SPECTRUM OF SEISMIC WAVES AND ITS DEPENDENCE ON MAGNITUDE (1)

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In order to study the dependence of a seismic spectrum on earthquake magnitude, spectral analysis for forty-three earthquakes is made by using an analog band-pass filtering method. A number of event pairs from nine seismic regions located in continents and island arcs are selected, and spectral ratios for two earthquakes from the same epicenter region but with different sizes are studied. The spectral ratio differs among the epicentral regions. Most of the results are generally in good agreement with the ω -square model proposed by Aki, but, some of them show ω^0 or ω^{-1} -dependence. This result is consistent with the observed regional variations of the mean M_s - m_b , which was taken for the events that occurred for about four years. Though regional variations of the spectral ratio are not definitely detected, it is tentatively proposed that the main factor causing the difference may be due to the difference in the source time function among the event pairs.

1. Introduction

It is well known that the greater the size of an earthquake, the more efficiently long-period waves are generated. MATUZAWA (1964) pointed out that large local earthquakes often radiate large long-period motions of P waves. Many seismologists have shown that the periods of spectral peaks of P waves, S waves, surface waves and even of coda waves increase with earthquake magnitude (ASADA, 1953; AKI, 1956; KASAHARA, 1957; MATUMOTO, 1960; TERASHIMA, 1968).

The relation between seismic spectrum and the magnitude of an earthquake has been studied in terms of a scaling law (AKI, 1967), and it was shown that a ω -square model successfully explained observations available at that time. Recently, two models A and B revised from the original ω -square model were proposed by AKI (1972) in order to explain the recent observations accumulated in about the last 10 years. The revised model A was constructed by changing the relation between M_s and the corner period over periods less than 10 sec keeping ω^{-2} -dependence, while in model B, ω^{-1} -dependence was adopted in the period range between 10 to 0.01 sec keeping the original relation. On the other hand, BRUNE and KING (1967), and BRUNE and ENGEN (1969)

Table 1. List of the epicenter region and earthquake parameters.

Date	Time	Epicenter		<i>h</i>	<i>mb</i>	<i>Ms</i>
1 Aleutian (6, 7)						
69 May 14	19 32 54.2	51.3N	179.9W	21	6.2	7.0
69 Oct. 2	22 06 00.0	51.4N	179.2E	1	6.5	5.0*
69 Oct. 31	11 33 04.8	51.3N	179.0W	49	6.0	6.3
69 Nov. 6	20 20 18.5	51.5N	178.9W	36	5.5	5.7
71 Jan. 25	16 08 15.1	51.5N	177.7W	38	5.9	6.3
71 May 2	06 08 27.3	51.4N	177.2W	43	6.0	7.1
2 New Hebrides (186)						
70 Aug. 11	10 22 20.0	14.1S	166.7E	N	6.2	7.0
71 Oct. 25	03 46 36.3	13.1S	166.5E	34	5.5	6.2
71 Oct. 28	18 00 00.5	13.4S	166.4E	N	5.7	6.7
72 Jan. 23	21 17 52.1	13.2S	166.4E	N	5.9	7.1
72 Apr. 2	21 30 05.4	13.3S	166.1E	N	5.4	6.6
3 Near N. coast of New Guinea (200)						
70 Oct. 31	17 53 09.3	4.9S	145.5E	42	6.0	7.0
72 Jan. 18	21 55 15.5	4.8S	145.0E	N	5.7	6.6
72 Jan. 18	22 08 12.9	4.7S	145.0E	N	5.5	6.4**
72 Jan. 19	15 00 54.2	4.7S	145.0E	N	5.8	6.4
4 South of Mariana (210)						
71 Oct. 23	22 33 30.9	11.8N	142.5E	28	5.9	6.3
71 Oct. 24	01 37 30.9	11.8N	142.3E	33	6.0	6.4
71 Oct. 24	02 21 02.3	11.9N	142.3E	33	6.2	6.0
71 Oct. 26	19 05 06.2	11.9N	142.5E	33	5.6	5.1
5 Philippines (248, 249)						
70 Apr. 7	05 34 05.6	15.8N	121.7E	37	6.4	7.3
70 Apr. 12	04 01 44.0	15.1N	122.1E	24	5.9	7.0
70 Apr. 15	13 14 21.4	15.1N	122.7E	12	5.7	6.0
71 Jul. 4	11 30 51.1	15.6N	121.9E	30	5.5	5.1
70 Feb. 5	22 05 58.3	12.6N	122.1E	11	6.0	6.6
71 Apr. 29	19 56 11.6	12.6N	122.3E	4	5.5	5.7
6 North of Halmahera (264)						
69 Jan. 30	10 29 40.4	4.8N	127.4E	70G	5.9	7.2**
69 Jan. 31	00 44 13.3	4.2N	128.1E	33	5.7	6.3
69 Feb. 3	21 41 41.9	4.9N	127.4E	N	6.1	6.4
69 Feb. 17	00 42 59.2	3.8N	128.4E	14	5.6	6.5
69 Feb. 20	09 55 33.8	3.5N	128.2E	33	5.7	6.4
Northern Celebes (265)						
68 Aug. 14	22 14 19.4	0.2N	119.8E	23	6.0	7.4
69 Feb. 4	01 38 26.2	0.6S	121.7E	33	4.8	6.1
7 Yunnan Province (318)						
70 Jan. 4	17 00 40.2	24.1N	102.5E	31D	5.9	7.5
70 Feb. 6	22 10 41.6	23.1N	100.8E	N	5.4	6.1
71 Apr. 28	15 32 00.9	22.9N	101.0E	15	5.6	6.3
8 Iran (348)						
68 Aug. 31	10 47 37.4	34.0N	59.0E	13	6.0	7.3
68 Sep. 1	07 27 30.2	34.0N	58.2E	15	5.9	6.3
9 Sakhalin (662)						
71 Sep. 5	18 35 25.0	46.5N	141.2E	9	6.3	7.1
71 Sep. 6	13 37 10.8	46.7N	141.4E	29	6.1	5.5
71 Sep. 8	11 48 23.4	46.4N	141.1E	6	5.9	6.6
71 Sep. 8	16 59 52.6	46.3N	140.9E	16	5.9	6.2
71 Sep. 27	19 01 45.3	46.4N	141.1E	21	5.9	6.0

* Underground explosion.

** *Ms* determined by Pasadena.

studied the amplitude ratio of 100 sec to 20 sec period surface waves as a function of magnitude, and concluded that the spectral amplitudes for earthquakes with magnitudes from 6.0 to 8.4 were more consistent with ω^{-1} -dependence than the ω^{-2} -dependence proposed by AKI (1967).

The purpose of the present paper is to obtain the spectral ratio for many pair events with different magnitudes from various seismic regions. It is hoped that the present study will contribute to the study of the spectral ratio for the source spectrum in terms of physical factors such as the effective stress, the orientation and shape of fault plane, crust-mantle structure *etc.* The present method will also be useful for comparing the spectra among foreshocks, main shocks, and aftershocks.

2. Data

The data used in this study were obtained at the Dodaira Micro-Earthquake Observatory (DDR). The DDR station has made continued observations by using a magnetic tape recording system since the end of 1967. Earthquakes with body-wave magnitudes larger than about 5.0 are transcribed on a commercial $\frac{1}{4}$ inch tape, and these tapes are preserved as a permanent data library.

Event groups whose epicenters were located within about 100 km from each other were selected from our tape library. Origin time, epicenter loca-

Fig. 1. Epicenter locations of the earthquake pairs used in the present study.

tion, depth (h), body-wave magnitude (mb) and surface-wave magnitude (M_s) were taken from the PDE cards of the United States NOAA.

Forty-three earthquakes were finally selected, in the range of $mb=4.8-6.5$ (or $M_s=5.0-7.5$), during 1968-1972. Table 1 lists the parameters of the events separately in each region. Figure 1 shows the epicenter locations of the nine selected event groups. Some of them belong to island arc regions and the other to continental regions.

3. Seismograph

In order to obtain a spectrum over a relatively wide frequency range, three kinds of seismograph i.e., medium-period (MP), long-period (LP) with high and low magnifications and ultra-long-period (ULP) seismographs are used. A detailed description of the seismograph system is given by TSUJIURA (1965, 1967). The magnification curves are shown in Fig. 2.

The ULP seismograph was newly constructed for the present purpose, and we shall describe it in some detail here. The DDR Seismological Observatory is a telemetering station, and all seismic signals to our Institute are telemetered by microwave (6780 MHz) and recorded together with telemetered signals from other satellite stations. Therefore, the operation of the seismograph system has been kept in more stable condition than that at ordinary stations. In order to prevent drift of seismometer pendulum, we adopted a comparatively short-period pendulum ($T_0=8$ sec), and also to suppress short-period seismic waves, heavy damping of $h=10$ is applied by using copper as a

Fig. 2. Magnification curves of the seismographs used.

Fig. 3. Comparison of the seismograms recorded on the LP and ULP seismographs. G denotes the gain of the seismograph.

bobbin of the main coil. The output power from a moving-coil type transducer is 190 volt/kine, and this output signal is fed to two DC amplifiers which are connected in series, and a RC-integrating circuit equivalent to the characteristics of a 360 sec galvanometer is inserted between the two amplifiers.

Figure 3 shows a comparison of the seismograms recorded with the LP (low magnification) and ULP seismographs. It is clearly seen that longer period components ($T > 60$ sec) are recorded on the ULP seismogram much larger than on the LP seismogram.

4. Analog-type Spectrum Analyzer

In order to process a large amount of data and also to see the detailed spectral structure of the waves, an analog-type spectrum analyzer is used. This analyzer is the same as that described by TSUJURA (1967) except for a difference in the center frequencies of the filters used. In the present analysis,

Table 2. Center frequency and channel number of the band-pass filters.

CH No.	No. 1		No. 2	
	Center Freq. Hz	Center Period sec	Center Freq. Hz	Center Period sec
1	0.012	85.0	0.11	8.95
2	0.024	42.5	0.14	7.10
3	0.047	21.3	0.18	5.62
4	0.094	10.7	0.22	4.47
5	0.187	5.35	0.28	3.56
6	0.374	2.68	0.36	2.81
7	0.746	1.34	0.45	2.23
8	1.51	0.66	0.56	1.79
9	3.03	0.33	0.71	1.41
10	6.06	0.17	0.89	1.12
11	12.1	0.08	1.12	0.89
12	24.2	0.04	1.41	0.71

two kinds of band-pass filters are used. One is a filter group with a one octave bandwidth (No. 1) and the other is with a $\frac{1}{3}$ octave bandwidth (No.2). The frequency allotments of the filters are shown in Table 2.

5. Method of Analysis

Our method for extracting the source spectrum is to compare the spectra observed from many earthquakes which share similar propagation paths. For this purpose, we compared the waveforms of the events with almost the same location and depth. In routine observations at our station, it has been recognized that seismic waves emitting from the same location and with similar sizes often show very similar waveforms. If we assume that the source mechanisms of these earthquakes with different sizes are the same, the difference in the spectra of these events may be directly explained in terms of the source spectrum, since the effects of propagation path are common. This idea is the same

Fig. 4. Comparison of seismograms of two earthquakes with almost the same magnitude in the same region.

Fig. 5. Comparison of seismograms of two earthquakes with different magnitudes (M_s) in the same region.

as that of BERCKHEMER (1962). Under this assumption we compared seismic waves from earthquakes having epicenters within about 100 km from each other but with different sizes.

Typical examples of the original records for two events with almost the same location and magnitude are shown in Fig. 4. Similarity of the waveforms in the two events is surprising. Figure 5 shows three-component seismograms for two earthquakes of different sizes which took place at almost the same location. These seismograms also show similar waveforms, although their magnitudes (M_s) differ by 0.8. In some cases, waveforms are not similar among the events even within 100 km, but these events are rejected in the present study.

Figure 6 shows the analyzed data for two events from the Yunnan Prov-

Fig. 6. Comparison of filtered seismograms for an event pair in the Yunnan Province, China, region.

Fig. 7. Amplitude ratio of an event pair with M_s of 6.3 and 6.1 in the Yunnan Province, China, region. Open circles and open circles with a cross mark show the ratios for surface- and P -waves respectively.

ince, China, region. The numerals from 1 to 5 indicate the channel number of the band-pass filter used (cf. Table 2). Each two traces in a channel indicate the filtered seismograms. The two traces give more clear similarity than those of the original records.

In order to obtain the spectral ratio for pair events, the amplitude of peaks and troughs for several periods is measured on the corresponding traces, and the relation between amplitude ratio and period is finally obtained from all five traces. However, rather high noise is included especially in the longer period channel (CH 1). In the case of signal-noise ratios smaller than a factor of three, we discarded the data. For the estimate of noise amplitudes, we took a value averaged over 10 min before P wave arrival. The result for surface waves is shown in Fig. 7. The larger event has longer period components than the small one. This tendency is more remarkable for events with a large difference of M_s . Figure 8 shows the result for a pair of events in the Yunnan Province, China, region. The difference of M_s is 1.4 and 1.2, respectively. The amplitude ratio of the surface waves is obtained by the long-period seismographs which have two levels of magnification, and that of P wave is by the medium-period seismograph. We made this kind of analysis for the earthquakes tabulated in Table 1 by use of the same technique. Although the number of earthquakes in each region was not large enough, the relation between spectrum and magnitude could be roughly estimated.

6. Regional Peculiarity of the Period Dependence

We classified the Aleutian region into two groups. One of the groups indicated by A is around 180°W (longitude) and the other indicated by B is around 177°W . The purpose of the selection of the area A is to compare the spectrum of earthquakes and that of underground explosions which took place in the same area. Figure 9 shows the spectral ratio of two events which took

Fig. 8. Amplitude ratio of event pairs having almost the same epicenter location in the Yunnan Province, China, region. The numerals indicate the earthquake magnitude for the pair. Open and closed circles show the ratios for Rayleigh waves, and open and closed circles with a cross mark are those of the P waves, respectively.

place in the area B. Figure 10 shows the ratios in the area A. Closed and open circles show the ratios for events with M_s ratios of 7.0/6.3 and 7.0/5.7, respectively. We see that the ratios are nearly constant over the period range between 8–80 sec, although their magnitudes differ by 0.7 and 1.3. This result is definitely different from the result for the China event. Crosses in the same figure show the spectral ratio of surface waves between an earthquake and an underground explosion. The ratio also shows nearly flat characteristics over the period range between 10–40 sec.

Figure 11 shows the spectral ratio of P waves between the explosion and earthquakes, and between different earthquakes. The ratio at about 1.3 sec period in the former pair is very predominant, and the ratio for relatively long-periods ($T > 1.5$ sec) decreases rapidly, comparing with those of the earthquake pairs. This may be due to the difference of source dimension among the earthquake and explosion. Wyss *et al.*, (1971) concluded that the source

Fig. 9. Amplitude ratio of an event pair having almost the same location in the Aleutian region. Explanation of the symbols used is the same as those in Fig. 8.

Fig. 10. Amplitude ratio of an event pair having the same location in the Aleutian region. The event of 5.0 is an underground explosion.

radius of an explosion is at least an order of magnitude less than the earthquake dimension. However, it must be noted that the ratio of surface waves for the earthquake/explosion does not show the difference clearly as is indicated by the P wave ratio.

Fig. 11. Amplitude ratio of P waves for event pairs having almost the same location in the Aleutian region. Open and closed circles show the ratios of explosion versus earthquake pairs, and open and closed circles with cross mark are the ratios of earthquake versus earthquake pairs, respectively.

In contrast, for events in the North coast of New Guinea and New Hebrides regions, remarkable period dependence of the ratio can be seen in Fig. 12, although the magnitude difference is much smaller than in the Aleutian region. Almost the same tendency is seen in event pairs from Halmahera, Celebes and Sakhalin in Fig. 12, respectively. The ratios for the Mariana events in Fig. 12 are not enough to obtain the period dependence, because the ratio for 6.4/5.1 cannot be obtained at short-period range. For events in the Philippine region (Luzon), the spectral ratios among six event pairs are also shown in Fig. 12. In spite of large difference in M_s (up to 2.2), the spectral ratios vary relatively less with periods than those in other regions except in the Aleutian. Almost the same tendency can be seen in an event pair for the Iran region as is shown in the same figure.

From above comparison of the spectral ratios, it can be shown that there are three groups in the period dependence. The 1st group is the event pairs

Fig. 12. Amplitude ratio of event pairs having almost the same location in nine seismic regions.

belonging to regions of China, New Guinea, New Hebrides, Halmahera and Sakhalin. The 2nd group is regions of the Philippines and Iran. Spectral variation of the 1st group is remarkable, comparing with those of the 2nd group. The 3rd is the events in the Aleutian region, and the spectral ratio for this region varies relatively less with periods than in the other groups. The above results suggest that regional variations of the spectral ratio seem to exist. Generally speaking, however, difference of an order of magnitude can sometimes be seen among the magnitudes estimated at different stations, in the EDR cards. This tendency is seen also in the present result, in which the absolute ratio at 20 sec period is not always consistent to the ratio expected from M_s of the CGS. Even if the uncertainty for magnitude determination were considered, regional difference of the spectral ratio seems to exist there.

In order to obtain the period dependence at shorter period range, the spectral ratio for *P* waves are studied; the amplitude of surface waves at periods less than about 10 sec decreases with decrease of period. Some of the results were shown in the previous figures. These figures show much scattering than those of surface waves except the explosion, and no firm conclusion can be obtained. For the present study, surface waves from near earthquake are much more useful than *P* waves from teleseismic events.

Figure 13 shows the seismogram of surface waves from 5 near events whose epicenters are located within 50 km each other. Source parameters

Fig. 13. Surface wave seismograms from near earthquakes with almost the same location.

Fig. 14. Amplitude ratio of near earthquake pairs having almost the same location.

(location, M and h) are taken from the Seismological Bulletin of Japan Meteorological Agency (JMA). A very similar wave-form can be seen among the events. Figure 14 shows the spectral ratio for pair events. Although the ratio still shows scattering in the short-period range ($T \approx 1.5$ sec), the ratio increases with increasing period ($T > 3$ sec). The scattering around 1.5 sec may be due to the effect of source depth. It is noticed that surface waves of deeper events contain relatively larger short-period components than that of shallow events. We present here only an example of near events. A more detailed comparison of spectral ratio for near events will be shown in a separate paper.

Another important feature of this study is the comparison of the scaling

Fig. 15. Comparison of the theoretical and observed amplitude ratios, plotted against periods, for event pairs having almost the same epicenter location in the nine seismic regions. Solid and dash-dot lines denote ω^{-2} model (Ak1, 1967) and ω^{-1} model (Ak1, 1972) respectively.

law of the seismic spectrum proposed by AKI (1967, 1972). The spectral ratios compared with those of Aki's models are shown in Fig. 15. Solid and dash-dot lines denote the predicted ratios for the ω^{-2} and ω^{-1} models which are determined from the figures 3 of AKI (1967) and 5 of AKI (1972) based on the ω -model of BRUNE and KING (1967) respectively. As is shown in this figure, it is rather difficult to conclude which model of ω^{-2} and ω^{-1} has good agreement with the observed ratio. However, if we dare to conclude that, the spectral ratios in regions of China, New Guinea, New Hebrides and Halmahera are in good agreement with ω^{-2} model than with ω^{-1} model. On the contrast, the spectral ratios in regions of the Philippines and Iran are in better agreement with ω^{-1} model. The spectral ratio in Aleutian does not agree with both models and shows nearly constant in the period range of 8–80 sec. It may be concluded that the spectral ratio in Sakhalin does not agree with any models since the ratio shows too much scattering for the model. As mentioned before, however, there is some difference in the magnitudes of a given earthquake estimated at different stations. Furthermore, the scaling law of the seismic spectrum applies to the source spectrum for individual earthquakes, while our result represents only the spectral ratio; the scaling law indicates the absolute value and the present study indicates the relative value. Considering the uncertainty for the magnitude and the difference in the basic method, it is noted that in this experiment, an uncertainty in the relation between the observed and predicted ratios might exist.

7. *Ms*–*mb* Relation

Since May, 1968 the USCGS (NOAA, NOS) has determined the surface-wave magnitude for shallow events ($h < 50$ km) using the amplitude for 20 sec-period surface waves. This magnitude is designated as *Ms*. We studied the *Ms*–*mb* relation in order to see its period dependence, as mentioned above.

The amplitude of short-period waves may be closely related to the rise time of fault slip at the source. The events with shorter rise time may generate larger short-period waves than that of long rise time for the same *Ms*. A most extreme case is the difference for seismic waves from underground explosions and earthquakes. LIEBERMANN *et al.*, (1966) and LIEBERMANN and POMEROY (1967, 1969) illustrated a significant difference in the *Ms* versus *mb* relationship between earthquakes and underground explosions. The underground explosions generated smaller surface waves than earthquakes for comparable *mb*. Different dimension of the seismic source in space and time was introduced in order to explain such relationship (LIEBERMANN and POMEROY, 1969). WYSS and BRUNE (1968, 1971) suggested that an order of magnitude difference for the source dimension can be found in earthquakes of the California region.

Table 3. Minimum and maximum M_s of the events used for the calculation of the mean value of M_s-mb for each region. N ; Number of shocks used.

Region		M_s min.	M_s max.	N	M_s-mb mean
Aleutian	7	4.6	7.1	20	0.07
New Hebrides	186	4.7	7.1	37	0.31
New Guinea	200	4.8	7.0	15	0.40
Mariana	210	4.9	6.4	7	-0.17
Philippines	248	4.4	7.0	11	0.03
Philippines	249	5.1	7.3	15	0.29
Halmahera	264	4.8	6.5	16	0.20
Celebes	265	4.7	7.4	6	0.43
Yunnan	318	4.8	7.5	6	0.52
Iran	348	4.8	7.3	7	0.17
Sakhalin	662	5.2	7.1	6	0.33

(3) In Iran (348) the mean M_s-mb shows an intermediate value and the ratio indicates the ω^{-1} -dependence. Although the difference of the range for the data of M_s and the distribution of M_s (i.e., at the boundary of $M_s=6\frac{3}{4}$) among the regions must be taken into account in the value of M_s-mb , this behavior might be attributed partly to the difference in the time function at the source. A multiple shock is a good example to explain this; the spectrum of long-periods for multiple shock will increase proportionally to the number N of events, while, short-period spectrum will be proportional to $\sqrt{N}$. Thus, the value of M_s-mb for multiple shock should be larger than that of normal shock. Great earthquakes are often reported as multiple shock by MIYAMURA *et al.*, (1965) and WYSS and BRUNE (1967). It is expected that such multiple shock may occur in intermediate-size earthquakes ($M_s \approx 7$) in certain regions.

8. Discussion and Conclusion

Spectral analysis for forty-three earthquakes was made by using an analog band-pass filter method. From comparison of spectral ratios for nine seismic regions, it is suggested that the regional characteristics of the ratio seems to exist there. The spectral ratios for six of the nine regions show relatively good agreement with the ω -square model proposed by AKI (1967), while the spectral behavior observed in three regions of Aleutian, the Philippines and Iran shows some deviations from the ω -square model. The ratio for the Aleutian events shows a nearly flat characteristics (ω^0) for the period range of 8–80 sec. The ratios for the Philippine and Iran regions show an intermediate value among the two models.

The mean value of M_s-mb was determined for each seismic region. The regions with large spectral ratios have relatively large value of M_s-mb , and

the variations of the mean M_s - m_b seem to be consistent to the variations of the spectral ratios.

The scaling law of the seismic spectrum proposed by AKI (1967, 1972) was based on a similarity assumption between large and small earthquakes. However, the results of the present study demonstrate that the scaling law does not always apply to all epicentral regions. If our result is true, the similarity assumption should be modified. For example, the stress drop for a given earthquake may be different in different regions (THATCHER, 1972). Unfortunately, quantitative discussion against the scaling law cannot be made in the present study, because our result represents only the relative ratio for many pair events, as pointed out in section 6.

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