Complicated repeating earthquakes on the convergent plate boundary: Rupture processes of the 1978 and 2005 Miyagi-ken Oki earthquakes

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Abstract

Source rupture processes of the 1978 and 2005 Miyagi-ken Oki earthquakes are revealed using waveform inversion. Though the hypocenters are almost the same and both rupture from the hypocenter to the deep part, our results show that these two earthquakes did not repeat the same rupture. In the case of the 2005 earthquake, several small asperities are all confined in the southern part, where it probably ruptured with a similar value of slip in 1978. The coupling factor of the subducting slab with the continental plate in the southern part is about 0.5. Main rupture of the 1978 earthquake, however, occurred in the northern part, where no slip is identified for the latest one. The seismic moment of the 1978 earthquake is four times of that of the 2005 earthquake. The Miyagi-ken Oki earthquake repeats in a very complex pattern. It may rupture only on those small asperities like the 2005 earthquake, or propagate to the northern large asperities like the 1978 one, or even develop to a vast earthquake rupturing to the shallow part and generate a large tsunami like the 1793 one.

1. Introduction

On August 16, 2005, an M_{JMA} 7.2 earthquake occurred offshore of Miyagi prefecture, named as the 2005 Miyagi-ken Oki earthquake by the Japan Meteorological Agency (JMA). This earthquake engaged extensive attention of Japanese seismologists because it occurred in the “area of specific observation” nominated by the Coordinating Committee for Earthquake Prediction (CCEP). 37 years ago, the 1978 M_{JMA} 7.4 Miyagi-ken Oki earthquake caused more than one thousand casualties and collapsed more than six thousand house. The warning for a large earthquake in this area was given out by seismologists (e.g. Seno, 1979). Historical literatures show that Miyagi prefecture in the northeastern Japan has been periodically inflicted by large offshore earthquakes. The large earthquake cycles in this area are featured with a relatively short period as follows: the largest earthquakes (above M 7.8) with a period of about 100 years occurred near the Japan Trench, whereas moderately large earthquakes (around M 7.4) took place in the inner side with a period of less than 40 years. According to the report by the Japanese Headquarters for Earthquake Research Promotion (2001, http://www.jishin.go.jp/main/index.html), one of the identified large historical earthquakes dates back to the year of 1793, probably with magnitude of 8.2, associated with a large tsunami (two to five meters high). This report further maintained that the probability of a large

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earthquake in the coming 30 years is larger than 0.9. It is said that the magnitude 7.2 of the 2005 earthquake is too small to meet the warning given by the headquarters and further attention to the near-future larger earthquake is called on. Tsunami associated with those seismic events is a significant characteristic of the Miyagi-ken Oki earthquakes. Comparing with the 1793 earthquake, tsunamis generated by the 1978 and 2005 earthquakes were relatively small (less than half a meter).

Previous studies on plate movement and seismic moment release pattern in this area indicates a high seismic coupling factor between the suducting oceanic plate and the overriding continental plate (e.g., Nishimura et al., 2000). Moreover, the study on historical earthquakes showed that large earthquakes on the subducting plate boundary along the Japan Trench have occurred repeatedly on the identified large asperities (Yamanaka and Kikuchi, 2004, here we denote it as the asperity model). Study on the rupture processes of the 1978 and 2005 earthquakes is helpful to understand the Miyagi-ken Oki earthquake cycles, hence the seismic moment release pattern (i.e., the movement of the plates). Also it would supply a valuable chance to test the asperity model proposed by Yamanaka and Kikuchi (2004). To construct a reasonable fault model, we taking into account the recent study results of the plate boundary model in this area (Yamamoto et al., 2004). Using strong motion data recorded in the near field for both earthquakes and teleseismic body waves in the case of the 2005 one, we invert the rupture processes of these two earthquakes.

2. Data

For the 1978 earthquake we collected strong motion records (three components at four stations) supplied by the Kowan Strong Motion Network and records at two stations by the Japan Public Works Research Institute, in addition to the JMA-51(52) low gain strong motion displacement records at eight stations (Yamanaka and Kikuchi, 2004). The former six stations are equipped with the SMAC acceleration seismographs, which start its recording when a threshold of the ground motion is matched. A time domain recursive bandpass filter at frequency 0.025 to 0.8Hz is applied to the raw data. The SMAC seismograms are then integrated into velocity waveforms. We devised some time-domain digital filters whose frequency response exactly follows the frequency response functions of the JMA seismometers. To avoid errors generated from baseline bias, we directly apply the devised filters to the calculated Green's functions instead of applying the de-convolution of frequency response to the observation data. Due to lack of precise time information in all records, we compare the wave phases recorded at nearby stations and picked up the S wave phase as the reference phase.

In the case of the 2005 earthquake, we collected underground strong motion records at 12 stations from KiK-net operated by the National Research Institute for Earth Science and Disaster Prevention (NIED). The strong motion data are integrated into velocity waveforms after application of the bandpass filtering at frequency 0.02 to 0.8Hz. Since the near field stations are deployed only on the landside, we also include 33 records of teleseismic P waves supplied by the Global Digital Seismic Network (GDSN) to better constrain the waveform inversion. All the data for both earthquakes are re-sampled at 2 Hz.

We construct the velocity structure models referring to the studies by Iwasaki et al. (2001) and Nakajima et al. (2002). We used a one-dimensional velocity model composed of two surface layers to account for used for the Sendai Plain sediment for the 1978 earthquake, whereas sedimentary surface layers varying with stations are added to the one-dimensional model on the basis of the borehole log data (NIED) in the case of the 2005 earthquake.

3. Inversion method and Fault models

Basically, we use the same linear inversion method described in the previous study (Wu and Takeo, 2004). In case of the 2005 earthquake, a joint inversion of strong motion data and teleseismic waveforms is carried out. Weight of the teleseismic waveforms is adjusted to keep the summation of their squared amplitudes (normalized for each component) equal to that of strong motion data. Since the teleseismic waveforms have been transformed into displacement waves, it follows that the weight for teleseismic data is comparatively small. This alignment is based on the fact that displacement waves are much more easily fitted than velocity waveforms. In the case of the 2005 earthquake, we follow the wave field formula for buried receivers (Kennett and Kerry, 1979) and calculate Green's functions for the underground receivers. Those for teleseismic waves are computed using the method proposed by Kikuchi and Kanamori (1982).

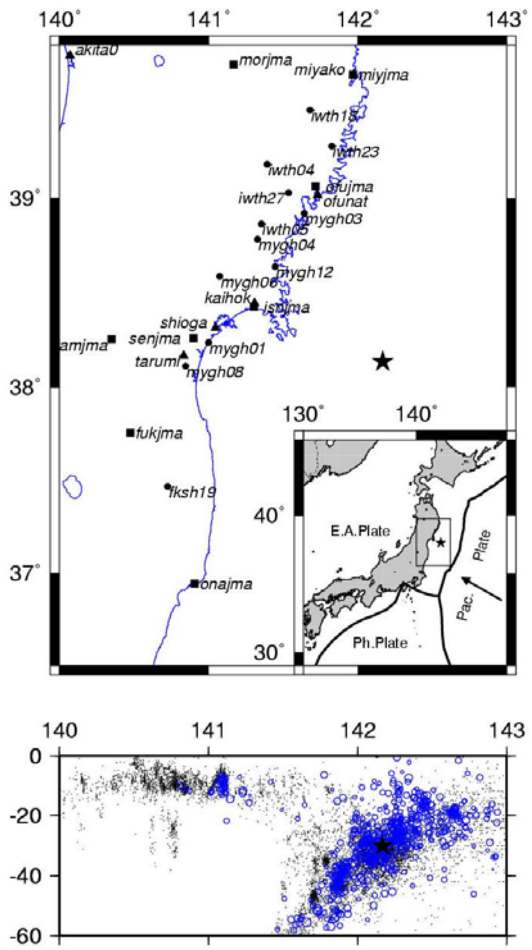

Figure 1. Tectonic settings and station map for the Miyagi-ken Oki earthquakes. Circles mean the strong motion stations for the 2005 earthquake. Squares mean stations for the 1978 earthquake. The asterisk is the epicenter. E.A. Plate means Eurasian Plate, N.A. Plate, North America Plate, P. Plate Pacific Plate, and Ph. Plate Philippine Sea Plate.

Referring to studies of Yamamoto et al. (2004), we assume 30km as the hypocenter depth of the 1978 earthquake. Such a depth is 10 km shallower than the JMA location, but consistent with the location result given by Seno et al. (1980). The cross-section illustration in Figure 1 shows the distribution of small earthquakes in this area (observed from October.31, 2002 to March

25, 2003, see Yamamoto et al., 2004). Since several ocean basis seismometers were included in this seismic observation, improvement of the depth resolution is expected. In the case of the 2005 earthquake, the hypocenter located by the Earthquake Research Institute (ERI) is used in this study. To constrain the fault parameters of the 2005 earthquake, we search for CMT solution using teleseismic body wave inversion. The minimum residuals are obtained when the depth is 36km, strike 211°, and dip 23°.

4. Inversion results

Our inversion results show that the 1978 earthquake starts its rupture at the hypocenter, propagates to the deep part in the southern part. In about 10 seconds, the second rupture occurs in the northern part for a duration of about 12 seconds. From 15 seconds on, the third rupture appears in the deep part under the first rupture. A seismic moment of 2.5×10^{20} Nm is released in about 26 seconds. This rupture pattern is similar to the three segment model proposed by Seno et al. (1980). The large slip (maximum 2.0m) is confined in the northern part and the relatively small slip in the southern part, whereas there was little slip in the hypocenter area (Figure 2). Aftershocks occurring in one year are mainly located on the area with small or no slip. Generally, waveform fittings are satisfactory, except at stations Akita, Senjma, and Onajma.

In the case of the 2005 earthquake, either for the strong motion data or the teleseismic body waves, we get an excellent fitting, except at station FKSH19 and MYGH10, which appears to be affected by the thick sedimentary layers like the situation of the 1978 earthquake inversion. Our inversion results show that rupture starts from the same place with the 1978 earthquake and propagates to the deep part with at least three small asperities identified, with duration of about 20 seconds. Seismic moments of the 2005 earthquake is 0.64×10^{20} Nm. The slip (maximum 1.2m) as well as the moment of the 2005 event is smaller than those of the 1978 event. Note that this earthquake did not rupture the northern asperity of the 1978 earthquake.

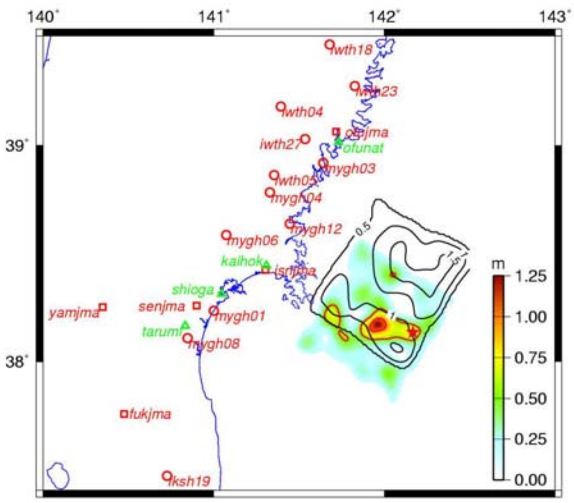

Figure 2. slip distribution map for the Miyagi-ken oki earthquakes. The blue contours are for the 1978 earthquake and the color tones for the 2005 earthquake. The hypocenter is marked by a red circle.

5. Discussion and conclusions

The previous study showed that high quality of the KiK-net seismograms and the proper structure model ensures a successful waveform analysis (Wu and Takeo, 2004). In the case of the 2005 earthquake, the synthetic seismograms fit the observation waveforms excellently. Misfits are observed for two stations located on the southern part, probably due to the over simplification of our one-dimensional structure model. To improve waveform fittings at those stations, a three-dimensional structure model including the sedimentary surface layers and the geometry of the subducting slab is necessary. We, however, did not get such a good fitting for the 1978 earthquake. The difference of fitting results between the 1978 and 2005 earthquakes is mainly from the following aspects. The observation data for the 1978 earthquake are digitized from paper seismograms. A small deviation (commonly observed in the raw seismograms and probably worsened during digitization) from the baseline may cause a large error when the SMAC acceleration seismograms are integrated into velocity ones. Lack of chronometric information is another disadvantage of the seismograms of the 1978 earthquake. For the worse, the SMAC seismograms did not record the beginning of the P waves because the seismographs will not start to record the ground motion unless the ground motion exceeds a triggering value. Lack of the first P phase brings further difficulty to our inversion. We meet a similar problem when we treat the JMA-51/52 displacement seismograms since the preceding P wave phases were so dwarfed by the following S waves that we can not pick up the first arrival of the P wave. Facing the above-mentioned difficulties, we think that the wave fitting for the 1978 earthquake is acceptable by using such a one-dimensional velocity structure.

In this study, hypocenters for the two earthquakes are almost the same. Hypocenter locations used in this study can be directly verified from the seismograms. The observed seismograms of these two earthquakes (Figure 3) are similar to each other in the beginning several seconds. The JMA-51/52 seismograms of the 1978 earthquake were over clipped at those near stations. Instead of filtering both seismograms, we apply a time-domain digital filter, which exactly follows the frequency response of the JMA-51/52 seismometer, to the KiK-net seismograms of the 2005 earthquake recorded at nearby stations. Since the latter is a broadband one compared with the former, it follows that we have reconstructed the JMA-51/52-type records. The similarity observed from the beginning waveforms of these two earthquakes suggests that these two hypocenters are very close. Moreover, using the ERI hypocenter brings out fitting improvement of more than 15 percentages than the JMA location.

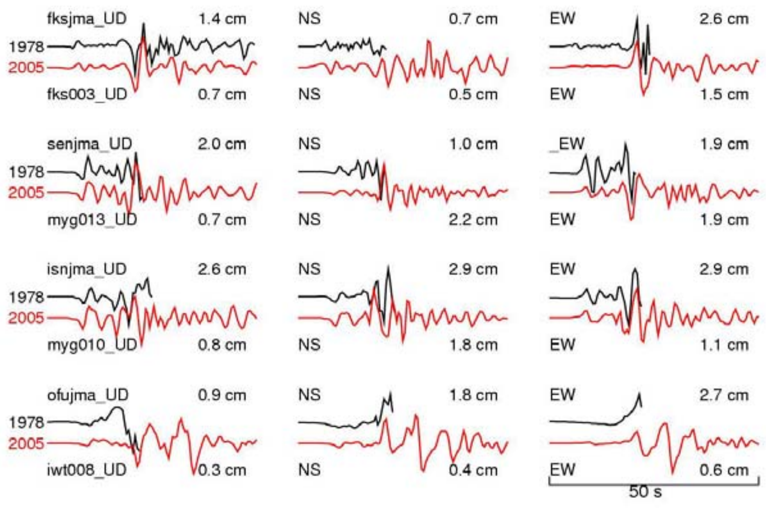

Figure 3 Comparison of observation waves for the two earthquakes. The JMA51/52 seismograms of the 1978 earthquake are in black. Those for the 2005 earthquake are drawn in red after application of devised filter.

Although the 2005 earthquake shared the similar hypocenter with the 1978 earthquake, their rupture patterns are quite different. In the case of the 1978 earthquake, a large asperity is observed in the northern part of the fault plane and comparatively small asperity is observed in the southern part (here we follow the definition of an asperity as the area with large slip). This fault model is similar to the model proposed by Yamanaka and Kikuchi (2004). Contrast to relative simple pattern of the 1978 earthquake, at least three asperities can by identified for the 2005 earthquake from the slip distribution map. Area of the asperities of the 2005 earthquake is comparatively small. Note that asperities of the 2005 earthquake are located in the southern part where it ruptured with similar values of slip in 1978. Large earthquakes repeat on the asperities in and around this area (Yamanaka and Kikuchi, 2004). This study shows that the southern part ruptured in 1978 and 2005 with slip of about 1 meter, while the northern part ruptured only in 1978 with slip of more than 2m. Time interval between the recent two earthquakes is merely 37 years, but the southern part experienced a similar value of slip in 1978 and 2005. It suggests that the coupling factor between the subducting slab and the overriding plate is about 0.5 if we use 8cm per year as the speed of the movement between the Pacific plate and the continental plate in this area. Our results further suggest that rupture pattern of a Miyagi-ken Oki earthquake is very complicated. It may rupture on several small asperities (the 2005 earthquake), or develop to the larger asperities (the 1978 earthquake), or even propagate to the trench side and cause a large tsunami (the 1793 earthquake).

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