocities and peak ground displacements from both the events are nearly the same. We point out that a peculiar S-wave ripple exists on the NS-component velocity waveform from the 2007 event. This may result from the rupture process of the 2007 event. The observed waveforms at the other stations also show the same waveform differences between the 2006 and 2007 events as shown in Fig. 3.

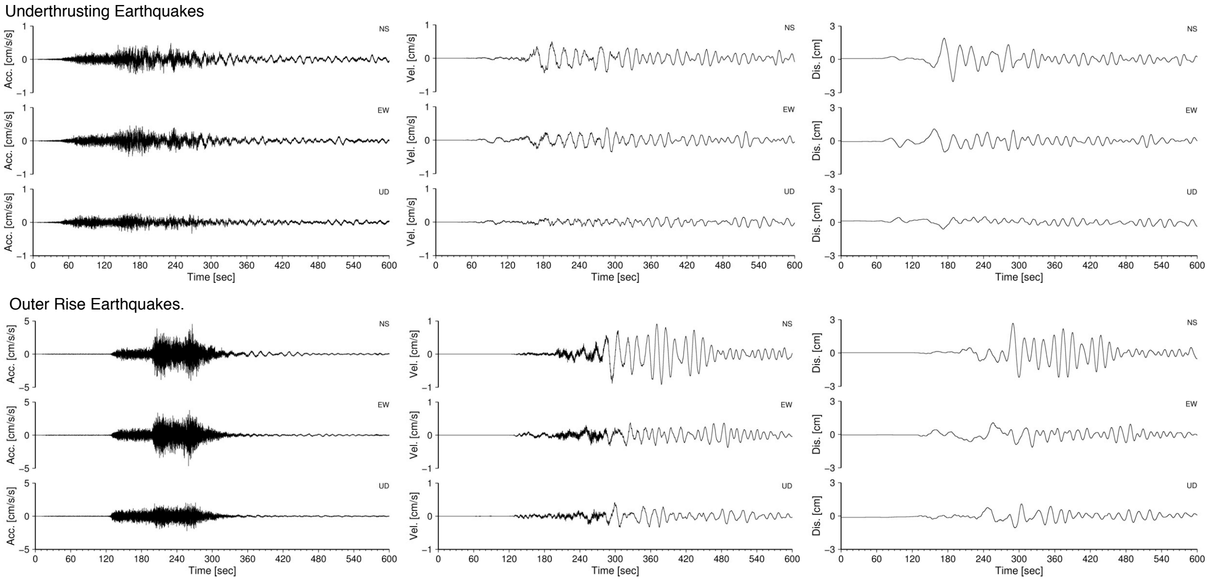

Figure 3. Observed seismograms at NMR. (upper : the 2006 event, bottom : the 2007 envent)

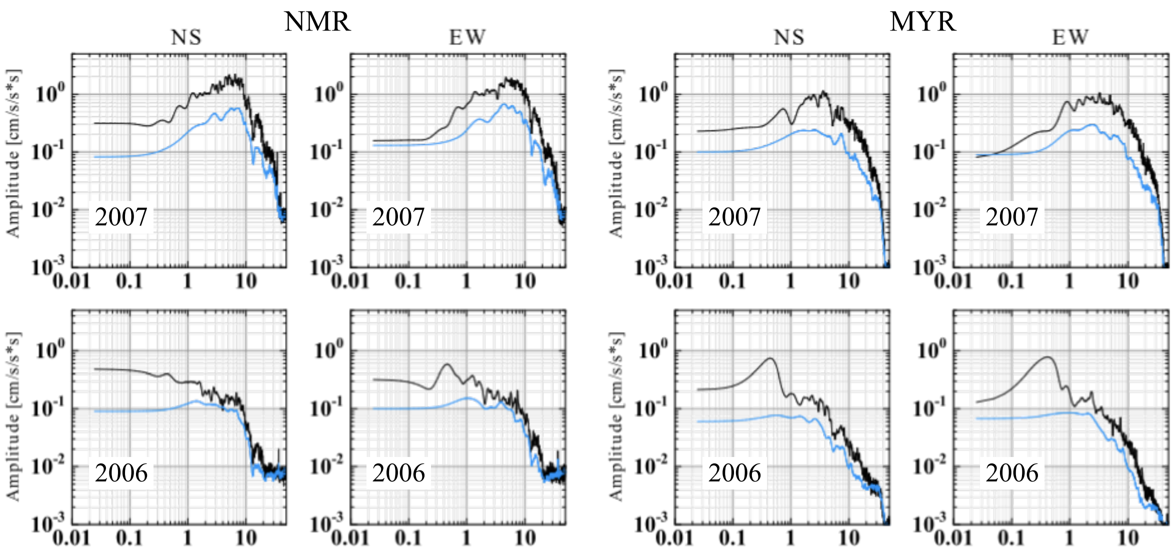

Figure 4. Observed S-wave spectra at NMR and MYR; only Horizontal components

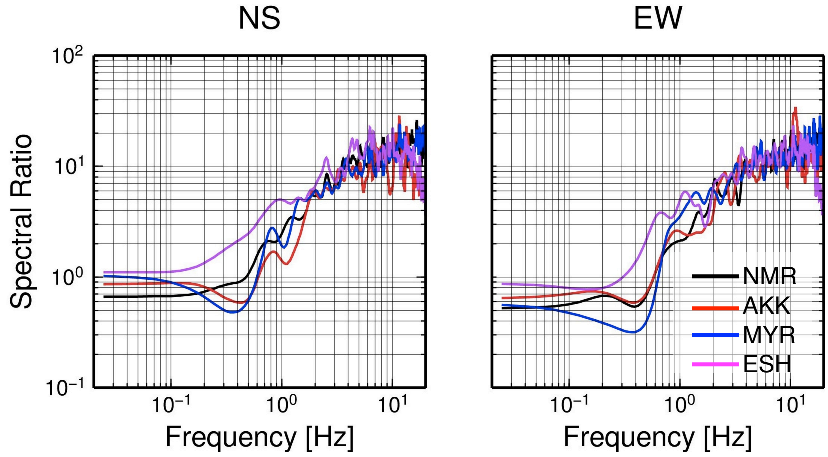

Figure 5. S-wave spectral ratios of the 2007 event to the 2006 event at four stations

Next we examine S-wave acceleration spectra for the doublet events. Figure 4 shows the S-wave acceleration spectra at NMR and MYR for the doublet events. Here we select the time window of about 40 sec to avoid contaminating the spectra by surface waves. The spectra of P-coda are also calculated to check the signal-to-noise ratio assuming the P-coda as noise. Figure 4 shows the signal-to-noise ratios are high at the frequency band of 0.1 ~ 20 Hz. After these examinations, we calculate the S-wave spectral ratios of the 2007 event to the 2006 event at four stations as shown in Fig. 5. The spectra change from station to station (Fig. 4), but the spectral ratios have similar shapes at four stations. This means the site and path effects are cancelled well by taking the spectral ratio and the ratios represent short-period source characteristic difference between the 2007 and 2006 events. The ratios have peculiar shapes; they increase with frequencies as 3 at 1Hz, about 10 at 5 Hz, and about 20 at 20 Hz. These facts demonstrate that the 2007 outer rise event radiates considerably strong short-period seismic waves compared with the 2006 thrust-faulting event.

4. SOURCE MODELING OF THE GREAT DOUBLET EARTHQUAKES

We make source modelling of the doublet events to understand the factor in the peculiar observations mentioned in the previous sections. Since the doublet earthquakes occurred fairly far from the strong motion stations in Hokkaido, the wave observed there passed through the long propagation path and was affected by the complex underground structure. In this case, it might be difficult for a theoretical approach to reproduce the strong motion records. So we use the EGF (Empirical Green's Function) method which calculates a record of a large (target) earthquake by summing up that of a smaller (element) event located near the target one (Hartzell, 1978; Irikura, 1986; Miyake et al., 2003).

4.1 Empirical Green's Function Method

Here we calculate the synthetic waveforms according to the EGF method developed by Miyake et al. (2003). This method simulates the observed wide-band strong-motion records well on the assumption of a characterized simple fault model which is a rectangle in shape with a constant slip and stress drop. This model is called the SMGA model (Miyake et al., 2003). First the fault plane is determined based on the focal mechanism of the target event and relevant information such as the aftershock distribution. Next the number to divide the SMGA into subfaults (N x N) and the ratio of the stress drop of the target event to the element one (C) are assumed. Finally we estimate the following parameters: the size and rupture starting point for the SMGA, the rise time for the target event (this is related to the filtering function to adjust the difference in the slip velocity functions between the target and element events), and the rupture velocity (rupture is assumed to propagate radially from the starting point). The estimation is done by fitting the synthetic waveforms (acceleration, velocity and displacement) to the observed ones by forward modelling.

The available stations are very far (750~1200 km) from the doublet source region. Furthermore, the stations used are located in the SW direction only. In this case, it is considerably difficult to apply the usual EGF method to estimate of the source model. So we refer to the waveform inversion results for the doublet events by Ammon et al. (2008).

4.2. Source Modeling of the 2006 Underthrusting Earthquake

Ammon et al. (2008) obtained the rupture model and slip distributions for this event as shown in Fig. 6. They selected the northwest-dipping nodal plane of the GCMT solution as the fault plane. The rupture propagated toward the northeast direction with the velocity of 2.0 km/s and the main rupture lasted about 120 sec. The slip distributions suggest a multiple SMGA model. We estimate the source model of the 2006 underthrusting event by using the EGF method referring to their rupture model. The 30 September 2006 foreshock (Mw6.6) is used as the element event. Figure 1 shows the epicentre and focal mechanism for this event; the source parameters are listed in Table 1. The frequency band used in the EGF simulation is set to be 0.1~20Hz.

Figure 6 shows the estimated SMGA model that is overlaid on the slip distributions by Ammon et al. (2008). The source model has five SMGAs each of which has the square in shape. The SMGA parameters are shown in Table 2. In Fig 7, we compare the observed and synthetic wide-band waveforms at two stations (NMR and MYR). The S-wave envelope shapes on the acceleration and velocity waveforms are fairly well reproduced by our SMGA model.

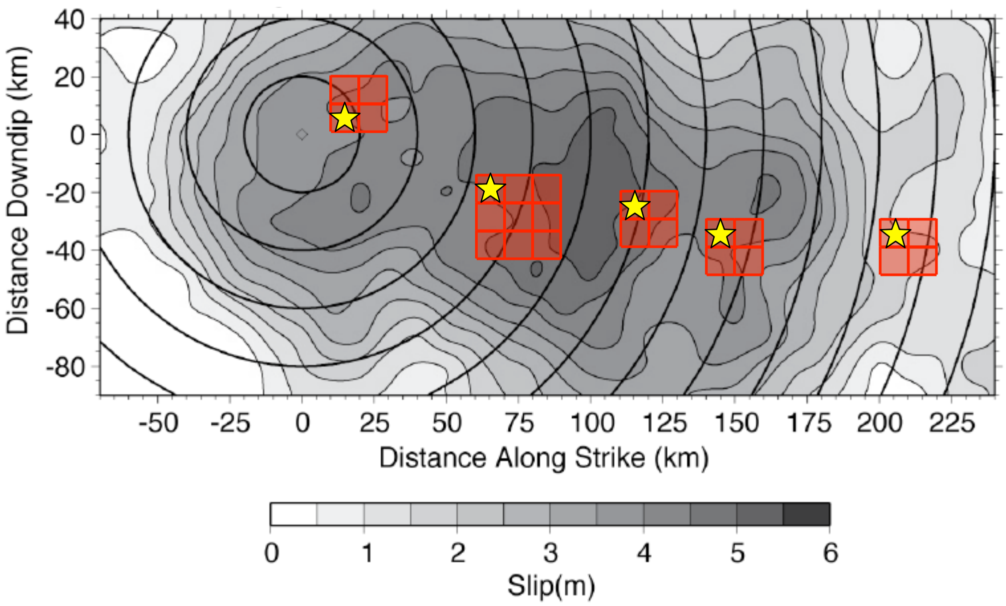

Figure 6. SMGA model of the 2006 Underthrusting Earthquake
(overlaid on the slip distributions by Ammon et al.)

Table 2. Source parameters of the SMGAs for the 2006 great underthrusting earthquake.

Parameters	SMGA 1	SMGA 2	SMGA 3	SMGA 4	SMGA 5	Element Event
N	2	3	2	2	2	-
C	1.5	1.1	1.1	1.2	1.1	-
Area [km^2]	400	900	400	400	400	100
Rupture Vel. [km/s]	2.6	2.7	3.0	2.8	2.6	-
Rise Time [s]	1.0	1.0	1.0	1.0	1.0	-
Rupture Time [s]	0.0	30.0	55	75.0	100	-
Stress Drop [MPa]	32.1	23.5	23.5	25.7	23.5	21

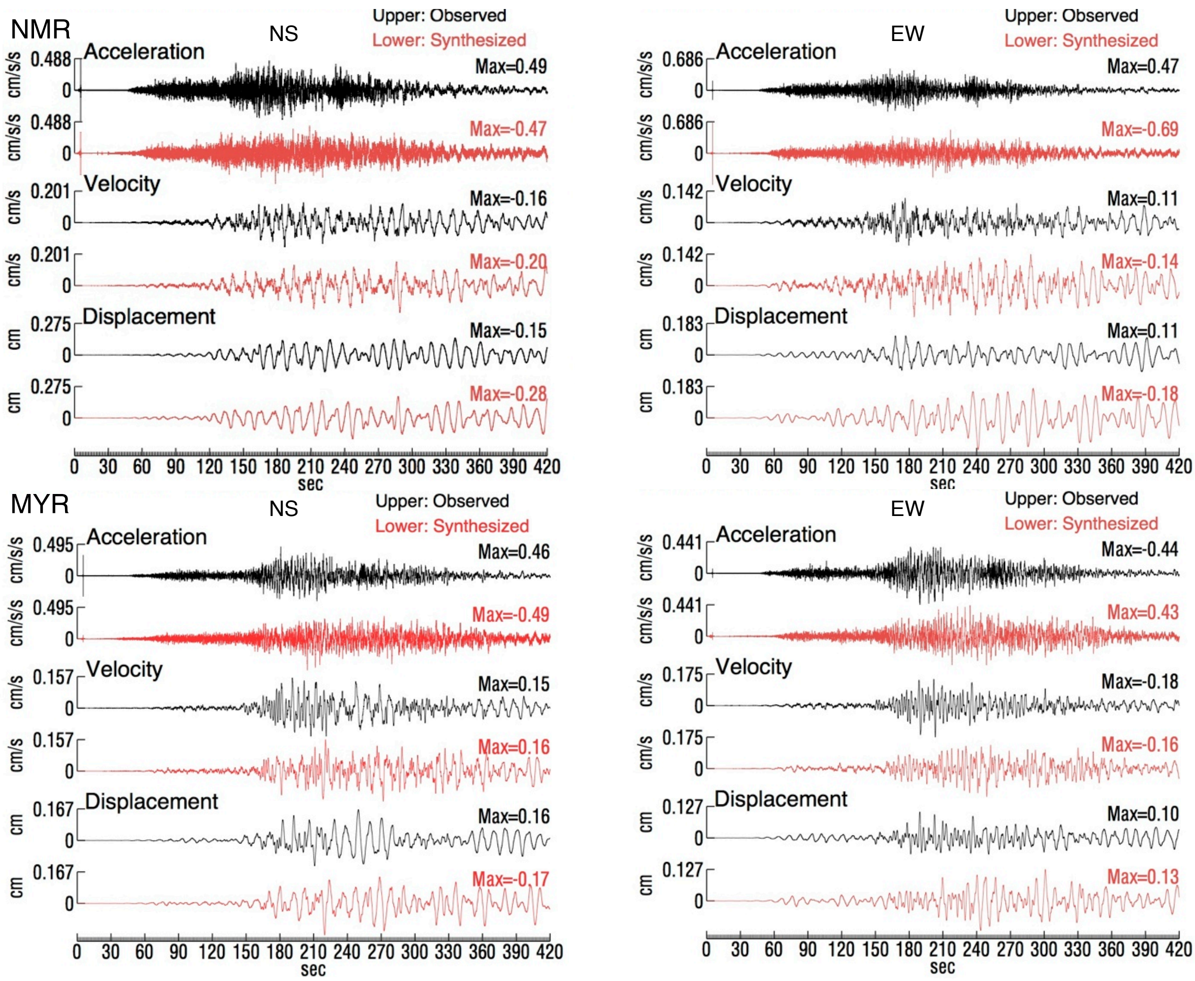

Figure 7. Comparison of observed and synthetic wide-band waveforms
for the 2006 great underthrusting earthquake.

4.2 Source Modeling of the 2007 Outer Rise Earthquake

Ammon et al. (2008) obtained the rupture model and slip distributions for this event as shown in Fig. 8. They selected the southeast-dipping nodal plane of the GCMT solution as the fault plane. The rupture propagated bilaterally with the velocity of 3.5 km/s and the main rupture lasted about 40 sec. The slip distributions suggest a multiple SMGA model. We estimate the source model of the 2007 outer rise event by using the EGF method referring to their rupture model. The 7 December 2006 foreshock (Mw6.4) is used as the element event. Figure 1 shows the epicentre and focal mechanism for this event; the source parameters are listed in Table 1. The frequency band used in the EGF simulation is set to be 0.1~20Hz.

Figure 8 shows the estimated SMGA model that is overlaid on the slip distributions by Ammon et al. (2008). The source model has six SMGAs each of which has the same square in shape. The SMGA parameters are shown in Table 3. In Fig 9, we compare the observed and synthetic wide-band waveforms at two stations (NMR and MYR). The S-wave envelope shapes on the acceleration waveforms and S-wave ripples on the velocity waveforms are fairly well reproduced by our SMGA model.

It is interesting to examine contribution of each SMGA to the synthetic waveforms. From Fig. 10 Right, we find that the SMGA 1 and 2 mainly contribute the synthetic velocity ripples due to the forward directivity effect; the other SMGAs have weak contribution to the ripples due to the backward directivity effect. The SMGA 5 and 6 are necessary to maintain the large acceleration level around 120 sec (see Fig. 9).

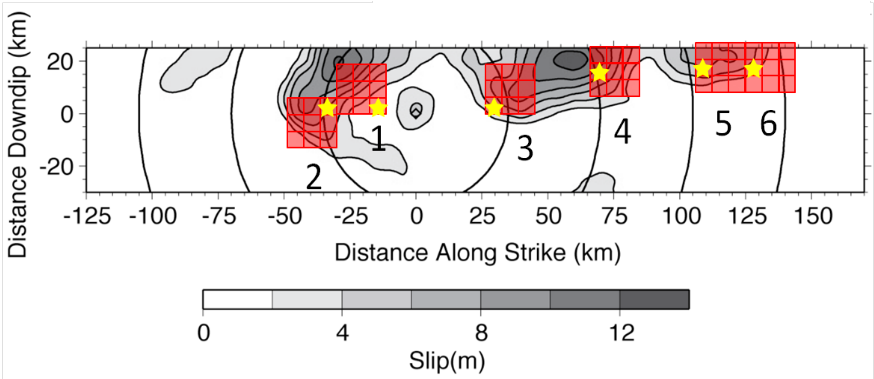

Figure 8. SMGA model of the 2007 Outer Rise Earthquake
(overlaid on the slip distributions by Ammon et al.)

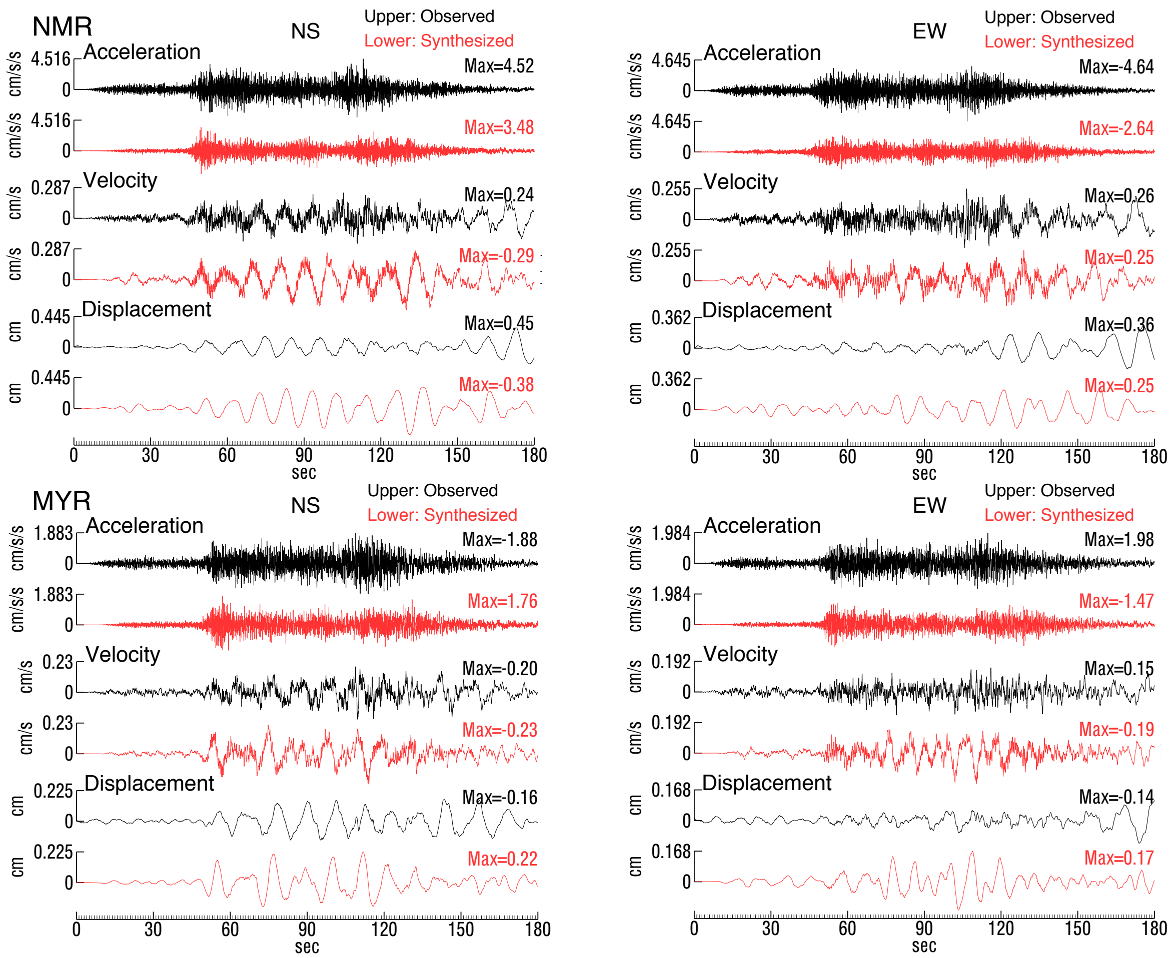

Figure 9. Comparison of observed and synthetic wide-band waveforms
for the 2007 Outer Rise Earthquake.

Table 3. Source parameters of the SMGAs for the 2007 great Kurile outer rise earthquake.

Parameters	SMGA 1	SMGA 2	SMGA 3	SMGA 4	SMGA 5	SMGA 6	Element Event
N	3	3	3	3	3	3	-
C	2.4	2.2	2.2	2.4	2.9	2.8	-
Area [km^2]	324	324	324	324	324	324	36
Rupture Vel. [km/s]	3.0	2.8	2.8	3.0	2.8	2.6	-
Rise Time [s]	1.0	1.0	1.0	1.0	1.0	1.0	-
Rupture Time [s]	5.0	11.0	8.5	19.0	31.0	38.0	-
Stress Drop [MPa]	107	98	98	107	130	125	45

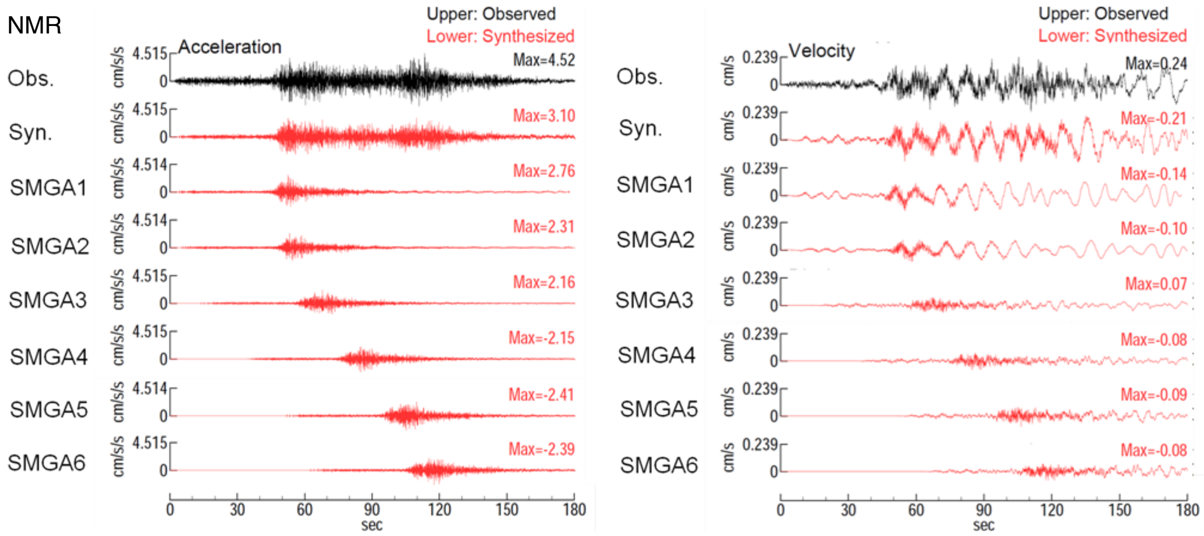

Figure 10. An example showing contributions of SMGAs at station NMR. We compared acceleration and velocity records(Obs. ; upper traces) with synthetic seismograms generated from the whole SMGAs(Syn. ; second traces) and six separate SMGAs (SMGA1-6; third to eighth); NS component.

5. DISCUSSIONS

We examine the stress drops on the SMGAs for the doublet earthquakes. The stress drop on the SMGA is obtained by multiplying the stress drop of the element event by the estimated parameter C (the stress drop ratio between the target event and the element event); the stress drop of the element event is obtained by assuming the crack model. The stress drops on the SMGAs are shown in Tables 2 and 3. The average stress drop on the SMGAs for the 2006 underthrusting event is 25.7 MPa, while that for the 2007 outer rise event is 111 MPa. Since the stress drop is directly related to excitation strength of short-period seismic waves, we conclude that this stress drop difference between the doublet earthquakes is the chief factor in the observed differences such as the intensity distributions (Fig.2), the peak ground accelerations (Fig. 3) and the S-wave spectral ratios (Fig. 5).

Ammon et al. (2008) compared the moment rate spectra for the doublet events (Fig. 11(a)) and noted the spectral amplitudes for the 2007 outer rise event are significantly larger, by ratios of 4 to 7, than those for the 2006 underthrusting event, despite the smaller seismic moment of the former event. In Fig.11, we show again the S-wave spectral ratios taken from Fig. 5. The spectral ratios also show the high-frequency enrichment for the 2007 event, by ratios of about 10 in the frequency range of 3 to 20 Hz. The difference in the moment rate spectra represents the differences in source characteristics logically. On the other hand, the S-wave spectral ratios do not represent directly the source characteristic difference, because they may be affected by source radiation pattern. However, recent studies (e.g., Satoh, 2002) showed the radiation pattern effects are nothing for high-frequency (> a few Hz) seismic waves. Combining both figures we may conclude that the 2007 outer rise event radiated strong seismic waves over the wide frequency band of 0.05 to 20 Hz compared with the 2006 underthrusting event. This conclusion implies that triggering of a large outer rise rupture with strong shaking over the wide frequency band constitutes an important potential seismic hazard.

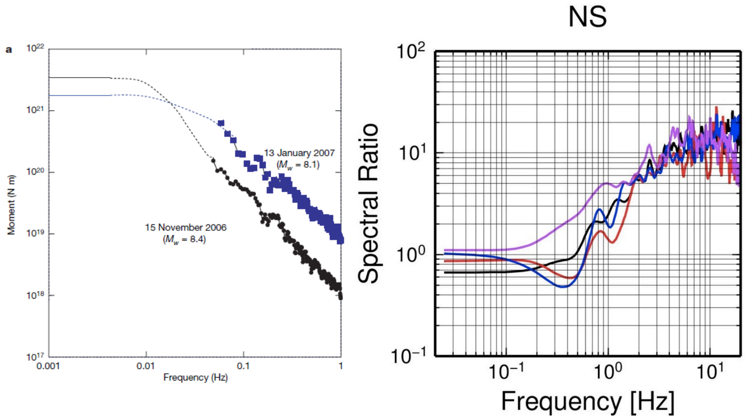

Figure 11. Comparison for the doublet events:
(a) Moment rate spectra for the 2006 and 2007 events(Ammon et al.)
(b) The S-wave acceleration spectra for the doublet events (NS component).

6. CONCLUSIONS

We studied the short-period source characteristics of the great earthquake doublet in the central Kurile islands; one is the 2006 great underthrusting event (Mw8.3) and the other, the 2007 great outer rise event (Mw8.1). We found the following features of strong ground motion: (1) the maximum seismic intensity and felt area for the 2007 event are considerably larger than those for the 2006 event, (2) the peak ground acceleration from the 2007 event is about ten times larger than that from the 2006 event, (3) the S-wave spectral ratios of the 2007 event to the 2006 event are about 10 around 10 Hz. The source models estimated by using the EGF method show that the stress drops on the SMGAs for the 2007 event are about four times higher than those for the 2006 events. These findings indicate that the 2007 great outer rise source generated considerably strong short-period seismic waves compared with the 2006 great underthrusting source.

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