STUDY ON HIGH-CUT FREQUENCY CHARACTERISTICS OF GROUND MOTIONS FOR INLAND CRUSTAL EARTHQUAKES IN JAPAN

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ABSTRACT :

High-cut frequency characteristics of ground motions for inland crustal earthquakes occurring in Japan are examined. It is very important to make clear spectral decay characteristics in high frequency range for strong ground motion prediction. The target earthquakes are the 2003 Miyagi-ken Hokubu earthquake (M_w:6.1) and the 2005 Fukuoka-ken Seiho-oki earthquake (M_w:6.6). The Butterworth type high-cut filter with cut-off frequency, f_{max} and its power coefficient of high-frequency decay is assumed to express the high-cut frequency characteristics of ground motions in this study. The four parameters such as seismic moment, corner frequency, cut-off frequency, and its power coefficient are estimated by comparing observed spectra at hard rock sites with theoretical spectra. The theoretical spectra are calculated, based on the omega squared source characteristics convolved with propagation-path effects and f_{max} filter shapes. In result, the f_{max} of the mainshock of the 2003 Miyagi-ken Hokubu earthquake is estimated as 8.3Hz and that of the 2005 Fukuoka-ken Seiho-oki earthquake is 6.5Hz, respectively. The power coefficients of high-frequency decay, *s*, are estimated about 1.0. From these results, the high-cut filter with about 7.0Hz as f_{max} and 1.0 as the power coefficient of high-frequency decay is useful for strong ground motion prediction at hard rock site. The f_{max}'s of aftershocks of those earthquakes are estimated in the range about 9Hz and 20Hz. The seismic moment dependency of f_{max} is not clear, however the f_{max}'s of large events are smaller than those of small events.

KEYWORDS: Strong ground motion prediction, Spectral decay characteristics, Cut-off frequency (f_{max}), High-cut filter, Seismic moment dependency

1. INTRODUCTION

It's well known seismic motions are composed by source, path and site characteristics. Recently, these characteristics can be evaluated accurately using observed records. Recipe for predicting strong ground motions from future large earthquakes based on fault rupture propagation model is proposed by Irikura *et al*.(2004). Procedure of source modeling and estimating Green's function considering path and site characteristics is summarized in the recipe. As a result, strong ground motion prediction based on fault rupture propagation model according to the recipe is becoming mainstream in Japan. One of problems for predicting strong ground motion based on fault rupture propagation model is characteristic of seismic motion in high frequency range. If a source Fourier spectrum of seismic motion is according to the omega squared model [Aki(1967)], a shape of acceleration Fourier spectrum is flat in high frequency range. Actually, observed acceleration Fourier spectrum shows decaying with increasing frequency above a certain frequency called cut-off frequency, f_{max} [Hanks(1982)]. The physical interpretation of f_{max} is still controversial, local site effect [for example, Hanks(1982), Anderson and Hough(1984)] or source-controlled factor [for example, Papageorgiou and Aki(1983)].

It's very important to make clear a seismic moment dependency of spectral decay characteristics in high frequency range for strong ground motion prediction using empirical Green's function method

[Hartzell(1978), Irikura(1986)], stochastic Green's function method [Kamae *et al.*(1991)] and hybrid method [Irikura and Kamae(1999)]. The authors examined spectral decay characteristic of ground motions during the 1995 Hyogo-ken Nambu earthquake (M_w:6.9) [Tsurugi *et al.*(2006)]. In this study, spectral decay characteristics in high frequency range, i.e. high-cut filter of inland crustal earthquakes occurring in Japan are evaluated to get basic information for strong ground motion prediction. Moreover, the filter to correct difference of spectral decay characteristics between large event and small event is evaluated.

2. METHOD FOR ESTIMATING HIGH-CUT FREQUENCY CHARACTERISRICS

Target earthquakes are the 2003 Miyagi-ken Hokubu earthquake (M_w:6.1) and the 2005 Fukuoka-ken Seiho-oki earthquake (M_w: 6.6). The epicenters of the earthquakes are shown in Fig.1.

Average source Fourier spectrum is calculated from observed records at several hard rock sites. Borehole data in the digital strong-motion seismograph network (KiK-net) deployed by National Research Institute for Earth Science and Disaster Prevention (NIED) are used as the observed records at hard rock sites. Observed spectrum can be remove effects of rupture directivity and radiation pattern by calculating from several rock sites. The vectorial summation of two horizontal components that are corrected amplitude characteristics of seismometers is used as observed spectrum. The multiple taper [Thomsom(1982), Lees and Park(1995)] is used to improve precision of spectrum calculation. Q-factor on propagation path route shown in Eqn.(2.1) and Eqn.(2.2) [Kawase and Matsuo (2004)] is used to calculate source spectra from observed spectra. These equations are obtained by spectral inversion analysis.

For the 2003 Miyagi-ken Hokubu earthquake : $Q(f)=93.2\times f^{1.01}$ (2.1)

For the 2005 Fukuoka-ken Seiho-oki earthquake : $Q(f)=112.0\times f^{0.70}$ (2.2)

The Butterworth type high-cut filters with cut-off frequency, f_{max} and its power coefficient of high-frequency decay, s or n shown in Eqn.(2.3) [Boore(1983)] and Eqn.(2.4) are usually used to express the high-cut frequency characteristics of ground motions. The high-cut filter shown in Eqn.(2.3) is assumed in this study based on the result of the previous study [Tsurugi *et al.*(2006)]. The four parameters such as seismic moment, corner frequency, cut-off frequency, and its power coefficient, s, are estimated by comparing observed spectra at hard rock sites with theoretical spectra. A flat level of displacement source spectrum in low frequency range, Ω_o and corner frequency, f_c are estimated by the automated objective method [Andrews(1986)], and a seismic moment, M_o is calculated by Eqn.(2.5). Moreover, a cut-off frequency, f_{max} and its power coefficient of high-frequency decay, s, are estimated by reannealing method [Ingber and Rosen (1992)].

$$P(f)=\frac{1}{\sqrt{1+\left(\frac{f}{f_{\max}}\right)^{2s}}} \tag{2.3}$$

$$P(f)=\frac{1}{\left(\frac{f}{f_{\max}}\right)^{n}} \tag{2.4}$$

$$M_o=\frac{4\pi\rho\beta^3}{R_{\phi\theta}}\times\Omega_o \tag{2.5}$$

where, ρ is density (assumed as 2.7g/cm^3), β is S-wave velocity (3.6km/sec), $R_{\phi\theta}$ is coefficient of radiation pattern (0.63) [Boore and Boatwright (1984)].

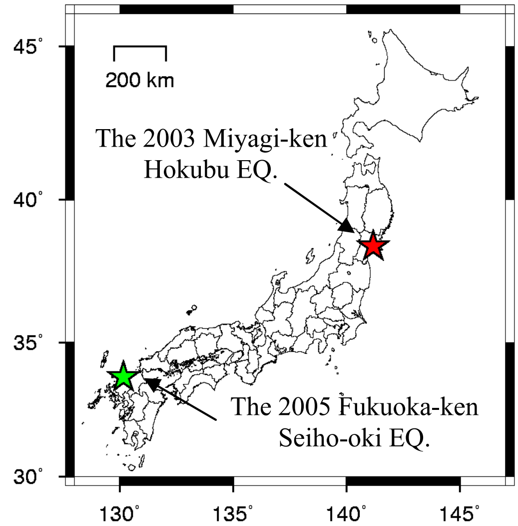


Fig.1 Epicenters of target earthquakes.

3. RESULTS

3.1. Estimated Parameters

Table1 and Table2 show the lists of earthquakes analyzed in this study and estimated parameters. The f_{max} of the mainshock of the 2003 Miyagi-ken Hokubu earthquake (Earthquake No.3 in Table1) is estimated as 8.3Hz and that of the 2005 Fukuoka-ken Seiho-oki earthquake (Earthquake No.1 in Table2) is 6.5Hz, respectively. The f_{max}'s of the aftershocks of those earthquakes are estimated in the range about 9Hz and 20Hz. The power coefficients of high-frequency decay, s, of the mainshocks are estimated about 1.0 and those of aftershocks are estimated in the range about 0.3 and 2.4.

3.2.High-cut Filters of Large Events, $P_L(f)$

Fig.2 shows comparison of averaged observed spectra and theoretical spectra of mainshocks of target earthquakes. The theoretical spectrum, $A(f)$ are calculated, based on the omega squared source characteristics convolved with propagation-path effects and f_{max} filter shapes, $P(f)$ [Eqn.(3.1)].

$$A(f) = CM_O S(f)\frac{1}{X}\exp\frac{-\pi f X}{Q(f)\beta}P(f) \tag{3.1}$$

where, $S(f)$ is source spectrum according to the omega squared model [Eqn.(3.2), Aki(1967)], X is average of hypocentral distance, C is constant.

$$S(f) = \frac{(2\pi f)^2}{1+\left(\frac{f}{f_C}\right)^2} \tag{3.2}$$

The relevance of the obtained parameters is confirmed from Fig.2, because of good agreement with the theoretical spectrum and observed one. The high-cut filters of large event, $P_L(f)$ are expressed in Eqn.(3.3) and Eqn.(3.4) and shown in Fig.3. In this figure, the high-cut filters of the 1995 Hyogo-ken Nambu earthquake obtained by the previous study [Eqn.(3.5), Tsurugi *et al.*(2006)] is shown, too. The high-cut filter of the 2005 Fukuoka-ken Seiho-oki earthquake is almost same with that of the 2003 Miyagi-ken Hokubu earthquake. However, these filters are not same with that of the 1995 Hyogo-ken Nambu earthquake, because of the difference of hardness used sites. The borehole data with over 2,000m/sec as S-wave velocity at the depth of the seismometer are used for the 2003 Miyagi-ken Hokubu earthquake and the 2005 Fukuoka-ken Seiho-oki earthquake. On the other hand, the records on ground surface with the range about 350m/sec and 700m/sec as S-wave velocity are used for the 1995 Hyogo-ken Nambu earthquake.

Table 1 List of earthquakes analyzed and estimated parameters
(The 2003 Miyagi-ken Hokubu Earthquake)

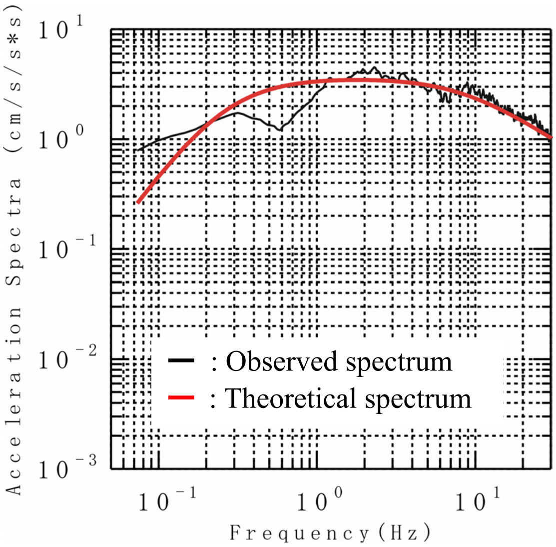
No.	Origin Time	Lat. (°)	Lon. (°)	D (km)	M_J	M_o (dyne·cm)	f_c (Hz)	f_{max} (Hz)	s	Sites
1	2003.07.26 00:13	38.430	141.167	12	5.6	2.09×10^{24}	0.45	16.7	1.36	9
2	2003.07.26 05:22	38.383	141.153	11	3.6	1.25×10^{21}	3.30	19.7	1.30	2
3	2003.07.26 07:13	38.402	141.173	12	6.4	2.23×10^{25}	0.26	8.3	0.96	8
4	2003.07.26 07:52	38.457	141.167	13	4.6	2.33×10^{22}	1.84	18.7	1.84	9
5	2003.07.26 10:22	38.453	141.167	13	5.1	1.04×10^{23}	1.14	18.8	1.13	10
6	2003.07.26 14:29	38.400	141.198	12	3.7	2.63×10^{21}	2.36	15.9	1.21	4
7	2003.07.26 15:03	38.463	141.190	11	3.9	2.33×10^{21}	3.50	18.1	1.00	7
8	2003.07.27 13:20	38.475	141.218	11	4.2	1.03×10^{22}	1.80	15.2	1.69	9
9	2003.07.28 04:08	38.455	141.152	14	5.1	1.89×10^{23}	1.09	15.8	1.08	9
10	2003.08.12 09:27	38.493	141.180	12	4.3	1.39×10^{22}	1.68	18.8	1.88	10
11	2003.08.23 01:05	38.448	141.172	13	3.5	9.57×10^{20}	3.80	16.0	0.61	3
12	2003.10.23 14:00	38.463	141.192	12	4.4	9.85×10^{21}	2.26	14.4	0.70	10
13	2005.11.01 11:01	39.067	140.813	9	4.6	4.38×10^{22}	1.20	13.9	0.84	10
14	2007.04.05 20:39	38.202	141.148	12	4.5	3.00×10^{22}	1.56	13.6	0.87	10

Earthquake No.3 is the mainshock.

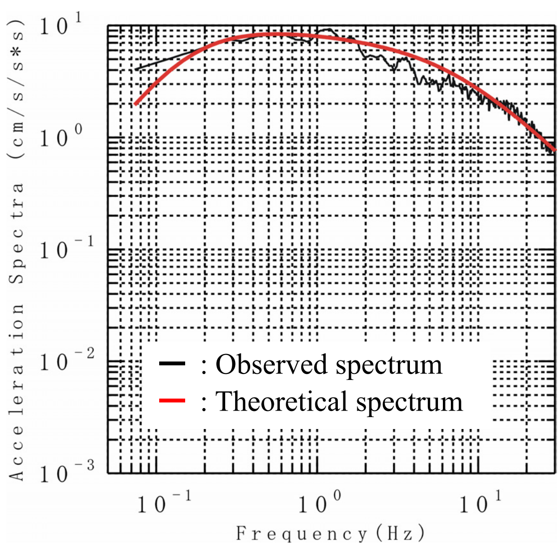
Table 2 List of earthquakes analyzed and estimated parameters
(The 2005 Fukuoka-ken Seiho-oki Earthquake)

No.	Origin Time	Lat. (°)	Lon. (°)	D (km)	M_J	M_o (dyne·cm)	f_c (Hz)	f_{max} (Hz)	s	Sites
1	2005.03.20 10:53	33.738	130.175	9	7.0	1.15×10^{26}	0.16	6.5	0.90	9
2	2005.03.20 14:32	33.797	130.087	12	4.5	3.98×10^{22}	0.78	14.6	0.80	3
3	2005.03.20 15:41	33.708	130.222	10	3.6	3.79×10^{21}	1.58	10.4	1.02	2
4	2005.03.20 16:08	33.762	130.143	12	4.1	9.83×10^{21}	1.48	9.2	0.33	4
5	2005.03.20 20:38	33.745	130.170	11	4.5	4.22×10^{22}	1.13	13.4	1.47	9
6	2005.03.21 06:17	33.728	130.193	12	3.9	1.03×10^{22}	2.02	19.0	2.35	7
7	2005.03.21 15:37	33.783	130.097	11	4.2	1.30×10^{22}	1.62	19.3	2.11	6
8	2005.03.21 23:59	33.785	130.100	12	4.8	9.42×10^{22}	0.97	16.5	1.78	8
9	2005.03.24 23:38	33.740	130.170	11	4.3	8.07×10^{21}	1.95	15.8	1.51	6
10	2005.03.25 03:43	33.722	130.215	11	4.0	1.00×10^{22}	1.54	17.2	1.83	4
11	2005.03.25 21:03	33.785	130.117	12	4.1	1.76×10^{22}	1.79	14.4	1.42	8
12	2005.04.20 06:11	33.677	130.287	14	5.8	1.43×10^{24}	0.67	8.8	0.98	9
13	2005.04.20 06:22	33.678	130.288	13	4.7	7.03×10^{22}	1.00	19.7	1.73	8
14	2005.04.20 09:09	33.678	130.283	13	5.1	2.12×10^{23}	1.01	11.0	1.40	9

Earthquake No.1 is the mainshock.
Lat. : Latitude, Lon. : Longitude, D : Focal depth, M_J : Magnitude in JMA scale,
M_o : Seismic moment, f_c : Corner frequency, Sites : Number of sites used



(1)The 2003 Miyagi-ken Hokubu earthquake



(2) The 2005 Fukuoka-ken Seiho-oki earthquake

Fig.2 Comparison of averaged observed spectrum and theoretical spectrum of the mainshock

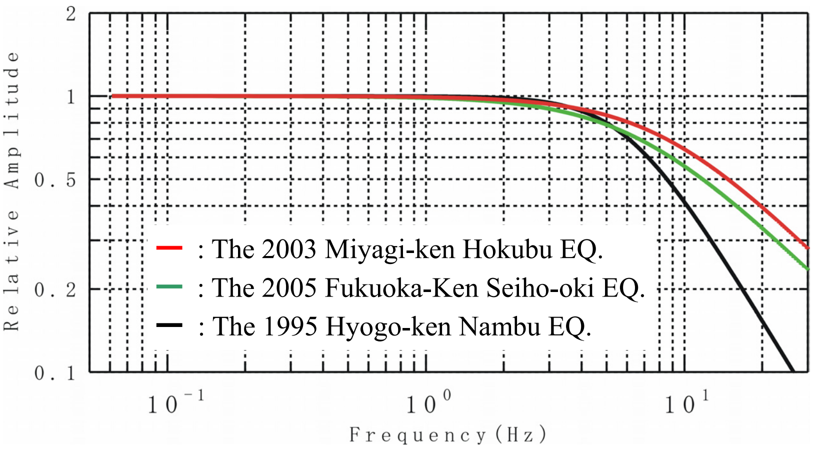


Fig.3 High-cut filter of large event, $P_L(f)$.

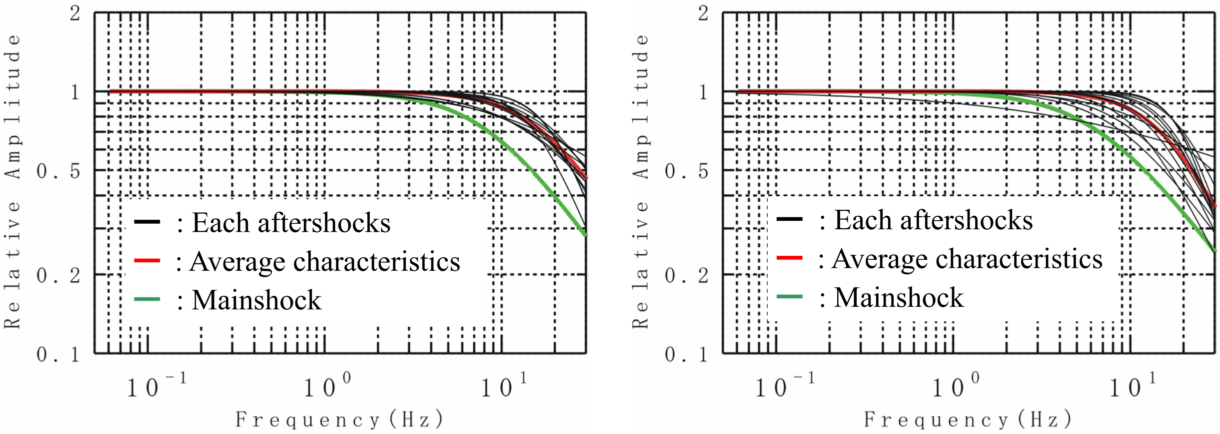
For the 2003 Miyagi-ken Hokubu earthquake : $P_L(f) = \dfrac{1}{\sqrt{1+\left(\dfrac{f}{8.3}\right)^{2\times 0.96}}}$ (3.3)

For the 2005 Fukuoka-ken Seiho-oki earthquake : $P_L(f) = \dfrac{1}{\sqrt{1+\left(\dfrac{f}{6.5}\right)^{2\times 0.90}}}$ (3.4)

For the 1995 Hyogo-ken Nambu earthquake : $P_L(f) = \dfrac{1}{\sqrt{1+\left(\dfrac{f}{6.0}\right)^{2\times 1.55}}}$ (3.5)

3.3. High-cut Filters of Small Events, $P_S(f)$

Fig.4 shows high-cut filters of aftershocks of target earthquakes. The red lines are average characteristics. The average characteristics of high-cut filter of small events, $P_S(f)$ can be approximated shown in Eqn.(3.6) and Eqn.(3.7).



(1)The 2003 Miyagi-ken Hokubu earthquake (2) The 2005 Fukuoka-ken Seiho-oki earthquake

Fig.4 High-cut filter of small events, $P_S(f)$.

For the 2003 Miyagi-ken Hokubu earthquake : $$P_S(f) \approx \frac{1}{\sqrt{1+\left(\frac{f}{16.7}\right)^{2\times 1.10}}} \quad (3.6)$$

For the 2005 Fukuoka-ken Seiho-oki earthquake : $$P_S(f) \approx \frac{1}{\sqrt{1+\left(\frac{f}{14.5}\right)^{2\times 1.30}}} \quad (3.7)$$

3.4. The Seismic Moment Dependency of fmax

Fig.5 shows relationship between seismic moment and f_{max}. In this figure, f_{max} of the mainshock of the 1995 Hyogo-ken Nambu earthquake obtained by the previous study [Tsurugi *et al.*(2006)], 6.0Hz, is shown, too. The seismic moment dependency of f_{max} is not clear especially in the case of a seismic moment is less than 10^{25}dyne･cm, however the f_{max}'s of large events are smaller than those of small events.

4. CORRECTING FILTER, $P_C(f)$

Eqn.(4.1) seems to be formed as the relationship between high-cut filter of large event, $P_L(f)$ and that of small event, $P_S(f)$.

$$P_L(f)=P_S(f)\times P_C(f) \quad (4.1)$$

where, $P_C(f)$ is a filter to correct difference of spectral decay characteristics between large event and small event. It's necessary to correct predicted strong motions by $P_C(f)$, when small event records are used in a process of prediction such as empirical Green's function method.

Fig.6 shows the correcting filter, $P_C(f)$ which is evaluated by taking spectral ratio of high-cut filter of large event, $P_L(f)$ against that of small event, $P_S(f)$ for target earthquakes. The shapes of both filters are almost same. The correcting filter, $P_C(f)$ does not shows decaying with increasing frequency unlike $P_L(f)$ and $P_S(f)$.

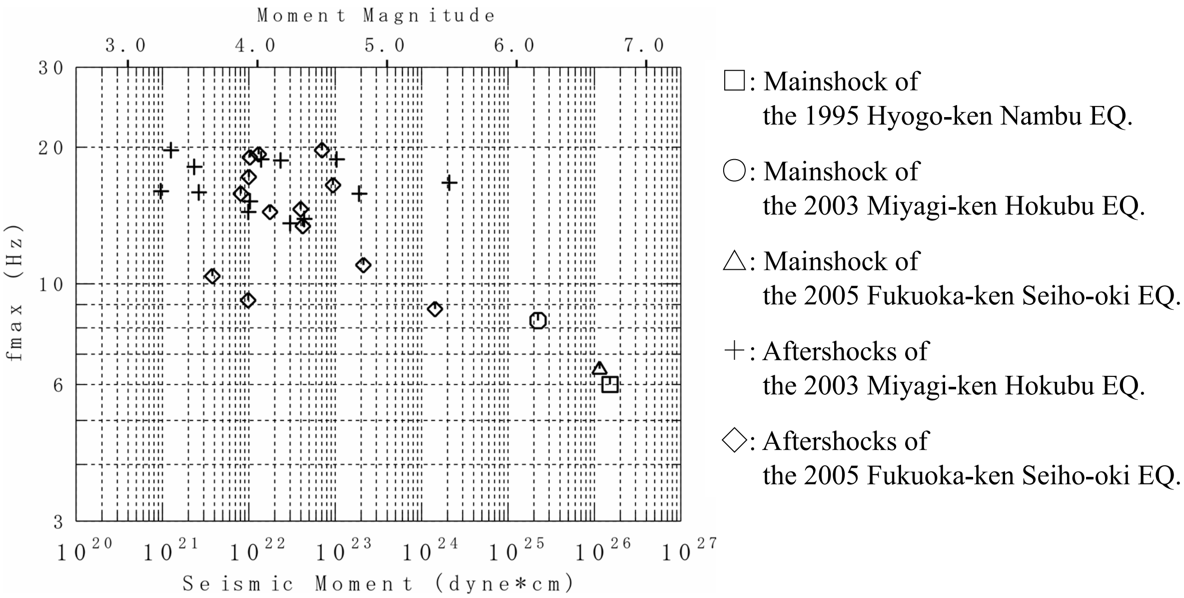


Fig.5 Relationship between seismic moments and f_{max}'s

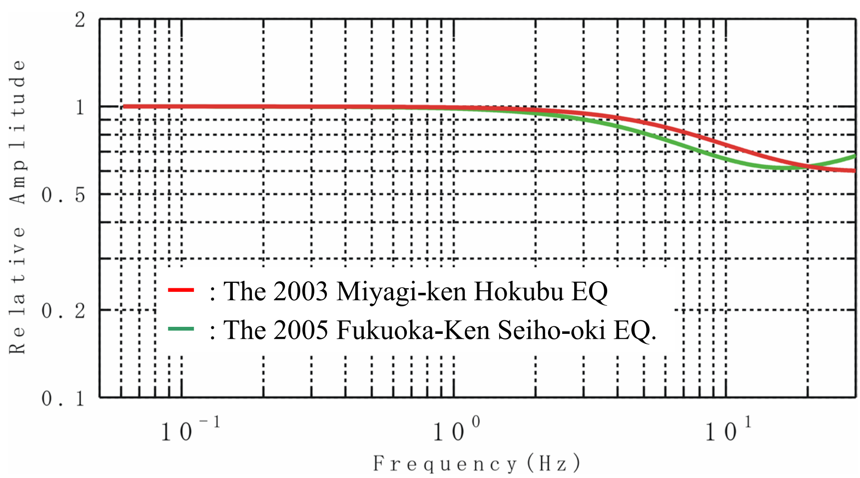


Fig.6 Filters to correct difference of spectral decay characteristics in high frequency range between large event and small event, $P_C(f)$.

5. CONCLUSION

In this study, spectral decay characteristics in high frequency, i.e. high-cut filter of inland crustal earthquakes occurring in Japan are evaluated to get basic information for strong ground motion prediction. In result, the f_{max} of the mainshock of the 2003 Miyagi-ken Hokubu earthquake is estimated as 8.3Hz and that of the 2005 Fukuoka-ken Seiho-oki earthquake is 6.5Hz, respectively. The power coefficients of high-frequency decay, s, are estimated about 1.0. The high-cut filter of the mainshocks are expressed in Eqn.(4.1) and Eqn.(4.2) and the shape of both filters are almost same. These filters are useful for strong ground motion prediction when small event records are not used in a process.

The f_{max}'s of aftershocks of those earthquakes are estimated in the range about 9Hz and 20Hz. The power coefficients of high-frequency decay, s, of aftershocks are estimated in the range about 0.3 and 2.4. Average characteristics of high-cut filter of the aftershocks can be approximated shown in Eqn.(4.3) and Eqn.(4.4). The seismic moment dependency of f_{max} is not clear, however the f_{max}'s of large events are smaller than those of small events.

Moreover, the filter to correct difference of spectral decay characteristics between large event and small event is evaluated. The obtained correcting filters of two events are almost same. The correcting filters are useful for strong ground motion prediction using observed small event records.

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