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CHARACTERISTICS OF SOURCE SPECTRA OF SMALL AND LARGE INTERMEDIATE DEPTH EARTHQUAKES AROUND HOKKAIDO, JAPAN

Mitsuya NAKATA[1], Daisuke SAKAMOTO[1], Takashi IKEDA[2], Masayuki TAKEMURA[2] and Kenichi KATO[2]

SUMMARY

Source spectra of intermediate depth earthquakes around Hokkaido are investigated. The analyzed events occurred at the lower seismic zone in the subducting slab beneath Hidaka and Kushiro region of Hokkaido, Japan and had the down dip extension type focal mechanisms. Their magnitudes MJ by Japan Meteorological Agency (JMA) ranged from 5.1 to 7.5 and they include the 1987 Hidaka earthquake (MJ6.6) and the 1993 Kushiro-oki earthquake (MJ7.5). Source spectra of these events are estimated from observed strong motion records on the rock. We can find two corner frequencies on the source spectra of the 1987 Hidaka earthquake and the 1993 Kushiro-oki earthquake, while the other small events have one corner frequency on their source spectra. The relationship between seismic moment and the corner frequency for the small events follows $\Delta\sigma$=30MPa as the Brune's stress drop, which also explains the seismic moment and the first corner frequency of the big ones. This implies that the second corner frequencies are strongly related to larger excitations of high frequency waves from the big events than those from the smaller events.

INTRODUCTION

The 1993 Kushiro-oki earthquake (MJ=7.5) is one of the typical damage earthquakes in the Hokkaido area, which is an intermediate depth earthquake, while other damage earthquakes usually belong to inter-plate earthquakes or inland shallow earthquakes. Large intermediate depth earthquakes have occurred frequently around Hokkaido, compared with the other areas in Japan [1].

According to the previous studies, a large excitation of strong ground motion in a high frequency range is one of the characteristics of intermediate depth earthquakes. Takemura [2] investigated the 1993 Kushiro-oki earthquake about the observed peak accelerations, and Kato et al. [3] also investigated other intermediate depth earthquakes occurring in the Tohoku and Kanto areas. They indicated that peak accelerations from the intermediate depth earthquakes are larger than those from shallow earthquakes (generally within 60km in depth) for the same JMA magnitude. Furthermore, Kato et al. [4] investigated source spectra of intermediate depth earthquakes by the spectrum inversion method, and indicated that the intermediate depth earthquakes beneath the Kanto area have large Brune's stress drops $\Delta\sigma$ and large

[1] Electric Power Development Co., Tokyo, Japan
[2] Kobori Research Complex, Kajima Co., Tokyo, Japan

excitations of ground motions in high frequency range, compared with shallower earthquakes occurred at off shore-Fukushima Prefecture and Southern Kanto District. Recently, Ikeda et al. [5] derived a scaling relation of source spectra from the intermediate depth earthquakes around Hokkaido, then indicated that $\Delta\sigma$ of intermediate depth earthquakes is larger than that of shallow earthquakes as indicated by Kato et al. [3] [4]. Most of these shallow earthquakes are inter-plate earthquakes in the subduction zone of the Pacific plate. Ikeda et al. also indicated that the values of $\Delta\sigma$ from large intermediate depth earthquakes are larger than those of small ones, which implies that the large and small intermediate depth earthquakes have different scaling relations of source spectra.

The previous studies mentioned above were investigated on the assumption that source spectra can be expressed by Brune's ω^{-2} model [6]. This assumption has been adopted to easily measure the strength of source spectra at high frequency. However, we have known that source spectra of large earthquakes don't follow the ω^{-2} model [7] [8]. Mahdavian and Sasatani [7] derived the source spectra from small and middle size events with MJ=3.7 to 6.4, which occurred around Hokkaido at about 40km to 130km depth, and they also derived the source spectrum from the 1993 Kushiro-oki earthquake (MJ=7.5). They obtained seismic moments Mo and corner frequencies fc for all the events, and concluded that the source spectra of small and middle size events could be shown by the ω^{-2} model, but the source spectrum of the 1993 Kushiro-oki had two corner frequencies, which couldn't be expressed by the ω^{-2} model. Two corner frequencies of source spectra had been indicated by Takemura et al. [8] as a common characteristic of inter-plate earthquakes with MJ larger than 6.0 from the data set for the earthquakes occurring off the coast of Fukushima Prefecture. However, Mahdavian and Sasatani [7] couldn't confirm whether the source spectrum with two corner frequency is a common characteristic of large intermediate depth earthquakes or not, because their data set didn't include the other large intermediate depth earthquake.

To solve this problem, we need a continuous long-term earthquake observation to get a lot of records of large events at a rock site near Hokkaido, where strong ground motion is not so much affected by the site effect. The observation at the OMA site located at the northern end of Shimokita Peninsula in Aomori Prefecture is satisfied with these conditions. In the present study, source spectra will be estimated from the records at OMA for large and small intermediate depth earthquakes to investigate the details of spectral structures of seismic waves excited from the sources of the intermediate depth earthquakes.

ANALYZED EVENTS AND OBSERVED RECORDS

Figure 1 shows the epicenters of analyzed events and focal mechanisms. The epicenters and focal mechanism solutions are reported by JMA and by Harvard University, respectively. All the events are intermediate depth earthquakes with down-dip extension (DE) type mechanism, which occurred at the lower seismic zone in the subducting slab beneath Hokkaido. Their magnitudes range from MJ=5.1 to 7.5. The location of the OMA site is shown by a solid square in this figure. It is found two earthquakes occurred around the Hidaka region. One of them is the 1987 Hidaka earthquake (MJ=6.6). And four earthquakes occurred around the Kushiro region including the 1993 Kushiro-oki earthquake (MJ=7.5). Table 1 shows the source parameters of analyzed events. Where D and Δ represent the depth of hypocenter and the epicentral distance at OMA , respectively.

The seismometers at OMA consist of two vertical arrays, whose deepest observation depths are GL-200m and GL-240m in the Tertiary rock, and they have some other observation points between the ground level and the deepest point. Subsurface observation records are usually influenced by the reflected waves from the ground surface. Therefore, we apply the 1-D multi-reflection theory to the observation records at GL-200m and GL-240m to obtain the outcrop motion of the rock. Table 2 shows the used subsurface structure models, and Fig. 2 shows the examples of calculated outcrop motions on the Tertiary rock from the observation records at GL-200m and GL-240m.

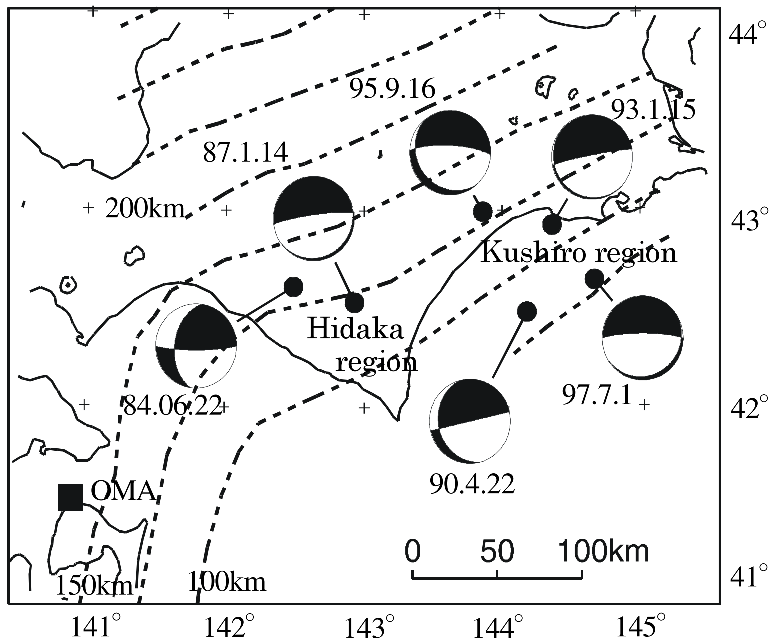

Fig 1 : Observation station and epicenter distribution of events analyzed in this study. Dotted lines represent depth of lower seismic plane.[13)]

Table 1 : Lists of events analyzed in this study

Date			Lat. (N)	Long. (E)	D (km)	Δ (km)	MJ	Mo (Nm)	fc (Hz)	fc* (Hz)	FLC (Hz)	FHC (Hz)	O.D. (m)
1984	6	22	42.61	142.49	103	177	5.3	8.8e+16	1.5	-	0.1	25	200
1987	1	14	42.53	142.93	119	201	6.6	1.7E+19	0.3	3.0	0.1	35	200
1990	4	11	42.48	144.17	69	289	5.5	2.4E+17	0.7	-	0.1	25	240
1993	1	15	42.92	144.36	101	324	7.5	2.7E+20	0.1	1.5	0.1	35	240
1995	9	16	42.99	143.86	112	293	5.2	6.6E+16	1.2	-	0.5	20	240
1997	7	1	42.64	144.66	73	334	5.1	6.0E+16	3.0	-	0.33	25	240

Note : FLC is the lower confidence limit of frequency .
: FHC is the higher confidence limit of frequency .
O.D. is the observation depth at OMA site.

Table 2 : subsurface structures of observation stations

(1) Borehole of 240m depth

G.L. (m)	ρ (g/cm³)	Vs (m/s)	h_0	α
0 - -10	1.59	220	0.115	0.68
-10 - -25	1.90	700		
-25 - -100	2.06	1000		
-100 - -170	1.51	510		
-170 - -240	1.52	690		
-240 -	1.61	850		

Note : damping constant $h = h_0 * f^{-\alpha}$

(2) Borehole of 200m depth

G.L. (m)	ρ (g/cm³)	Vs (m/s)	h_0	α
0 - -48	1.83	850	0.295	0.80
-48 - -110	2.12	1290		
-110 - -144	2.01	890		
-144 - -215	1.48	660		
-215 -	1.52	820		

Note : damping constant $h = h_0 * f^{-\alpha}$

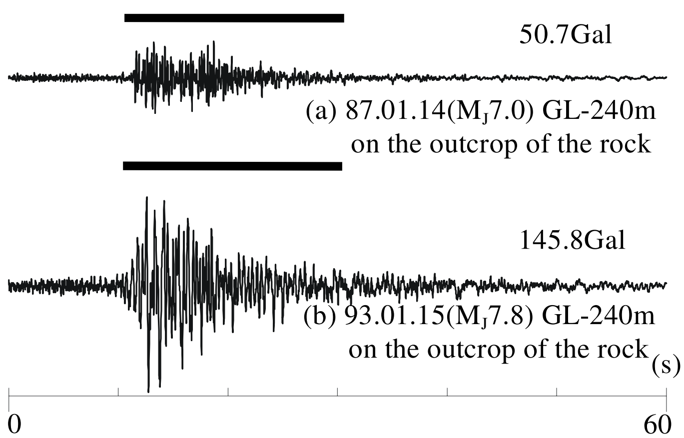

Fig 2 : Examples of calculated accelerograms of NS component on the outcrop of the rock. Thick horizontal lines represent the portion to calculate source spectra.

METHOD OF ANALYSIS

Analysis of source spectrum

Source spectrum M(f) of each earthquake is estimated by using equation (1), which shows a far-field S-wave displacement spectrum Uo(f) from a point source with M(f) in an infinite homogeneous elastic medium.

$$Uo(f)= R_{\theta\phi}\, M(f)/(4\pi\rho Vs^3 X) \qquad (1)$$

where f is a frequency , $R_{\theta\phi}$ is a point source radiation coefficient, ρ is a medium density, Vs is a S-wave velocity , and X is a hypocentral distance. Fourier amplitude spectra Us(f) in acceleration of the outcrop motion on the rock are written as equation (2).

$$Us(f)= (2\pi f)^2 Uo(f)\, H_I(f)\, Hg(f) \exp(-\pi f X/Qs\, Vs) \qquad (2)$$

where $H_I(f)$ is an instrumental response, Hg(f) is a site response, and Qs is a quality factor of S waves along the propagation path from source to station. $R_{\theta\phi}$ was assumed to be $1/\sqrt{2}$ in consideration of the partition of vector into two horizontal components. And $\rho = 3.2 g/cm^3$ and Vs=4.5km/s were adopted, which were the same values by Mahdavian and Sasatani [7]. $H_I(f)=1$ was obtained based on the instrumental response curves of used accelerometers and Hg(f) was assumed to be 2.0, because of the outcrop motion on the rock. Qs will be estimated later from the inclination of acceleration spectrum in high frequency range.

Thick horizontal lines in Fig.2 indicates the parts of accelerograms used for calculating Us(f), which correspond to the direct S-waves portions from source to observation station. Considering the duration of source rupture time, the length of the thick line was determined to be 7seconds for the events with less than MJ=6, and 20seconds for the events with more than MJ=6 respectively. Reliable range of the calculated Fourier amplitude spectrum is estimated for each event using the method by Anderson and Hough [9] for the upper limit frequency FHC, and the method by Omote et al. [10] for the lower limit frequency FLC. The values of estimated upper and lower limit frequencies are also shown in Table 1.

Correction by Qs-value

The amplitudes of source spectra M(f) at the f'requency higher than the corner frequency are usually in proportion to f^{-2}. Therefore, Uo(f) could be also in proportion to f^{-2} and Us(f) could be constant without the effect of Qs value, taking into account of the equations (1) and (2). Upper figure in Fig.3 shows the Fourier amplitude spectrum Us(f) of observed accelerogram. The envelope of the amplitudes inclines toward high frequencies. If the inclination of the envelope is considered due to the effect of Qs-value, we can estimate Qs-value on the contrary from the inclination of the spectral envelope by using the exponential term of the equation (2). Then, S wave velocity is assumed 4.8km/s as the average from source to the observation station. Lower figure in Fig.3 shows the spectrum after the correction by Qs-value, which is obtained to be 1242 so as to make the envelope of the amplitudes constant irrespective of the frequency.

The results of the Qs-values are summarized for all the events in Table 3. The Qs-values estimated from the events occurring in the Kushiro region are about 1500, and from the events occurring in the Hidaka region are about 800. Mahdavian and Sasatani [11] proposed a relation between average Qs-value along the wave propagation path and hypocental distance X. According to their results, Qs value from Kushiro region to OMA is about 1400, and from Hidaka region to OMA is about 800. These results are almost consistent with the present results. Ikeda et al. [5] also estimated the similar relationship by the same method to the present study, and indicated that the increase of Qs-value with hypocentral distance X is due to that the wave propagation path of the distant earthquake goes through the deeper part of the earth with high Qs. To estimate the source spectrum M(f) from observed one Us(f), we will use Qs=800 for 2 events in the Hidaka region and 1500 for 4events in the Kushiro region. as Qs value of S wave, being based on the results of the above analysis.

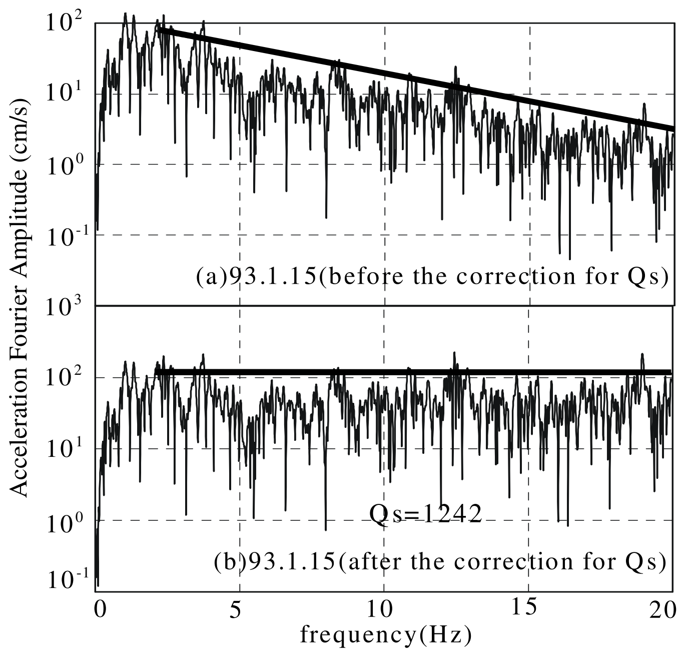

Fig 3 : Examples of acceleration Fourier spectra of NS component of observed S waves. (a) is spectrum not corrected for Qs, (b) is spectrum corrected for Qs

Table 3 : Qs estimated in this study for each events

Region	Date			X (km)	Qs	
					NS	EW
Hidaka	1984	6	22	205	720	862
	1987	1	14	234	835	914
Kushiro	1990	4	11	298	1396	1834
	1993	1	15	339	1242	1291
	1995	9	16	314	1884	1487
	1997	7	1	341	1169	1182

RESULTS

Figure 4 shows the source spectra of analyzed events. Solid lines represent the envelopes of the source spectra, and Mo indicates a seismic moment from the CMT solution for each event obtained by Harvard University, which was shown in Table 1. The source spectra don't have a simple shape as like the ω^{-2} model in the case of the 1993 Kushiro-oki earthquake (MJ=7.5) and the 1987 Hidaka earthquake (MJ=6.6), while those of the small earthquakes corresponding to the results in Figure 4(C) ~ (F) were mostly expressed by the ω^{-2} model. It can be found in Fig.4(A) that the 1993 Kushiro-oki earthquake has a corner at about 1.5Hz in both the figures of NS and EW components. We specify this corner as a second corner frequency fc*, because its frequency is approximately the same as the second corner at 1.1Hz indicated by Mahdavian and Sasatani [7]. And furthermore, the value of Mo* corresponding to fc* shows approximately the same seismic moment density of 7.5×10^{18}Nm as they obtained. In the same manner, we identify the second corner frequency fc* as 3 Hz for the 1987 Hidaka earthquake in Fig.4(B).It is generally recognized that spectral amplitudes at very low frequencies agree with the value of seismic moment Mo. However, the spectral amplitudes of the 1993 Kushiro-oki event are only 1/10 of the seismic moment Mo obtained from the CMT solution, while the amplitudes of the source spectrum obtained by Mahdavian and Sasatani [7] are not so much different from the value of seismic moment Mo in the low frequency range. It might be because the data used for calculating source spectra were obtained by accelerometers at OMA, whose performance is relatively low in the low frequency range. On the other hand, Mahdavian and Sasatani [7] used a velocity-type strong motion seismometer, whose performance is generally much higher than the accelerometer in the low frequency range. Therefore, we cannot use the amplitudes of calculated source spectrum to discuss the shape of the source spectrum in the frequency range lower than 0.3 or 0.4 Hz, and we substitute the value of the seismic moment from the CMT solution for them in the low frequency range. Since we can estimate Mo* from the obtained source spectra for the 1993 Kushiro-oki earthquake and the 1987 Hidaka earthquake, assuming that the source spectra at frequencies higher than the first corner frequency fc are in proportion to f^{-2} [8], corner frequency fc can be identified as 0.1 Hz for the Kushiro-oki earthquake and 0.3Hz for the Hidaka earthquake at the crossing of the level of seismic moment Mo estimated from the CMT solution. This value of fc for the 1993 Kushiro-oki earthquake is consistent with the value obtained by Mahdavian and Sasatani [7]. In the same way, the spectral envelopes are specified from the seismic moment Mo and calculated spectral amplitudes for the other events, though they have the source spectra expressed by the ω^{-2} model with one corner frequency fc. Obtained values of fc and fc* are shown in Table 1 for each event.

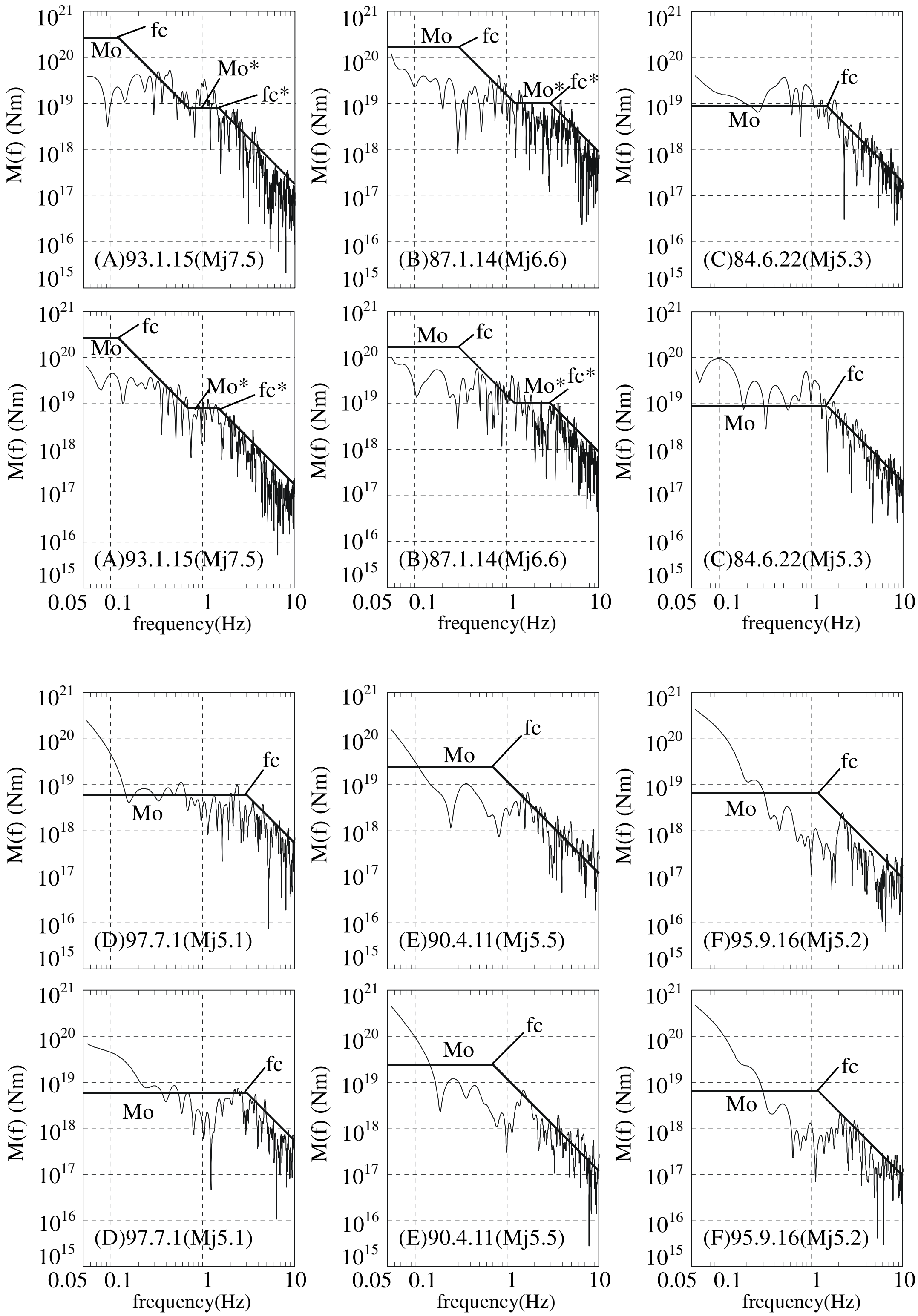

Fig 4 : Source spectra of events calculated in this study.

DISCUSSION

Figure 5 shows the relationship between Mo and fc and data are represented by the solid circles. And solid circles with star * represent the second corner frequencies for the 1993 Kushiro-oki earthquake and the 1987 Hidaka earthquake. Ikeda et al. [5] obtained about 30MPa as the average of Brune's stress drop $\Delta\sigma$ [6] for the 15 intermediate depth earthquakes with MJ smaller than 6.5 occurring in and around Hokkaido. All of them have the DE type focal mechanisms.

The solid line shows Mo-fc relation with $\Delta\sigma$=30MPa. It is in accordance with the data in the present study. Ikeda et al. [5] indicated that 30MPa is obviously higher than the average stress drop of inter-plate earthquakes whose hypocenters are usually shallower than the DE type earthquakes and that it is a reason of the large high frequency amplitudes of strong ground motions from the intermediate depth earthquakes. And they also indicated that the larger intermediate depth events such as the 1993 Kushiro-oki earthquake (MJ=7.5) and the 1987 Hidaka earthquake (MJ=6.6) had larger Brune's stress drops $\Delta\sigma$ and the excitations of high frequency waves were much more than expected from $\Delta\sigma$=30MPa.

Figure 6 shows the obtained envelopes of source spectra of the Jun.22th, 1984 earthquake (MJ5.4), the'87Hidaka earthquake, the'93 Kushiro-oki earthquake. The solid line shows Mo-fc relation with $\Delta\sigma$=30MPa. the first corner frequencies of the 1987Hidaka earthquake and the 1993Kusiro-oki earthquake coincide with the relation of $\Delta\sigma$=30MPa. On the other hand, these large events have the second corner frequencies. According to Fig.6, it is concluded that the second corner frequencies of them caused the larger Brune's stress drops $\Delta\sigma$ and the larger excitations of high frequency waves comparing with the smaller events indicated by Ikeda et al. [5]. The second corner of source spectrum appears due to some heterogeneity in the fault and it may be related to the size of the heterogeneity. The seismic moment density Mo* at the second corner frequency is dependent of the strength of the heterogeneity [7] [8]. It can be recognized that the large excitation of high frequency waves from big intermediate depth events are caused by the heterogeneities of their faulting larger than those expected from the scaling relation of the source spectra for the small intermediate depth events.

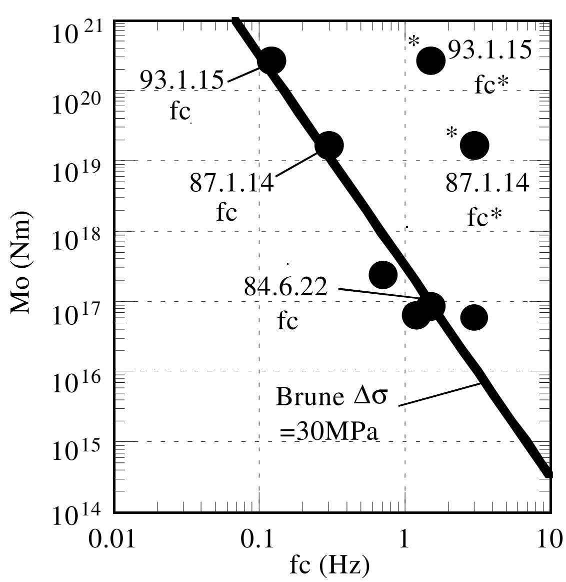

Fig.5 Relation between seismic moment M_0 and corner frequency fc for each event. The second corner frequency fc*s are also plotted for the 1993 Kushiro-Oki and the 1987 Hidaka earthquake.

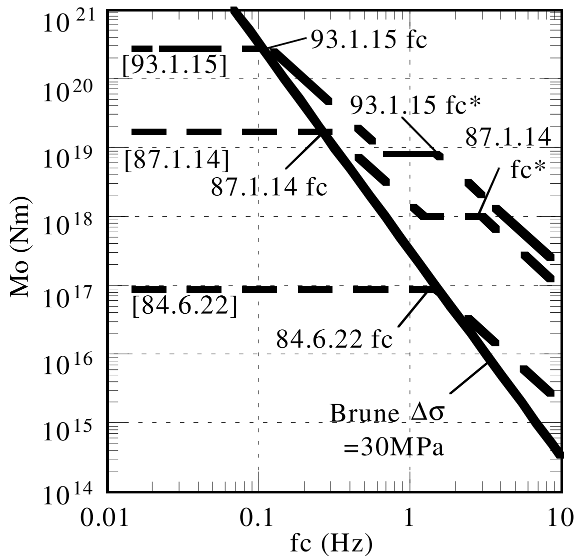

Fig 6 : Structures of source spectra of small and large DE type events.

CONCLUSIONS

We investigated the relationships of the intermediate depth earthquakes between seismic moment Mo and corner frequency fc. The analyzed events, whose focal mechanism was DE type, occurred at the lower seismic zone in the subducting slab beneath Hokkaido, Japan. Their magnitudes range from 5.1 to 7.5 in JMA scale, including the Jan.14th, 1987 Hidaka earthquake (MJ6.6) and the Jan.15th, 1993 Kushiro-oki earthquake (MJ7.5). Source spectra of these intermediate depth earthquakes are estimated from observation records at the OMA site. The results obtained are summarized as follows:

① The 1987 Hidaka and the 1993 Kushiro-oki earthquakes have the first and second corner frequencies on their source spectra, while the small events have one corner frequency, which can be expressed by the ω^{-2} model.

② The relationship between seismic moment and the corner frequency follows $\Delta\sigma$=30MPa as the Brune's stress drop $\Delta\sigma$ [6] for the small events. This value is larger than that of the inter-plate earthquakes in the same seismic region.

③ Brune's stress drop $\Delta\sigma$ of the two big events is meaningfully larger than the small events, while the relation with $\Delta\sigma$=30MPa explains the seismic moment and the first corner frequency of them. This implies that the second corner frequencies are strongly related to larger excitations of high frequency waves, comparing with the smaller events, of the big intermediate depth events.

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