Study on High Frequency Cut-off Characteristics of Ground Motions for Intra-Slab Earthquakes Occurred in Southwest Japan

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SUMMARY:
High frequency cut-off characteristics of ground motions for intra-slab earthquakes occurring in southwest Japan are examined by comparing spectra of large earthquakes to those of small earthquakes. It is very important to clarify spectral decay characteristics of strong ground motion in high frequency range for engineering use. The 2004 SE off Kii peninsula earthquake (M_w 7.5) and the 2001 Geiyo earthquake (M_w 6.8) are included in the target earthquakes. The high-cut characteristics of ground motions are defined as the Butterworth type high-cut filter with cut-off frequency, f_{max} and its power coefficient of high-frequency decay [Boore (1983)]. As results, the f_{max}'s of the large earthquakes are estimated about 7.8Hz. This values are almost same with those of large crustal earthquakes occurred in Japan. The power coefficients of high-frequency decay are estimated in the range from 1.5 and 1.8. These values are notably larger than those of large crustal earthquakes.

Keywords: High frequency cut-off characteristics, Cut-off frequency, Strong motion prediction, Intra-slab earthquakes

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 the problems for predicting strong ground motion based on fault rupture propagation model is characteristics of seismic motion in high frequency range. If Fourier spectrum of seismic motion is according to the omega squared model [Aki (1967)], a shape of Fourier acceleration spectrum is flat in high frequency range. Actually, observed Fourier acceleration 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 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 2005 Fukuoka-ken Seiho-oki earthquake (M_w 6.6) [Tsurugi *et al*. (2008)]. In this study, spectral decay characteristics in high frequency range, i.e. high-cut filter of intra-slab earthquakes occurring in Southwest Japan are evaluated and compared with that of inland crustal earthquake to get basic information for strong ground motion prediction. The seismic moment dependency of f_{max} is evaluated based on obtained results. Moreover, the filter to correct difference of spectral decay characteristics between large and small earthquake is evaluated.

2. METHOD FOR ESTIMATING HIGH FREQUENCY DECAY CHARACTERISTICS

Target earthquakes are intra-slab earthquakes occurring in Kinki region and Geiyo region, southwest Japan. The 2004 SE off Kii peninsula earthquake (M_w 7.5) and the 2001 Geiyo earthquake (M_w 6.8) are included in the target earthquakes. The epicenters of target earthquakes are shown in **Fig.1**.

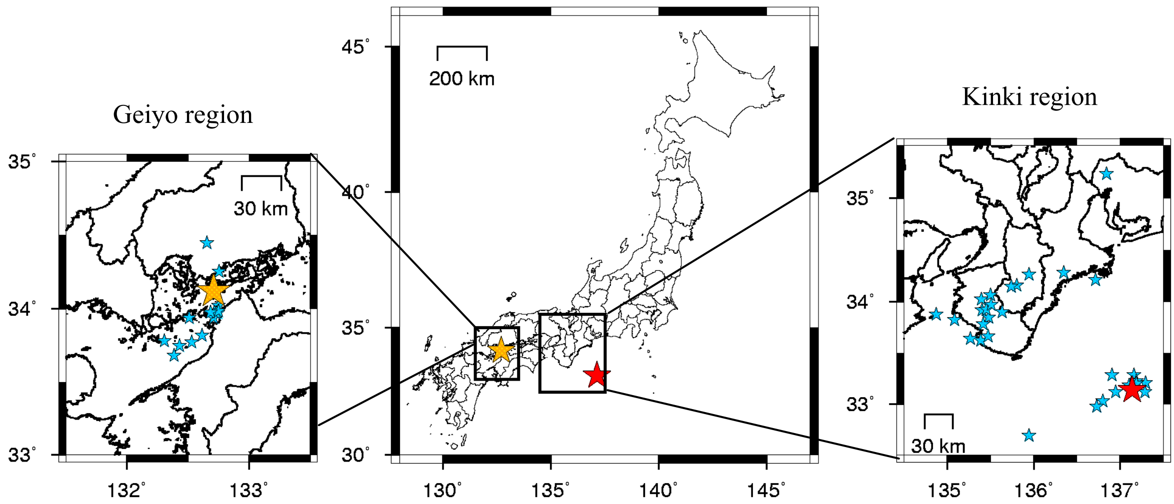


Figure 1. Epicenters of target earthquakes.
Red star is mainshock of the 2004 SE Off Kii peninsula earthquake (Mw 7.5). Orange color star is mainshock of the 2001 Geiyo earthquake (Mw 6.8). Blue stars are small earthquakes.

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. Effects of rupture directivity and radiation pattern can be removed from observed spectrum 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, 2.2, and 2.3 are used to calculate source spectra from observed spectra. These equations are obtained by spectral inversion analysis using observed records at target sites during target earthquakes.

For earthquakes occurred in Kinki region (focal depth < 20km) : $Q(f)=149.2\times f^{1.00}$ (2.1)

For earthquakes occurred in Kinki region (focal depth >= 20km) : $Q(f)= 79.4\times f^{0.74}$ (2.2)

For earthquakes occurred in Geiyo region : $Q(f)=147.0\times f^{0.88}$ (2.3)

The Butterworth type high-cut filters with cut-off frequency, f_{max} and its power coefficient of high-frequency decay, s shown in Eqn.2.4 [Boore (1983)] is assumed in this study. 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_0 and corner frequency, f_c are estimated by the automated objective method [Andrews (1986)], and a seismic moment, M_0 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)].

$$P(f) = \frac{1}{\sqrt{1+\left(\dfrac{f}{f_{\max}}\right)^{2s}}} \tag{2.4}$$

$$M_O = \frac{4\pi\rho\beta^3}{R_{\theta\phi}} \times \Omega_O \quad (2.5)$$

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

3. RESULTS

3.1. Estimated Parameters

Table 1 and **Table 2** shows the lists of earthquakes analyzed in this study and estimated parameters. **Fig.2** shows comparison of averaged observed spectra and theoretical spectra of large 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).

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

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

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

The relevance of the obtained parameters is confirmed from **Fig.2**, because of good agreement with the theoretical spectra and observed one. The f_{max}'s of the foreshock and mainshock of 2004 SE off Kii peninsula earthquake (M_w 7.2 and 7.5, Earthquake No.15 and No.16 in **Table 1**.) are both estimated as 7.7Hz and that of the 2001 Geiyo earthquake (M_w 6.8, Earthquake No.5 in **Table 2**.) is 7.8Hz, respectively. The f_{max}'s of the small earthquakes (M_w<6.0) are estimated in the range about 8Hz and 25Hz. The power coefficients of high-frequency decay, s, are estimated in the range about 1.1 and 2.9.

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

The high-cut filters of large earthquakes, $P_L(f)$ are shown in **Table 3** and **Fig.3**. In the figure, the high-cut filters of the 2005 Fukuoka-ken Seiho-oki earthquake obtained by the previous study [Eqn.3.7, Tsurugi *et al*. (2008)] is also shown. The 2005 Fukuoka-ken Seiho-oki earthquake is large inland crustal earthquake occurred in Southwest Japan with M_w 6.6. The values of f_{max}'s of large intra-slab earthquakes are almost same with that of the 2005 Fukuoka-ken Seiho-oki earthquake, but, the power coefficient of high-frequency decay, s, of large intra-slab earthquakes are larger than that of the 2005 Fukuoka-ken Seiho-oki earthquake.

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

Fig.4 shows high-cut filters of target small earthquakes (M_w<6.0). The red lines are average characteristics. The average characteristics of high-cut filter of small earthquakes, $P_S(f)$ can be approximated as Eqn.3.8 and Eqn.3.9. It's confirmed that the average characteristics of high-cut filter of small earthquakes in Kinki region and Geiyo region are almost same.

Table 1. List of the earthquakes analyzed and estimated parameters (Kinki region)

No.	Origin Time	Lat. (°)	Lon. (°)	D (km)	M_J	M_o (N•m)	f_c (Hz)	f_{max} (Hz)	s	N
1	1999.07.18 00:27:13	34.157	135.805	50	4.0	1.08×10^{15}	1.94	18.8	2.93	2
2	1999.11.01 01:52:34	33.845	135.482	62	3.8	6.90×10^{14}	2.38	16.8	1.76	2
3	2000.04.15 02:41:10	33.622	135.387	38	4.8	3.91×10^{16}	1.07	11.6	1.60	7
4	2000.04.28 11:42:15	33.897	135.637	47	4.2	2.84×10^{15}	1.58	20.8	1.67	4
5	2000.06.02 15:05:54	34.022	135.393	56	4.0	3.02×10^{15}	1.90	19.5	2.27	4
6	2000.09.10 22:36:26	33.667	135.475	32	3.8	3.25×10^{14}	3.59	17.6	2.52	4
7	2000.10.31 01:42:52	34.280	136.348	38	5.5	2.80×10^{17}	0.66	11.2	1.80	8
8	2001.02.26 12:48:50	33.917	135.405	53	3.5	4.71×10^{14}	2.56	18.8	2.81	2
9	2002.10.29 18:55:33	34.148	135.742	53	3.8	7.15×10^{14}	3.40	17.1	1.87	5
10	2002.11.06 08:23:49	33.922	135.455	56	3.7	8.87×10^{14}	2.19	19.4	1.38	3
11	2003.02.26 03:03:44	33.780	135.420	41	3.7	1.89×10^{14}	2.80	19.5	1.74	2
12	2003.06.05 10:42:32	34.062	135.500	65	3.8	9.04×10^{14}	2.49	18.5	1.81	4
13	2003.07.06 08:30:24	32.690	135.945	5	4.6	1.58×10^{16}	0.75	10.3	1.86	6
14	2004.01.06 14:50:52	34.212	136.717	38	5.4	7.99×10^{16}	0.86	17.5	1.75	13
15	2004.09.05 19:07:07	33.032	136.797	14	7.1	4.53×10^{19}	0.10	7.7	1.69	10
16	2004.09.05 23:57:16	33.137	137.140	11	7.4	1.65×10^{20}	0.06	7.7	1.69	11
17	2004.09.06 05:30:59	33.288	136.905	5	5.9	3.83×10^{17}	0.20	7.9	1.83	9
18	2004.09.06 07:48:43	33.185	137.100	11	4.3	4.25×10^{15}	1.32	10.0	1.84	5
19	2004.09.06 19:29:19	33.287	137.163	8	4.5	6.80×10^{15}	0.71	12.0	1.84	5
20	2004.09.07 08:29:36	33.208	137.292	11	6.5	4.50×10^{18}	0.21	7.9	1.83	11
21	2004.09.08 03:36:21	33.225	137.188	11	5.5	1.99×10^{17}	0.35	12.1	2.28	11
22	2004.09.08 23:58:23	33.117	137.287	5	6.5	2.37×10^{18}	0.17	5.0	1.54	10
23	2004.09.10 11:05:54	32.977	136.730	5	5.6	1.49×10^{17}	0.23	9.3	1.54	7
24	2004.10.01 13:25:27	33.878	134.872	35	3.5	3.71×10^{14}	3.54	25.5	2.41	3
25	2004.10.17 07:05:41	33.205	137.190	14	4.8	3.36×10^{15}	1.36	11.5	1.88	5
26	2004.10.27 21:27:33	33.640	135.268	35	4.4	4.33×10^{15}	1.52	18.2	2.69	5
27	2005.02.04 01:08:47	33.973	135.510	59	4.0	1.50×10^{15}	1.85	19.7	2.63	3
28	2005.11.01 12:47:38	33.823	135.083	41	4.3	4.39×10^{15}	2.17	10.3	1.14	5
29	2005.12.24 11:01:55	35.231	136.840	41	4.8	2.20×10^{16}	1.42	20.1	2.25	6
30	2007.02.25 20:41:21	33.122	136.948	11	4.6	1.05×10^{16}	0.75	11.4	2.17	4
31	2007.07.16 17:24:19	34.261	135.947	47	4.7	1.03×10^{16}	1.25	19.4	1.63	7

D: Focal depth, M_J: Magnitude in Japan Meteorological Agency scale, N: Number of sites analyzed

Table 2. List of the earthquakes analyzed and estimated parameters (Geiyo region)

No.	Origin Time	Lat. (°)	Lon. (°)	D (km)	M_J	M_o (N・m)	f_c (Hz)	f_{max} (Hz)	s	N
1	1999.11.04 23:31:16	33.748	132.433	44	4.0	1.07×10^{15}	1.43	16.1	1.28	7
2	2000.05.04 11:02:05	33.680	132.388	50	4.0	1.39×10^{15}	1.51	15.2	1.49	8
3	2000.11.02 21:21:49	34.448	132.653	41	3.7	3.00×10^{14}	2.50	20.9	2.23	3
4	2001.01.05 05:15:06	33.775	132.532	41	4.0	1.99×10^{15}	1.40	17.0	2.01	10
5	2001.03.24 15:27:54	34.120	132.708	50	6.7	8.98×10^{18}	0.25	7.8	1.51	8
6	2001.03.24 22:37:33	33.978	132.715	41	4.1	2.65×10^{15}	1.04	10.2	1.06	9
7	2001.03.25 02:19:52	33.973	132.745	38	3.8	4.98×10^{14}	2.06	14.0	1.78	5
8	2001.03.25 19:19:11	34.022	132.750	41	4.4	6.55×10^{15}	1.31	12.5	1.81	17
9	2001.03.26 02:16:00	33.940	132.710	32	3.9	2.72×10^{15}	1.48	10.9	1.45	14
10	2001.03.26 05:40:53	34.108	132.720	38	5.0	6.43×10^{16}	0.67	8.4	1.58	19
11	2001.08.24 21:44:32	33.977	132.742	44	4.3	1.55×10^{15}	1.85	13.4	2.31	11
12	2002.03.25 22:58:17	33.820	132.617	44	4.7	1.56×10^{16}	1.07	11.5	1.78	16
13	2002.07.01 20:49:37	33.940	132.513	32	4.0	3.80×10^{14}	1.91	20.5	1.90	8
14	2002.12.20 03:48:58	33.972	132.732	38	3.8	4.52×10^{14}	2.02	15.7	2.05	8
15	2004.03.10 04:56:37	33.985	132.752	35	3.6	4.16×10^{14}	1.98	24.5	2.72	8
16	2004.09.21 10:13:17	34.253	132.757	50	4.2	2.77×10^{15}	1.76	14.4	1.83	21
17	2008.03.08 03:52:18	33.975	132.685	41	4.1	2.10×10^{15}	1.73	12.2	1.85	22
18	2008.09.19 07:23:31	33.783	132.307	56	3.8	5.67×10^{14}	2.08	11.4	1.80	8

D: Focal depth, M_J: Magnitude in Japan Meteorological Agency scale, N: Number of sites analyzed

$$\text{For Kinki region}: P_S(f) \approx \frac{1}{\sqrt{1+\left(\frac{f}{12.8}\right)^{2\times1.60}}} \tag{3.8}$$

$$\text{For Geiyo region}: P_S(f) \approx \frac{1}{\sqrt{1+\left(\frac{f}{13.5}\right)^{2\times1.60}}} \tag{3.9}$$

3.4. The Seismic Moment Dependency of f_{max}

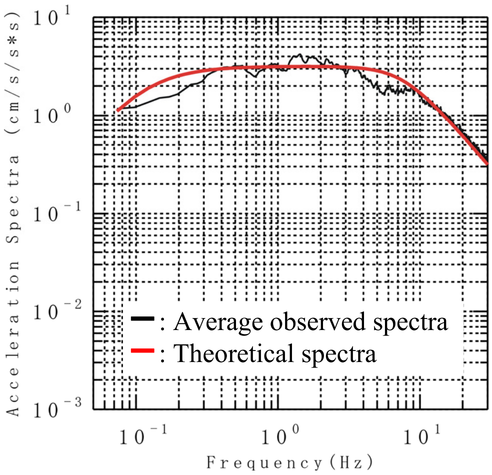
Fig.5 shows relationship between seismic moment and f_{max}. The seismic moment dependency of f_{max} is not clear especially in the case of a seismic moment is less than 10^{17} N・m. However, it can be said that the f_{max}'s of large earthquakes are smaller than those of small earthquakes.

3.5. Correction Filters, $P_C(f)$

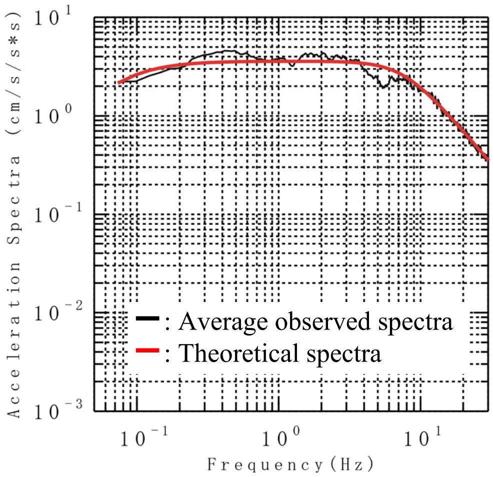
Eqn.3.10 seems to be formed as the relationship between high-cut filter of large earthquake, $P_L(f)$ and that of small earthquake, $P_S(f)$.

$$P_L(f)=P_S(f)\times P_C(f) \tag{3.10}$$

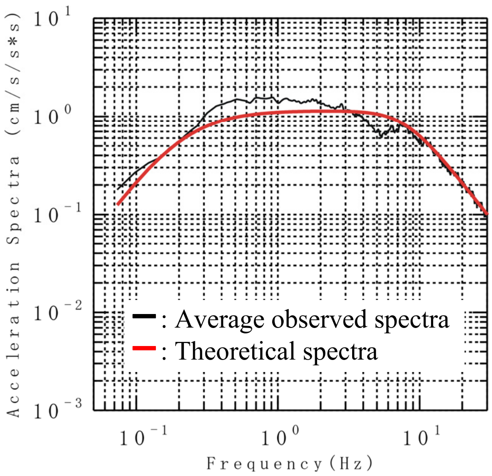
where, $P_C(f)$ is a filter to correct difference of spectral decay characteristics between large and small



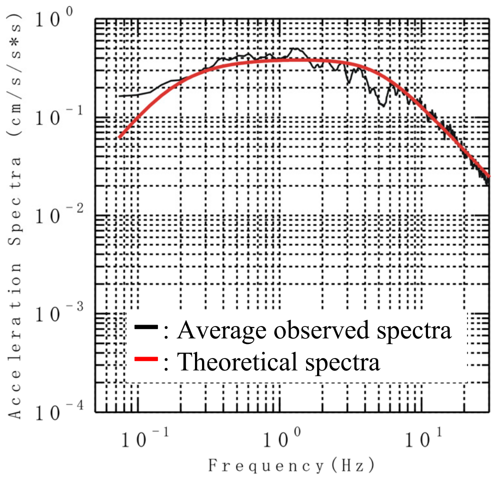
(1) EQ No.15 in Table 1 (M_w 7.2)



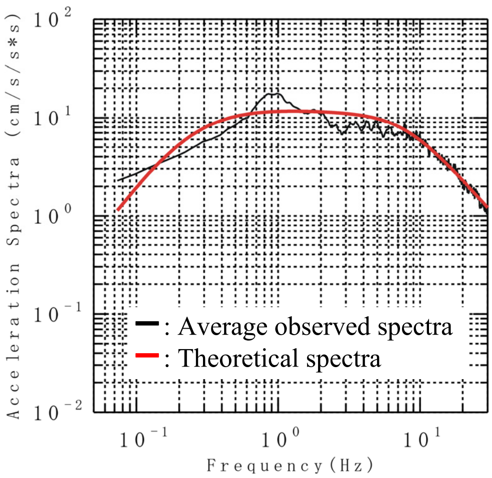
(2) EQ No.16 in Table 1 (M_w 7.5)



(3) EQ No.20 in Table 1 (M_w 6.5)



(4) EQ No.22 in Table 1 (M_w 6.1)



(5) EQ No.5 in Table 2 (M_w 6.8)

Figure 2. Comparison of observed average spectra and theoretical spectra of large earthquakes

Table 3. The high-cut filters of large earthquakes, $P_L(f)$

Earthquake		M_w	High-cut filters of large earthequakes	Eqn. No.
The foreshock of the 2004 SE off Kii peninsula earthquake	EQ No.15 in Table 1	7.2	$P(f)=\frac{1}{\sqrt{1+\left(\frac{f}{7.7}\right)^{2\times 1.69}}}$	(3.3)
The mainshock of the 2004 SE off Kii peninsula earthquake	EQ No.16 in Table 1	7.5	$P(f)=\frac{1}{\sqrt{1+\left(\frac{f}{7.7}\right)^{2\times 1.69}}}$	
The aftershock of the 2004 SE off Kii peninsula earthquake	EQ No.20 in Table 1	6.5	$P(f)=\frac{1}{\sqrt{1+\left(\frac{f}{7.9}\right)^{2\times 1.83}}}$	(3.4)
The aftershock of the 2004 SE off Kii peninsula earthquake	EQ No.22 in Table 1	6.1	$P(f)=\frac{1}{\sqrt{1+\left(\frac{f}{5.0}\right)^{2\times 1.54}}}$	(3.5)
The mainshock of the 2001 Geiyo earthquake	EQ No.5 in Table 2	6.8	$P(f)=\frac{1}{\sqrt{1+\left(\frac{f}{7.8}\right)^{2\times 1.51}}}$	(3.6)
The mainshock of the 2005 Fukuoka-ken Seiho-oki earthquake	-	6.6	$P(f)=\frac{1}{\sqrt{1+\left(\frac{f}{6.5}\right)^{2\times 0.90}}}$	(3.7)

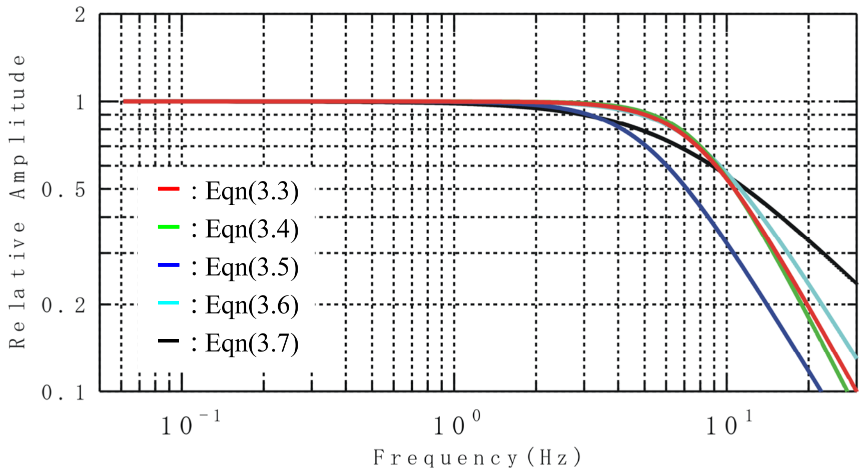


Figure 3. Obtained high-cut filter of large earthquakes, $P_L(f)$..

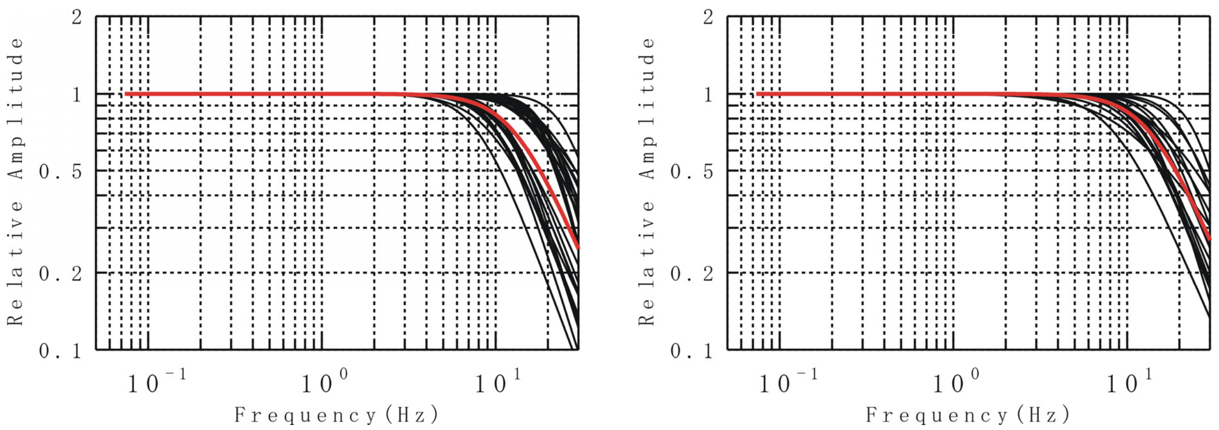


Figure 4. Obtained high-cut filter of small earthquakes, $P_S(f)$
(Left: Kinki region, Right: Geiyo region,
(Black lines are high-cut filters of each target small earthquakes. Red lines are average characteristics)

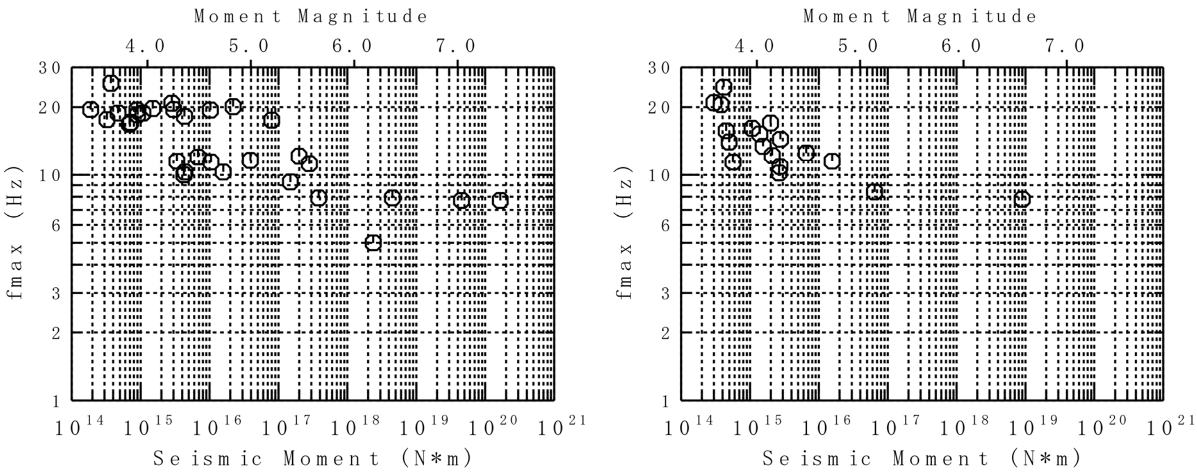


Figure 5. Seismic moment dependency of f_{max}.(Left : Kinki region, Right : Geiyo region)

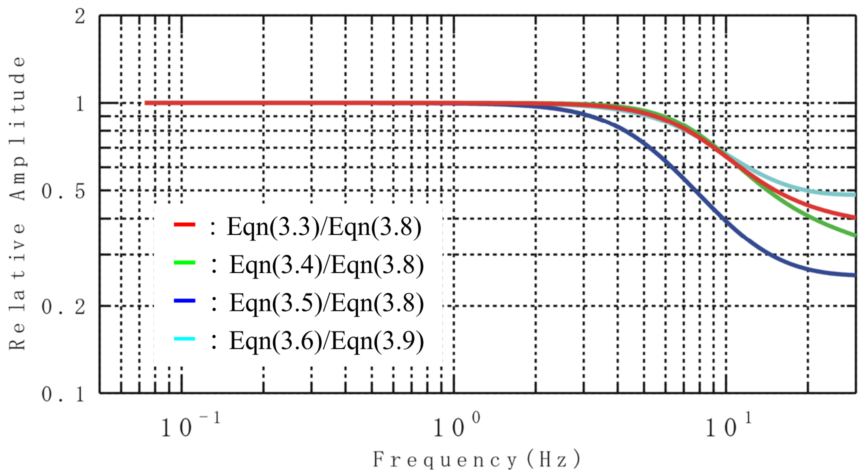


Figure 6. Filters to correct difference of spectral decay characteristics in high frequency range between large and small earthquake, $P_C(f)$.

earthquakes. It's necessary to correct predicted strong motions by $P_C(f)$, when small earthquake records are used in a process of prediction such as empirical Green's function method. **Fig.6** shows the correction filters, $P_C(f)$ that are evaluated by taking spectral ratio of high-cut filter of large earthquake, $P_L(f)$ against that of small earthquake, $P_S(f)$ for target earthquakes. The shapes of correction filters are almost same except one earthquake. The correction filter, $P_C(f)$ does not shows decaying with increasing frequency unlike $P_L(f)$ and $P_S(f)$, because, the power coefficient of high-frequency decay, *s*, of large and small earthquake are almost same.

4. CONCLUSION

In this study, spectral decay characteristics in high frequency, i.e. high-cut filter of intra-slab earthquakes occurring in Southwest Japan are evaluated to get basic information for strong ground motion prediction. In result, the f_{max}'s of the large intra-slab earthquakes are estimated about 7.8Hz. This value is almost same with those of large crustal earthquakes occurred in Japan. The power coefficients of high-frequency decay, *s*, of the large intra-slab earthquakes are estimated in the range from 1.5 to 1.8. These values are larger than those of large crustal earthquakes. The high-cut filter of the large earthquakes (M_w>=6.0) can be approximated as shown in **Table 3**. These filters are useful for strong ground motion prediction when small earthquake records are not used in a process.

The f_{max}'s of the small earthquakes (M_w<6.0) are estimated in the range about 8Hz and 25Hz. The power coefficients of high-frequency decay, *s*, of small earthquakes are estimated in the range about 1.1 and 2.9. Average characteristics of high-cut filter of the small earthquakes (M_w<6.0) can be approximated shown in Eqn.3.8 and Eqn.3.9. The seismic moment dependency of f_{max} is not clear, however the f_{max}'s of large earthquakes are notably smaller than those of small earthquakes.

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

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REFERENCES

Aki,K.(1967). Scaling relation of seismic spectrum. *Journal of Geophysical Research* **72**, 1217-1231.

Anderson,J.G. and Hough,S.E.(1984). A model for the shape of the Fourier amplitude spectrum of acceleration at high frequencies. *Bulletin of Seismological Society of America* **74**, 1969-1993.

Andrews,D.J.(1986). Objective determination of source parameters and similarity of earthquakes of different size. *Geophysical monograph* **37:6**, 259-267.

Boore,D.M.(1983). Stochastic simulation of high-frequency ground motion based on seismological models of the radiated spectra. *Bulletin of Seismological Society of America* **73**, 1865-1894.

Boore,D.M. and Boatwright,J.(1984). Average body-wave radiation coefficient. *Bulletin of Seismological Society of America* **74**, 1615-1621.

Hartzell,S.H.(1978). Earthquake aftershocks as Green's functions. *Geophysical Research Letters* **5**, 1-4.

Hanks,T.C.(1982). f_{max}. *Bulletin of Seismological Society of America* **72**, 1867-1879.

Ingber,L. and Rosen,B.(1992). Genetic algorithms and very fast simulated reannealing: A comparison. *Mathematical and Computer Modeling* **16**, 87-100.

Irikura,K.(1986). Prediction of strong acceleration motion using empirical Green's function. *Proceedings of the 7th Japan Earthquake Engineering Symposium*, 151-156.

Irikura,K., Miyake,H., Iwata,T., Kamae,K., Kawabe,H., and Dalguer,L.A.(2004). Recipe for predicting strong ground motions from future large earthquakes. *Proceedings of the 13th World Conference on Earthquake Engineering*, 1341.

Irikura,K. and Kamae,K.(1999). Strong ground motions during the 1948 Fukui earthquake - Estimation of broad-band ground motion using a hybrid simulation technique -. *Journal of the Seismological Society of Japan* **52**, 129-150. (In Japanese with English abstract)

Kamae,K., Irikura,K., and Fukuchi,Y.(1991). Prediction of strong ground motion based on scaling law of earthquake –By stochastic method-. *Journal of Structural and Construction Engineering (Transactions of AIJ)* **430**, 1-9. (In Japanese with English abstract)

Lees,J.M. and Park,J.(1995). Multiple-taper spectral analysis: A stand-alone C-subroutine. *Computers and Geo-sciences* **21**, 199-236.

Papageorgiou,A.S. and Aki,K.(1983). A specific barrier model for the quantitative description of inhomogeneous faulting and the prediction of strong ground motion II. Application of the model. *Bulletin of Seismological Society of America* **73**, 953-978.

Thomsom,D.J.(1982). Spectral estimation and harmonic analysis. *Proceedings of the Institute of Electrical and Electronic Engineers* **70**, 1055-1096.

Tsurugi,M., Kagawa,T., and Irikura,K.(2008). Study on a high-cut frequency characteristics of ground motions for inland crustal earthquakes, *Proceedings of the 14th World Conference on Earthquake Engineering*, 1341.

Wessel,P. and Smith,W.H.F.(1998). New, improved version of the Generic Mapping Tools released, *Eos Trans. AGU*, **79**, 579.