Characteristics of Source Spectra of Moderate Earthquakes in a Subduction Zone along the Pacific Coast of the Southern Tohoku District, Japan

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Strong motion records for 22 earthquakes from 1982 to 1987 in the subduction zone off Fukushima Prefecture are analyzed. Magnitude M of the earthquakes ranges from 4.0 to 6.7. The source spectrum of each earthquake is obtained from S-waves in horizontal components. Seismic moment M_0 of each event is evaluated from spectral amplitudes in a low frequency range. Two corner frequencies are identified on the source spectra for 7 events of $M \geq 6$, while source spectra of 15 events of $M < 6$ are characterized by one corner frequency. The first corner frequency f_c of the $M \geq 6$ events satisfies a relation of $M_0 \propto f_c^{-3}$, which is consistent with the data of seismic moment and fault area for the $M=7$ to 8 class events in the 1938 large earthquake sequence off Fukushima Prefecture. Complicated S-wave forms for $M \geq 6$ events suggest that the second corner frequency f_c^* is related to the complex faulting process with small-scale fault heterogeneities. This means that f_c^* corresponds to the patch corner frequency. It is found that the seismic moment density M_0^* at a frequency of f_c^* is correlative to the excitation of high frequency waves, while the values of f_c^* are nearly constant, about 1 Hz, for all the $M \geq 6$ events. We found two types of earthquakes with $M \geq 6$ off Fukushima Prefecture: high frequency events and low frequency events. High frequency events show larger peak accelerations than a value expected from the attenuation curve, and show larger M_0^* values compared with low frequency events with the same seismic moment. High frequency events mostly occurred in the northwestern part, while low frequency events occurred in the southeastern part off Fukushima Prefecture. This indicates that the faulting process is more heterogeneous in the northwestern part than the southeastern part. Concerning the events of $M < 6$ which occurred mostly in the northwestern part, simple S-wave forms suggest that those earthquakes are due to a single fault patch rupture process. These events satisfy another relation of $M_0 \propto f_c^{-3}$ on the average, which is different from one for larger events. Stress drop deduced from this relation is about ten times as high as the average stress drop from the M_0 - f_c relation for the event of $M \geq 6$. Higher stress drop of these events may be due to fault patches with large intensity.

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1. Introduction

Excitation of high frequency seismic-waves strongly depends on heterogeneities of slip distribution on a fault plane of an earthquake. These heterogeneities are described by stochastic fault models (e.g., Izutani, 1981; Koyama, 1983; Papageorgiou and Aki, 1983; Suzuki and Hirasawa, 1984). According to these models, source spectra of complex earthquakes are characterized by two corner frequencies: f_c and f_c^* . The first corner frequency f_c is related to the rupturing of the whole fault. The second corner frequency f_c^* is related to the average scale length of heterogeneities on a fault plane (Koyama, 1983, 1984). Irikura and Yokoi (1984), Izutani (1984), Koyama (1983), Papageorgiou (1988), Sato (1985), and Umeda (1981) evaluated values of f_c^* from observed records for local earthquakes and obtained empirical relations between seismic moment M_0 and f_c^* .

An earthquake sequence off Fukushima Prefecture in 1938 includes 3 thrust fault events with magnitude $M=7.0$, 7.5, and 7.3, and 2 normal fault events with $M=7.4$ and 6.9 as well as a large number of $M=6$ class events. M is earthquake magnitude determined by JMA (Japan Meteorological Agency). These were the only earthquakes of $M \geq 7.0$ for at least 800 years (Usami, 1987). Takemura *et al.* (1989) studied strong ground-motion records of moderate-size earthquakes off Fukushima Prefecture in the past several years and also of the 1938 earthquakes. Their results indicate a regional variation of source spectra in the subduction zone off Fukushima Prefecture. For example, the April 7, 1987 event of $M=6.6$ is classified as a high frequency event and the Feb. 6, 21h, 1987 event of $M=6.4$ is classified as a low frequency event. Peak acceleration from the former event is about 8 times as large as that from the latter event at the same observation station.

In the present study, a new data-set of strong motion records is added to the previous data. A further study is made on source spectra of moderate size events off Fukushima Prefecture from the new data-set. Source parameters of M_0 , f_c , f_c^* , and seismic moment density M_0^* at f_c^* are evaluated from obtained source spectra. Furthermore, we will discuss a regional variation of heterogeneities on a fault plane in the subduction zone.

2. A New Data-Set of Strong Motion Records

Epicenters of analyzed earthquakes and location of an observation station are shown in Fig. 1. Date of occurrence is shown for the events of $M \geq 6$. The observation station IWK (Iwaki), comprising a vertical array of accelerometers in the depth range from 0 to 330 m, was established in 1982 (Omote *et al.*, 1984). A velocity-type strong motion seismometer was also installed in 1985 at 21 m depth in a stratum of the period of Oligocene. The stratum is characterized by a shear-wave velocity of 1.2 to 1.4 km/s. The data in this study are obtained from the accelerometer for 11 events from Aug. 1982 to July 1985 and also from the velocity-type seismometer for 11 events from Aug. 1985 to April 1987. Both the instruments are installed at 21 m depth.

Table 1 lists the earthquakes in this study. Magnitude M ranges from 4.0 to 6.7 and hypocentral distance X to IWK ranges from 48 to 142 km. Figure 2 shows examples

Fig. 1. Location of a station and epicenters of analyzed events. Date of occurrence is shown for each event of $M \geq 6$, where M is the JMA magnitude. Dotted line is a boundary between the northwestern part and the southeastern part determined by Takemura *et al.* (1989), based on regional differences of an excitation of high frequency waves obtained for moderate size earthquakes.

of observed records. It is found that the S-wave form for the April 7, 1987 event of $M = 6.6$ is very complicated, compared with that for the Oct. 14, 1986 event of $M = 5.7$.

Figure 3 also shows velocity seismograms integrated from observed accelerograms at other stations near IWK and at the deepest point (GL-330 m) of IWK for two events: the April 7, 1987 event of $M = 6.6$ and the Dec. 19, 1984 event of $M = 5.3$. These two earthquakes locate at almost the same place. All the records are observed on or in the basement of granite with a shear-wave velocity of 2.0 to 2.8 km/s. The basement is located at 310 m depth at IWK and 920 m depth at TMK, and outcrops at the other stations. We can also find that the S-wave form for the 1987 event is very complicated at every station, compared with that for the 1984 event. This complex nature of S-wave forms is commonly found on records of events of $M \geq 6$. These results suggest that the complicated wave-forms for events of $M \geq 6$ are mainly due to multiple shocks at their sources.

3. Method of Analysis

A cosine tapered data-window is applied to S-waves on horizontal components (Takemura *et al.*, 1989). The length of the data window is from 3 to 20 s, which is

Table 1. List of the analyzed events. H and X show a focal depth and a hypocentral distance for each event, and M_0 and f_c show a seismic moment and a corner frequency.

Date	M	H (km)	X (km)	$M_0 \times 10^{23}$ (dyn·cm)	f_c (Hz)
82 Aug. 28 21:12	4.9	60	64	3.3	2.4
82 Sep. 14 3:03	5.0	60	90	2.4	1.6
83 May 24 2:55	5.8	42	142	12	1.1
83 Jul. 2 7:03	5.8	54	64	23	1.2
83 Nov. 16 19:44	5.3	39	85	5.3	1.1
84 Mar. 26 3:59	5.2	42	86	4.2	1.7
84 May 1 10:15	5.2	46	92	4.7	1.4
84 Dec. 18 1:07	4.0	37	48	0.17	4.3
84 Dec. 19 4:35	5.3	44	75	8.4	1.5
84 Dec. 19 4:50	4.5	45	70	0.41	3.0
85 Jul. 29 4:33	5.5	90	95	27	1.5
85 Aug. 12 12:49	6.4	52	124	320	0.13*
86 Feb. 12 11:59	6.1	44	88	180	0.12*
86 Oct. 14 6:17	5.7	52	60	38	0.90
87 Feb. 6 21:23	6.4	30	99	660	0.11
87 Feb. 6 22:16	6.7	35	97	1,800	0.10
87 Feb. 13 19:01	5.2	48	72	4.8	2.3
87 Apr. 7 9:40	6.6	37	100	1,100	0.096*
87 Apr. 17 4:23	6.0	42	77	170	(0.066*)
87 Apr. 23 5:13	6.5	49	81	830	0.12*
87 Apr. 24 13:32	4.6	52	78	0.86	3.1
87 Apr. 30 22:46	5.1	54	76	3.9	1.6

* First corner frequency. Parentheses indicate the value evaluated from only the EW component of the spectrum.

determined from a duration time of faulting estimated empirically. Seismic moment density $M(f)$ as a function of frequency f is obtained from a Fourier amplitude spectrum $U_o(f)$ of S-wave in the frequency range from 0.03 to 20 Hz to evaluate seismic moment and corner frequencies of each earthquake.

Generally speaking, a far-field amplitude spectrum $U_s(f)$ of S-waves within an infinite homogeneous elastic medium can be expressed in terms of the seismic moment density $M(f)$ as follows (Kanamori, 1972):

$$U_s(f) = R_{\theta\phi} M(f) / (4\pi\rho V_s^3 X), \quad (1)$$

where $R_{\theta\phi}$ is a point-source radiation coefficient, X is a hypocentral distance, and V_s and ρ are shear-wave velocity and density of the medium, respectively. Amplitude spectrum $U_o(f)$ obtained from an observation may be related to $U_s(f)$ as follows:

$$U_o(f) = U_s(f) H_1(f) H_g(f) \exp(-\pi f X / (Q_s V_s)), \quad (2)$$

where $H_1(f)$ and $H_g(f)$ are Fourier amplitude spectra of the instrumental response and the ground response. The exponential term in Eq. (2) is a correction for the seismic energy attenuation. Q_s is an average quality factor for S-waves.

Considering an average radiation coefficient of SH and SV waves for a dip-slip

Fig. 2. Examples of analyzed velocity seismograms observed at IWK station for the Oct. 14, 1986 event of $M=5.7$ and the April 7, 1987 event of $M=6.6$. Bars indicate the parts of S-waves used for the spectral analysis.

S-waves in NS comp.

Fig. 3. Velocity seismograms in NS component integrated from accelerograms at TMK, IDG, HKD, KDG, and IWK stations for the Dec. 19, 1984 event of $M=5.3$ and the April 7, 1987 event of $M=6.6$. All of them are recorded on or in the basement of granite, with a shear-wave velocity of 2.0 to 2.8 km/s. The basement is located at 920 m depth for TMK and at 310 m depth for IWK, and outcrops at the other stations. The arrows indicate the S-wave onset times.

fault (Boore and Boatwright, 1984), $R_{\theta\phi}$ is assumed to be 0.4. It is further assumed that $H_g(f)$ is 2.0, though the seismometers are located at 21 m depth. This is because the natural frequency of surface layers over the seismometers is about 10 Hz (Omote *et al.*, 1984) and the records in this study are not significantly affected by the effect of surface layers in a frequency range lower than 10 Hz. Furthermore, the assumption of $H_g(f)=2$ is consistent with an amplification factor of S-waves from the basement at 310 m depth (Takemura *et al.*, 1991) within a factor of 1.5. The accelerometers and the velocity-type seismometer in IWK are servo-controlled instruments with flat frequency characteristics from 0.03 to 30 Hz. The value of $H_l(f)$ can be expressed as $H_l(f)=(2\pi f)^2$ for the accelerometer and $H_l(f)=2\pi f$ for the velocity-type seismometer in the frequency range of analyses from 0.03 to 20 Hz.

4. Results

4.1 Source spectra

Figure 4 shows spectral amplitudes for the Oct. 14, 1986 and the April 7, 1987 events. Corresponding record sections are indicated by bars in Fig. 2. The spectra are corrected for $H_l(f)$ and for the effect of seismic energy attenuation. The Q_s -value for the attenuation correction is assumed to be 500 (Umino and Hasegawa, 1984). From these spectra, we can see the frequency characteristics of source spectra, because $H_g(f)$ is 2.0, irrespective of frequency f . It is found that the corrected spectrum for the April

Fig. 4. Spectra of the Oct. 14, 1986 and the April 7, 1987 events corrected for the frequency characteristics of instrument $H_l(f)$ and for the effect of seismic energy attenuation due to the Q_s -value. The 1987 event of $M=6.6$ has two corner frequencies: f_c and f_c^* , while the 1986 event of $M=5.7$ has one corner frequency f_c .

7, 1987 event has two corner frequencies: f_c and f_c^* , where the spectral envelope changes its general trend. Meanwhile, that for the Oct. 14, 1986 event is characterized by only one corner frequency f_c . The corrected spectra for all the events are summarized in Appendix. Two corner frequencies are always found on spectra of all the events of $M \geq 6$, while all the events of $M < 6$ follow the simple ω^{-2} model with one corner frequency (Aki, 1967; Sato and Hirasawa, 1973).

It is also found from the spectra without the attenuation correction that one corner frequency characterizes source spectra of $M < 6$ earthquakes and that two corner frequencies for $M \geq 6$ events. This is because hypocentral distances of almost all the events are shorter than 100 km. These results indicate that the attenuation correction does not strongly affect the present conclusion.

In addition to the analysis of S-waves, P-wave spectra are also examined to confirm two corner frequencies on source spectra of the events of $M \geq 6$. Velocity records of P-waves in vertical component at the same depth of the IWK station are analyzed in the same manner as for S-waves. The data window for P-waves is somewhat shorter than that for S-wave analysis, because S-P time is about 7 to 12 s for all the events. Figure 5 shows examples of P-wave spectra corrected for $H_i(f)$. Solid lines indicate envelopes for S-wave spectra in the NS and EW components divided by a factor of $(V_s/V_p)^{-3}$, where the value of V_p/V_s is assumed to be 1.73. The envelopes for the S-wave spectra are referred from Fig. 4 and Appendix, which are used as a reference to identify the corner frequencies on the P-wave spectrum. Two corner frequencies are found for P-wave spectra in the same manner as for the cases of S-wave spectra. The same results

Fig. 5. P-wave spectra corrected for the frequency characteristic of instrument $H_i(f)$ for the April 7, 1987 and the Feb. 6 21h, 1987 events. Solid lines indicate the envelopes for the S-wave spectra divided by the factor of $(V_s/V_p)^{-3}$. V_p/V_s is assumed to be 1.73.

Table 2. Second corner frequency f_c^* and seismic moment density M_o^* at the frequency of f_c^* for the events of $M \geq 6$.

Date	M	$M_o^* \times 10^{23}$ (dyn · cm)	f_c^* (Hz)	$HML^{1)}$
85 Aug. 12 12:49	6.4	45	1.0	<i>M</i>
86 Feb. 12 11:59	6.1	29	0.90	<i>L</i>
87 Feb. 6 21:23	6.4	32	0.94	<i>L</i>
87 Feb. 6 22:16	6.7	54	1.2	<i>L</i>
87 Apr. 7 9:40	6.6	146	0.92	<i>H</i>
87 Apr. 17 4:23	6.0	(23)	(0.76)	<i>L</i>
87 Apr. 23 5:13	6.5	60	1.3	<i>H</i>

¹⁾ Letters *H*, *M*, and *L*, mean high, medium, and low frequency events classified by Takemura *et al.* (1989). Parentheses indicate the value evaluated from only the EW component of the spectrum.

are obtained for the other $M \geq 6$ events. These results also support that two corner frequencies on the wave spectra for the $M \geq 6$ events are due to the complex faulting process of large earthquakes and not to the wave propagation effect.

Koyama (1983,1984) and Suzuki and Hirasawa (1984) introduced the second corner frequency f_c^* and seismic moment density M_o^* at f_c^* to represent the heterogeneity of the fault plane of complex earthquake sources. Furthermore, the importance of these parameters has been pointed out by Izutani (1984) on the excitation of strong ground motion. Therefore, we measure not only seismic moment M_o and corner frequency f_c but also M_o^* and f_c^* from the corrected spectra as shown in Fig. 4 and Appendix.

4.2 Seismic moment and corner frequencies

The seismic moment M_o is evaluated from the spectral amplitude in a frequency range below f_c , and the value of M_o^* is from the spectral amplitude at f_c^* . We assume the shear-wave velocity V_s of 4.0 km/s and the density ρ of 3 g/cm³ in the present analysis. Estimated values of M_o and f_c are summarized in Table 1 and those of M_o^* and f_c^* are summarized in Table 2. They are obtained as an average from two horizontal components, except for the April 17, 1987 event (f_c and f_c^* could not be identified on the spectrum for the NS component for this event).

Figure 6 shows seismic moment M_o obtained in the present study and M_o (HRV) from centroid moment tensor solutions by the group of Harvard University (e.g., Dziewonski *et al.*, 1981), which are reported in Earthquake Data Report by USGS. The solid line in Fig. 6 shows the relation of $M_o = M_o$ (HRV), and the dotted lines show the range of the deviation of a factor of 2 from the relation. Although our seismic moment is obtained from the acceleration/velocity records at one station, it is consistent within a factor of 2 with the HRV-value.

Figure 7 summarizes seismic moments and corner frequencies of earthquakes in this study. Circles indicate f_c for the events of $M < 6$, which have one corner on their source spectra. The values of M_o and f_c in Fig. 7 satisfy a relation of $M_o \propto f_c^{-3}$ on an average. The relation is understood as that a stress drop is constant irrespective of seismic moment (Aki, 1967). The dotted line indicates the best fit relation for them as

Fig. 6. Seismic moment M_o obtained in the present study and M_o (HRV) from centroid moment tensor solution by the group of Harvard University (e.g., Dziewonski *et al.*, 1981). Solid line shows a relation of $M_o = M_o$ (HRV) and dotted lines show the range of the deviation of a factor of 2 from the relation.

Fig. 7. Relation between seismic moment and corner frequencies. Squares indicate the corner frequencies evaluated from fault areas for the events in the large earthquake sequence in 1938. Open and solid triangles indicate the first corner frequencies f_c and the second corner frequencies f_c^* for the events of $M \geq 6$, respectively. Parentheses distinguish the data for the April 17, 1987 event because of the uncertainties. Circles indicate the corner frequencies f_c for the events of $M < 6$. Solid line indicates the M_o - f_c relation from Eq. (6) and dotted line from Eq. (3).

$$\log M_0 = -3 \log f_c + 24.26. \quad (3)$$

This relation indicates a higher corner frequency for the same seismic moment than the value from a relation for local earthquakes in California obtained by Hanks and McGuire (1981).

Open and solid triangles show f_c and f_c^* for the events of $M \geq 6$, respectively. A parenthesis distinguishes the data for the April 17, 1987 event because of the uncertainties mentioned previously. Squares indicate corner frequency f_c evaluated from a fault radius r for the five earthquakes of $M=7$ to 8 class in 1938. They are estimated from an equation of

$$f_c = 0.3 V_s / r. \quad (4)$$

This relation is obtained from the assumption that the ratio of the rupture velocity to the shear-wave velocity is 0.8, based on the result of the circular crack model by Sato and Hirasawa (1973). Each value of r is calculated from the fault area obtained by Abe (1977). Squares with an asterisk in Fig. 7 indicate normal fault events (Abe, 1977), whose data show no systematic difference from those for the thrust events.

Sato (1979, 1989) obtained empirical relations among source parameters for earthquakes of $M \geq 6.0$, in and around Japan. Most of these events occurred in the subduction zone off the Pacific coast of northeastern Honshu Island. A relation between seismic moment M_0 and fault area S is obtained as

$$\log M_0 = 1.5 \log S + 22.3. \quad (5)$$

The solid line in Fig. 7 indicates a M_0 - f_c relation obtained from Eqs. (4) and (5), assuming $S = \pi r^2$ and $V_s = 4$ km/s, as

$$\log M_0 = -3 \log f_c + 23.28. \quad (6)$$

This relation is consistent with the result by Houston and Kanamori (1986), which is obtained as a reference relation between M_0 and f_c for $M=7$ to 8 class events in the world.

It is found in Fig. 7 that both the first corner frequency f_c for the $M \geq 6$ events and the corner frequency f_c from the earthquake sequence in 1938 are consistent with the relation of Eq. (6). This result suggests that the data of the seismic moment M_0 and the fault area S for the events of $M \geq 6$ off the Pacific coast of northeastern Honshu are well explained by Eq. (5). If we compare Eqs. (3) and (6), there is a constant difference as much as 0.98. This corresponds to a difference of stress drops, since the corner frequency f_c relates to an earthquake source size (Brune, 1970). The stress drop $\Delta\sigma$ of the $M < 6$ events is about 9.5 times as high as that for the $M \geq 6$ events, judging from the constant difference.

Second corner frequencies f_c^* for the $M \geq 6$ events are about 1.0 Hz. This value is almost equal to the corner frequency f_c of the maximum event with one corner on its spectrum.

5. Discussion

Umeda (1981) indicated from P-wave spectra that the second corner frequency f_c^*

is weakly dependent on the earthquake magnitude around the frequency of 5 Hz for the events of M from 4 to 7 in and around Japan. In S-wave spectra, the second corner frequency f_c^* which ranges from 2 to 7 Hz has been obtained by Izutani (1984) for the events of M from 5.5 to 7.4 off the Pacific coast of northeastern Honshu, Japan. Irikura and Yokoi (1984) obtained a relation of $M_0 \propto f_c^{*-6}$ for aftershocks of M from 4 to 6 of the 1983 Nihonkai-chubu earthquakes of $M=7.7$. The value of f_c^* is about 1 Hz for an event of $M=6$. These results show weak or no dependence of f_c^* on magnitude. On the other hand, Koyama (1983) pointed out that f_c^{*} 's for Matsushiro earthquakes with M from 4.2 to 5.1 have a proportionality to $M_0^{1/3}$. Recently, Papageorgiou (1988) also found f_c^{*} 's for the 1979 Imperial Valley event of $M=6.6$ and the 1984 Morgan Hill event of $M=6.1$ in California, which are about 0.4 Hz. These previous results show that f_c^* is roughly estimated about 1 Hz as an average for $M=6$ class event, in spite of large regional variations. The present result is almost consistent with the average.

In the meantime, physical meanings of the second corner frequency f_c^* have been discussed by some authors (Izutani, 1981; Koyama 1983; Papageorgiou, 1988; Suzuki and Hirasawa, 1984). Koyama (1983, 1984) explained the second corner frequency f_c^* in relation to the average scale length of the fault heterogeneities. Patch corner frequency $\lambda (=2\pi f_c^*)$ is defined by Koyama (1983) using a stochastic fault model as

$$\lambda = \bar{v}/\bar{d}, \quad (7)$$

where $\bar{d}$ is an average characteristic length of fault patches and $\bar{v}$ is a velocity of the rupture propagation. This explanation is supported in the present study by the fact that the events of $M \geq 6$ whose source spectra have f_c^* show complicated S-wave forms due to the multiple shocks at their sources, while the events of $M < 6$ whose source spectra have one corner show simple wave-forms.

The simple wave-form suggests that the event of $M < 6$ is due to the failure of single fault patch. Therefore, the average stress drop for these events from Eq. (3) probably shows an average intensity of fault patches. This leads us to understand that a stress drop on a fault patch is about 9.5 times as high as the average stress drop $\Delta\sigma$ for the events of $M \geq 6$. Some stochastic parameters: the rms (root mean square) stress drop $E(\tau^2)^{1/2}$ (Izutani, 1981), the variance of dislocation velocity σ^2 (Koyama, 1983), local stress drop $\Delta\sigma_L$ (Papageorgiou and Aki, 1983), and so on, are introduced to measure the intensity of fault patches statistically. Using strong motion records for the events of M from 5.5 to 7.4, Izutani (1984) obtained the average stress drop $\Delta\sigma$ and the rms stress drop $E(\tau^2)^{1/2}$ on the fault plane. His results show the ratios of $E(\tau^2)^{1/2}/\Delta\sigma$ range from 2 to 10. The ratio of the stress drops on the fault patch and fault plane in the present study is almost consistent with his result.

Takemura *et al.* (1989) classified moderate-size earthquakes off Fukushima Prefecture into high (H), medium (M), and low (L) frequency events. These classifications are based on the deviation of strong motion response spectrum for each event from an average value evaluated from an empirical attenuation curve, and are based on the difference between two magnitude scales. Letters H , M , and L in Table 2 indicate this classification. It can be found that the values of M_0^* are correlative to this classification, while f_c^{*} 's do not show any correlation. The values of f_c^{*} 's of all the events are about 1 Hz. Figure 8 shows the values of M_0 and M_0^* of each earthquake. The April 7, 1987

Fig. 8. Seismic moment M_0 and seismic moment density M_0^* at the frequency of f_c^* for the events of $M \geq 6$. Solid circles indicate the high and medium frequency events and open circles the low frequency events, which are classified by Takemura *et al.* (1989). The values with parentheses show the second corner frequencies f_c^* . Date of occurrence is also shown for each event. Solid line indicates a relation of $M_0 \propto M_0^{*2}$ shown as a reference.

earthquake is classified as a high frequency event. It shows M_0^* about 4.6 times larger than the Feb. 6, 21 h, 1987 earthquake of a low frequency event. This contrasts to the fact that the seismic moment M_0 for the former event is only 1.7 times larger than that for the latter event.

Koyama (1983) and Koyama and Zheng (1985) derived the source spectrum S_0 in high frequency range based on the stochastic fault model as

$$S_0 \propto (2\sigma^2 \lambda / (\omega^2 + \lambda^2))^{1/2} W L T_0^{-1/2}, \quad (8)$$

where ω is an angular frequency ($=2\pi f$), σ^2 is the variance dislocation velocity, and L , W , and T_0 are macroscopic source parameters: fault length, fault width, and duration time of dislocation, respectively. Furthermore, the seismic moment can be written as

$$M_0 \propto L W T_0. \quad (9)$$

The value of M_0^* in this study is considered to be equal to S_0 , when $\omega = \lambda$. On the assumption of the similarity rule for the macroscopic parameters L , W , T_0 and that λ is constant, the value of M_0^{*2}/M_0 may be expressed as

$$M_0^{*2}/M_0 \propto \sigma^2. \quad (10)$$

A relation of $M_0 \propto M_0^{*2}$ is shown in Fig. 8 as a reference. Taking Eq. (10) into account, it is found that the high frequency event has large σ^2 value, while the low frequency event has small σ^2 value. Koyama and Izutani (1990) derived a relation between variance of dislocation velocity σ^2 and variance stress drop $\langle \Delta \sigma^2 \rangle$ on the fault plane. According to their results, the large σ^2 value corresponds to the large $\langle \Delta \sigma^2 \rangle$ value for the same

macroscopic parameters and the same patch corner frequency λ . Therefore, the high frequency event is accompanied by, in other words, a large variance of stress drop on the fault plane.

Takemura *et al.* (1989) indicated that high frequency events are distributed in the northwestern part of the region off Fukushima Prefecture and low frequency events in the southeastern part. The boundary between two parts is shown by a dotted line in Fig. 1. Taking the results for σ^2 and $\langle \Delta\sigma^2 \rangle$ into account, the regional differences of the events indicated by Takemura *et al.* (1989) probably show that there is a number of fault patches with large intensity in the northwestern part. Almost all the events of $M < 6$ in this study occurred in the northwestern part (Fig. 1). Higher stress drop of these events may be caused by those fault patches with large intensity.

Koyama and Zheng (1985) estimated a high frequency source-spectrum M_1 at about 1 Hz for large earthquakes which have occurred along subduction zones in the world. An empirical relation of $M_0 \propto M_1^2$ is obtained, in spite of a large variation of the data. Koyama and Zheng (1985) suggested that the large variation of the data is due to the regional differences of the characteristics of heterogeneities on the fault plane. The value of M_0^* evaluated in the present study is almost equivalent to the value of M_1 , because the f_c^* 's are about 1 Hz for all the $M \geq 6$ events. The result for the values of M_0 and M_0^* shown in Fig. 8 is one of the examples for the regional differences of the heterogeneities suggested by Koyama and Zheng (1985).

6. Conclusion

Source spectra are obtained for the 22 earthquakes of $M = 4.0$ to 6.7 which occurred off Fukushima Prefecture from the analysis of S-wave strong motion records. The characteristics of source spectra are summarized as follows:

(1) Source spectra of 7 events of $M \geq 6$ have two corner frequencies, while those of 15 events of $M < 6$ have one corner frequency. Taking into account the complicated S-wave forms for the $M \geq 6$ events, the second corner frequency for these events corresponds to the patch corner frequency (Koyama, 1983), which is caused by multiple shocks at their sources.

(2) The first corner frequency f_c of the events of $M \geq 6$ satisfies a relation of $M_0 \propto f_c^{-3}$, which is consistent with the data of seismic moments and corner frequencies evaluated from fault areas for the $M = 7$ to 8 class events in the 1938 large earthquake sequence.

(3) The second corner frequency f_c^* is almost constant, about 1.0 Hz, for all the events of $M \geq 6$. The seismic moment density M_0^* at f_c^* is correlative to the classification of high, medium, and low frequency events by Takemura *et al.* (1989). The high frequency events in the northwestern part off Fukushima Prefecture show relatively large M_0^* values, compared with the low frequency events in the southeastern part with the same seismic moment. This suggests that the faulting process is more heterogeneous in the northwestern part than the southeastern part, and that there is a number of fault patches with relatively large intensity in the northwestern part.

(4) The events of $M < 6$ satisfy another relation of $M_0 \propto f_c^{-3}$ on an average. The stress drop deduced from this relation is about ten times as high as the average stress

drop from the M_0 - f_c relation for the events of $M \geq 6$. Almost all the events of $M < 6$ occurred in the northwestern part. Higher stress drop of these events may be caused by the fault patches with large intensity.

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APPENDIX

Spectra of All the Analyzed Events Corrected for the Frequency Characteristic of Instrument and for the Effect of Seismic Energy Attenuation

Spectra of observed S-waves at IWK station are corrected for the frequency characteristics of instruments $H_i(f)$ and for the effect of seismic energy attenuation due to the Q -value along the propagation path of seismic waves. From these spectra, we can see the frequency characteristics of source spectra, because the Fourier amplitude spectrum of the ground response $H_g(f)$ can be assumed to be 2.0, irrespective of the frequency.

It is found that the events of $M \geq 6$ have two corner frequencies: f_c and f_c^* , on their spectra, while the events of $M < 6$ have one corner frequency f_c . The spectra are

Fig. A1

Fig. A2

Fig. A3

obtained from records by an accelerometer for the events before July 1985, while those are from records by a velocity-type seismometer for the events after Aug. 1985. Reliability of the records by the accelerometer is relatively low in the low frequency range, compared with the records by the velocity-type seismometer. Steep increases of the spectra as the frequency decreases in the low frequency range are due to the instrumental noise included in the records for the events before July 1985.