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Scaling of short-period source spectrum for earthquakes in mid Niigata, Japan

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Strong motion records at K-NET and KiK-net stations for earthquakes which occurred in the mid Niigata area are analyzed to examine the relationship between the amplitude of the short-period source spectrum and the seismic moment. Large earthquakes radiate more short-period seismic energy per unit seismic moment than small ones, which suggests a deviation from the similarity of earthquake source. Appropriate correction for the deviation from the similarity should be made when we synthesize strong ground motion for future large earthquakes by the empirical Green's function method.

Key words: Short-period source spectrum, similarity of earthquake source, mid Niigata earthquake.

1. Introduction

The similarity of earthquake source assumed in the ω-square model by Aki (1967) approximates well observed source spectrum (e.g., Kanamori and Anderson, 1975; Dan *et al.*, 2001; Ide and Beroza, 2001). It has been used as a basic assumption for the simulation of strong ground motion by the empirical Green's function (EGF) method (e.g., Irikura, 1983). However, observations indicate that the ratio of radiated energy to seismic moment increases with earthquake size (e.g., Kanamori *et al.*, 1993; Abercrombie, 1995; Izutani and Kanamori, 2001; Mayeda *et al.*, 2005; Izutani, 2005a), which suggests a break in the similarity.

Irikura (1986), Yokoi and Irikura (1991), and Irikura and Kamae (1994) introduced a parameter, the stress-drop ratio, into the EGF method to make a correction for the deviation from the similarity between a large and a small earthquake. Although the stress-drop ratio has been applied to the simulation of records for large earthquakes by using their aftershock records as empirical Green's functions (e.g., Masui *et al.*, 1994; Harada *et al.*, 1995; Imanishi *et al.*, 1995; Kamae and Irikura, 1995; Tsurugi *et al.*, 1995), it has not yet been clarified how we should assume the value of stress-drop ratio in synthesizing strong ground motion for future large earthquakes by the EGF method.

Izutani (2005b) analyzed accelerograms observed at K-NET and KiK-net stations operated by the National Research Institute for Earth Science and Disaster Prevention, Japan (NIED) for earthquakes in the northwestern Kagoshima area, the western Tottori area, and the northern Miyagi area. The location of epicenter and the focal mechanism solution for the largest event in each suite of earthquakes are shown in Fig. 1(a). Izutani found that relationship between amplitude of short-period source spectrum and the seismic moment deviates from that expected for the ω-square source scaling model. The larger events radiate more short-period seismic energy per unit seismic moment than the smaller ones.

The mid Niigata earthquake of October 23, 2004 occurred in the central part of Japan, as shown in Fig. 1(a). It was followed by many aftershocks. Since the epicenters of the mainshock and the aftershocks are well surrounded by K-NET and KiK-net stations, there are a large quantity of high-quality close-in records for these earthquakes. In the present study, we examine whether short-period source spectra for these earthquakes show such a deviation from the similarity as was found by Izutani (2005b). We also discuss how we should make a correction for the deviation from the similarity in synthesizing strong ground motion for future large earthquakes by the EGF method.

2. Data and Analysis

The earthquakes analyzed in the present study are 33 events of $M_w = 3.3\sim6.6$ which occurred in the mid Niigata area from 1998 to 2004. The origin time and the hypocenter location were determined by Japan Meteorological Agency (JMA). The seismic moment, M_0, the moment magnitude, M_w, and the focal mechanism solution were determined by F-net of NIED. The values of M_0 by F-net are adopted here because the ground acceleration data analyzed in the present study do not have enough signal-to-noise ratio in the low-frequency range to determine M_0 with sufficient accuracy.

Figure 1(b) shows the epicenters of the earthquakes. One of the earthquakes occurred on February 21, 1998, and 31 of them are aftershocks of the mid Niigata earthquake of October 23, 2004. All of the epicenters are located within 10 km from that of the mainshock. According to JMA and F-net, these earthquakes are shallow events and have reverse-faulting, focal mechanism solutions similar to that of the mainshock in Fig. 1(a). Figure 1(b) also shows the locations of the K-NET and KiK-net stations whose accelerograms are analyzed in the present study. They are

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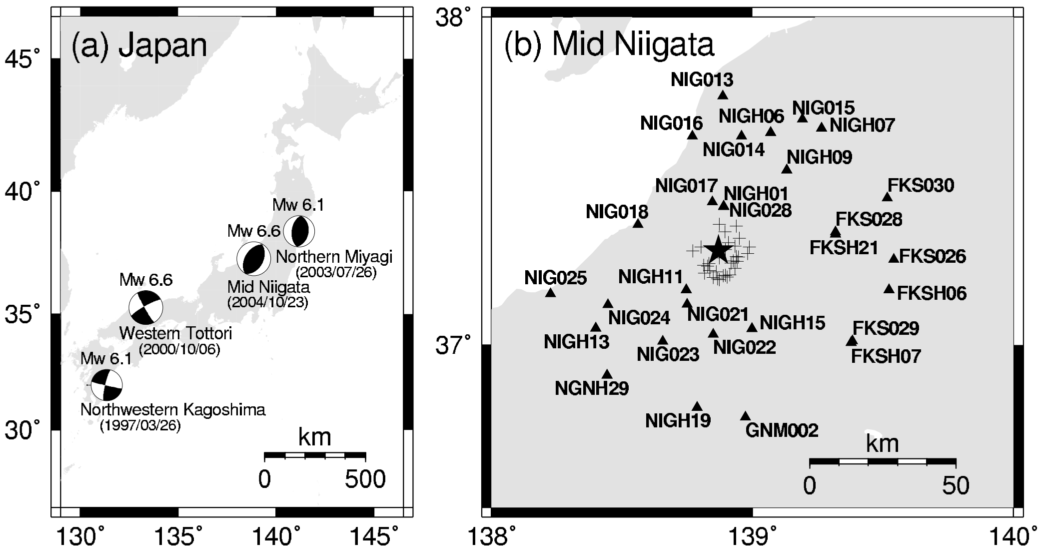

Fig. 1. (a) Location of epicenter and focal mechanism solution for the mid Niigata earthquake of October 23, 2004. The epicenters and the focal mechanism solutions for the northwestern Kagoshima earthquake of March 26, 1997, the western Tottori earthquake of October 6, 2000, and the northern Miyagi earthquake of July 26, 2003 are shown together. (b) Epicenters and observation stations for the earthquakes in the mid Niigata area. star: epicenter of the mid Niigata earthquake of October 23, 2004; crosses: epicenters of the other events; triangles: K-NET and KiK-net stations.

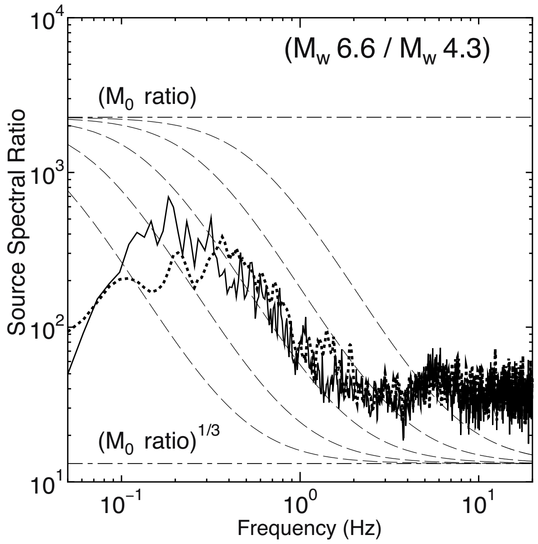

Fig. 2. An example of spectral ratio. Solid curve: observed spectral ratio for 60-s-long records from the first P-wave arrival; dotted curve: observed spectral ratio between 10-s (M_w 6.6 event) and 5-s (M_w 4.3 event)-long records from S-wave onset; upper dot-dash line: ratio of seismic moment between the paired events; lower dot-dash line: the one third power of the seismic moment ratio; dashed curves: spectral ratios expected for ω-square source scaling model with five tentative pairs of corner frequencies.

located between 15 and 60 km from the epicenter of the mainshock and surround the epicenters of the earthquakes well.

The method of analysis used here is the same as that used in Izutani (2005b). We analyze the transverse component records obtained by rotating the two horizontal components. We windowed 60-s long records from the first P-wave arrival. Since S-wave is dominant on the transverse component, the Fourier spectra obtained from the records are regarded as S-wave spectra of the transverse component ground acceleration. We take the spectral ratio between Fourier spectra of the main shock and one of the other events to obtain source spectral ratio by removing the effects of radiation pattern, path, and site.

The obtained spectral ratios for the same paired events vary from station to station. This variation is due to some factors which are not perfectly removed by the above procedure, such as the directivity effect, effects of the small difference in focal mechanisms, and the small difference in hypocenter locations. Assuming that the influence of these factors is removed by taking average of logarithmic amplitudes of the spectral ratios at stations well distributed around the epicenters, we regard the average spectral ratio as the source spectral ratio.

An example of spectral ratio is shown in Fig. 2. The solid curve in Fig. 2 shows the spectral ratio of the records. Since the ω-square source scaling model assumes

$$M_0 \propto f_0^{-3} \tag{1}$$

between the seismic moment, M_0, and the corner frequency, f_0, the theoretical source spectral ratio expected for the ω-square source scaling model approaches M_{01}/M_{0i} in the low-frequency range and $(M_{01}/M_{0i})^{1/3}$ in the high-frequency range, where 1 and i stand for the mainshock and one of the other events. The upper and lower dot-dash lines in Fig. 2 show M_{01}/M_{0i} and $(M_{01}/M_{0i})^{1/3}$, respectively, and the dashed curves show spectral ratios expected for the ω-square source scaling model with five tentative pairs of f_{01} and f_{0i}.

The observed spectral ratio does not approach M_{01}/M_{0i} but falls in the low-frequency range. Since the signal-to-noise ratio for small events at low frequencies is poor, the spectral ratio at frequencies lower than 0.5 Hz is not reliable. We deal with not the spectral ratio in the low-frequency range but the short-period spectral ratio in the frequency range from several Hz to 10 Hz. Judging from the

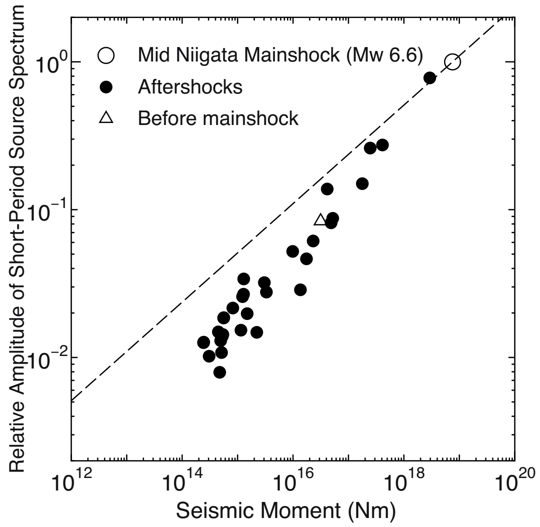

Fig. 3. Relative amplitude of short-period source spectrum, $\tilde{A}$, plotted against the seismic moment for the earthquakes in the mid Niigata area. $\tilde{A}$ for the mid Niigata earthquake of October 23, 2004 is fixed at 1.0. The dashed line indicates the expectation for the ω-square source scaling model.

shape of the observed spectral ratio, this frequency range is higher than the corner frequency of the smaller event. If the earthquake sources of the paired events are similar to each other, it is expected that the short-period source spectral ratio becomes $(M_{01}/M_{0i})^{1/3}$. However, the spectral ratio of the records is larger than $(M_{01}/M_{0i})^{1/3}$ in the high-frequency range, which suggests a break in the similarity. The amplitude of short-period source spectrum of the mainshock is too large or that of the smaller event is too small in comparison with the expectation for the ω-square source scaling model.

The dotted curve in Fig. 2 shows an observed spectral ratio between the 10-s ($M_w = 6.6$ event) and 5-s ($M_w = 4.3$ event) long records from S-wave onset. Although spectral ratios calculated strictly for S-waves may be preferable for the study on source spectrum (e.g., Iwata and Irikura, 1986, 1988), the difference between the spectral ratios for different time windows shown by the solid and the dotted curves in Fig. 2 is very small in the frequency range dealt with in the present study. Since we aim at a comparison of the present result with that by Izutani (2005b), we adopt the same time window as that used by Izutani (2005b), that is 60 s from the first P-wave arrival.

3. Results

Figure 3 shows the relative amplitude of the short-period source spectrum, $\tilde{A}$, plotted against the seismic moment. The open circle in the figure indicates $\tilde{A}$ for the mainshock and is fixed at 1.0. The solid circles show $\tilde{A}$'s for the aftershocks, and the open triangle shows $\tilde{A}$ for the event which occurred before the mainshock. The dashed line indicates the expectation for the ω-square source scaling model, that is,

$$\tilde{A} = (M_{0i}/M_{01})^{1/3}. \qquad (2)$$

The plots for events whose seismic moments are smaller than 10^{18} Nm are located below the dashed line without exception, which suggests that the short-period source spectra for the small events are smaller than those expected from the similarity of earthquake source.

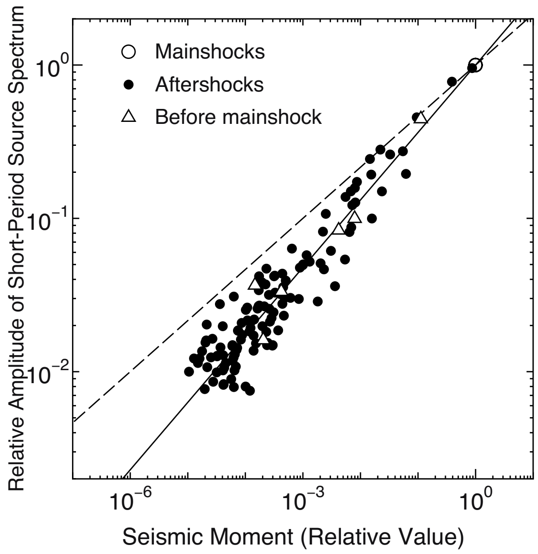

Fig. 4. Relationship between the relative amplitude of the short-period source spectrum, $\tilde{A}$, and the relative value of seismic moment, $\tilde{M}_0$. The result of the present study for earthquakes in the mid Niigata area and those by Izutani (2005b) for earthquakes in the northwestern Kagoshima area, the western Tottori area, and the northern Miyagi area are compiled. $\tilde{A}$ and $\tilde{M}_0$ for the largest event in each area are fixed at $\tilde{A} = 1.0$ and $\tilde{M}_0 = 1.0$. The dashed line indicates the expectation for the ω-square source scaling model. The solid line indicates the result of regression analysis, $\tilde{A} = \tilde{M}_0^{0.435}$, in Eq. (4).

There is no clear difference between the aftershocks and the event which occurred before the mainshock. Also, the result is very similar to those for earthquakes in the northwestern Kagoshima area, the western Tottori area, and the northern Miyagi area obtained by Izutani (2005b) despite the difference in focal mechanism and the difference in tectonic environment.

4. Discussion

Figure 4 compiles the results of the present study and those of Izutani (2005b). The vertical axis shows the relative amplitude of the short-period source spectrum, $\tilde{A}$, and the horizontal axis shows the relative value of the seismic moment, $\tilde{M}_0$. $\tilde{A}$ and $\tilde{M}_0$ are both fixed at 1.0 for the largest event in each area, as shown with the open circle in Fig. 4. The solid circles indicate $\tilde{A}$'s for aftershocks. $\tilde{A}$'s for six events (three events in the western Tottori area, two events in the northern Miyagi area, and one event in the mid Niigata area) which occurred before the mainshock in each area are shown with the open triangles. There is no clear difference between the six events and the aftershocks.

If earthquake sources in each area are similar,

$$\tilde{A} = \tilde{M}_0^{1/3} \qquad (3)$$

is expected. Equation (3) is shown by the dashed line in Fig. 4. The plots in the figure obviously deviate from the dashed line. The linear regression line between $\log\tilde{A}$ and $\log\tilde{M}_0$ is obtained as,

$$\tilde{A} = \tilde{M}_0^{0.435\pm0.004}, \qquad (4)$$

which is shown by the solid line in Fig. 4. The solid line explains the observation better than the dashed line. Large earthquakes radiate more short-period seismic energy per unit seismic moment than small ones, which suggests a deviation from the similarity of earthquake source. The deviation from the similarity may be due to the heterogeneity of the source of large earthquakes because heterogeneous source models radiate more high-frequency seismic energy than homogeneous source models (e.g., Hirasawa, 1979; Izutani, 1981; Papageorgiou and Aki, 1983). There is a difference by a factor of about 2 in $\tilde{A}$ between Eqs. (3) and (4) at $\tilde{M}_0 = 10^{-3}$. This suggests that we shall underestimate short-period strong ground motion for a large earthquake by a factor of about 2 if we synthesize it from records of a event whose seismic moment is 10^{-3}-fold of the large event by using the EGF method with the similarity assumption.

Izutani (1998) examined the relationship between the amplitude of short-period source spectrum and the JMA magnitude for shallow earthquakes around Japan. He also compiled values of the stress-drop ratio assumed in the studies for earthquakes in and around Japan by Masui *et al.* (1994), Harada *et al.* (1995), Imanishi *et al.* (1995), Kamae and Irikura (1995), and Tsurugi *et al.* (1995) and obtained

$$\log\tilde{A} = 0.65 M_D, \tag{5}$$

where M_D is the difference in JMA magnitude between a large and a small earthquakes.

The relationship between the seismic moment and the moment magnitude is (Kanamori, 1977)

$$\log M_0 = 1.5 M_w + 9.1. \tag{6}$$

Assuming a similar relationship as Eq. (6) between the seismic moment and JMA magnitude,

$$\log\tilde{M}_0 = 1.5 M_D. \tag{7}$$

is expected. Inserting (7) into (5),

$$\tilde{A} = \tilde{M}_0^{0.433} \tag{8}$$

is obtained. This is very close to the present result of Eq. (4). Therefore, it is suggested that Eq. (4) represents a general feature of short-period source spectrum for shallow earthquakes in and around Japan.

We should make an appropriate correction for the deviation from the similarity of earthquake source when we synthesize strong ground motion for future large earthquakes by the EGF method. If we have accurate knowledge about the stress drop of a small earthquake whose records are used as EGF, the stress-drop ratio could be obtained as the ratio between an assumed value of stress drop for a future large earthquake and the stress drop of the small earthquake. However, stress drop of small earthquakes can scarcely be determined because it is very difficult to estimate the source dimension of small earthquakes. Therefore, for the present, it is hardly to be expected to know the stress-drop ratio deterministically.

Equation (8) gives an empirical relationship between the stress-drop ratio, C, and the relative value of seismic moment, $\tilde{M}_0$. According to Irikura and Kamae (1994),

$$\tilde{A} = 1/CN, \tag{9}$$

and

$$\tilde{M}_0 = 1/CN^3, \tag{10}$$

where N is a constant. From Eqs. (9), (10) and (8),

$$C \simeq \tilde{M}_0^{-0.15} \tag{11}$$

is obtained. When we synthesize strong ground motion for a future large earthquake from records of a small earthquake whose seismic moment is 10^{-3}-fold of the large earthquake, $C \simeq 3$ is recommended as a first approximation.

5. Conclusion

The relationship between the amplitude of the short-period source spectrum and the seismic moment for earthquakes which occurred in the area of the 2004 mid Niigata earthquake is examined. The result is very similar to those for earthquakes in the northwestern Kagoshima area, the western Tottori area, and the northern Miyagi area obtained by Izutani (2005b). Large earthquakes radiate more short-period seismic energy per unit seismic moment than small ones, which suggests a deviation from the similarity of earthquake source. Therefore, it is important to make an appropriate correction for the deviation from the similarity when we synthesize strong ground motion for future large earthquakes by the EGF method.

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