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Research on local magnitude (M_L) scale in and near the Korean Peninsula

Ik Bum Kang, Myung-Soon Jun and Jin Soo Shin
Korea Earthquake Research Center of Korea Institute of Geology, Mining and Materials, Daejon, Korea

Abstract
After synthesizing Wood-Anderson seismograms from broadband recordings at FDSN stations (BJT, SSE, INCN and MDJ) in and near Korea, the empirical equations, for the vertical and horizontal components, respectively, for determination of local magnitude (M_L) in and near Korea, were estimated through a process of regression. Around 200 data, from events with epicentral distance (Δ) ranging from 50 km to 1000 km, measured from synthetic Wood-Anderson seismograms were used. According to the regression with the constraint that the magnitude for an amplitude of 0.001 m measured at epicentral distance of 100 km is 3, the empirical formula ($\log_{10} A_0$) for the horizontal components is, with standard deviation (σ) of 0.52, $M_L = \log_{10} A(\Delta) + 1.71 \log_{10} A_0 (\Delta) - 0.42 + C$, and that for the vertical components is, with standard deviation (σ) of 0.56, $M_L = \log_{10} A(\Delta) + 1.70 \log_{10} A_0(\Delta) - 0.4 + C$, where, C is a station correction factor and A is the amplitude. This result shows that the attenuation in and near Korea is stronger than that in the East United States (Kim, 1998) and weaker than that in South California (Kanamori *et al.*, 1993).

Key words *Wood-Anderson seismograms – local magnitude (M_L) – epicentral distance – regression – attenuation*

1. Introduction

Among the various methods for estimating the size of earthquakes, magnitude scales have been introduced due to their simplicity.

There are several magnitude scales which can be used nowadays to measure the quantitative size of earthquakes locally and teleseismically, such as, M_L for local magnitude, $m_b(Pg)$ for magnitude on 1 s period *Pg* phase waves, $m_b(Lg)$ for magnitude on 1 s period *Lg* waves, M_s for magnitude on long-period surface waves, and M_N for magnitude on 2 to 10 Hz *Lg* waves.

Among other magnitude scales, for estimation of magnitude scale for local and regional earthquakes, the geological structure of the local area must be seriously taken into consideration. So, empirical equations for estimation of local magnitude scale must be developed.

To develop empirical equations for local magnitude M_L, synthetic Wood-Anderson seismograms have become widely used by deconvolution of the recording instrument response and convolution of the signal with the standard Wood-Anderson torsion seismograph which has a natural period (*To*) of 0.8 s, damping factor (*H*) of 0.8, and static magnification (*V*) of 2800 (Anderson and Wood, 1925; Richter, 1935; Bakun *et al.*, 1978) (fig. 1).

After synthesizing Wood-Anderson seismograms from each record, maximum amplitude of synthetic seismograms in horizontal and vertical components can be used to determine the coefficients of the empirical formula as indicat-

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Mailing address: Dr. Ik Bum Kang, Korea Earthquake Research Center, KIGAM, 30 Kajung-Dong Yusung-Ku, Daejon, Korea; e-mail: kang@rock25t.kigam.re.kr

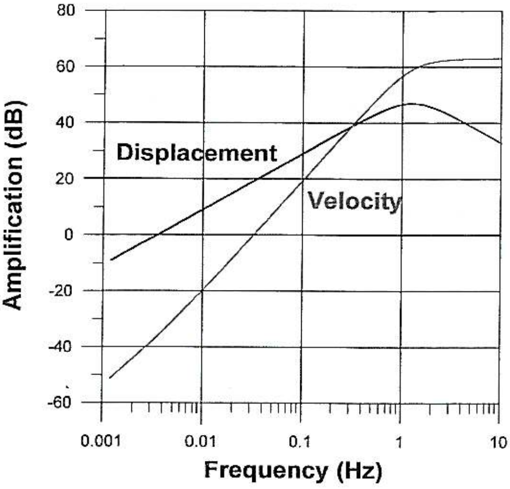

Fig. 1. Intrument response of the Wood-Anderson seismometer.

ed below:

$$M_L = \log_{10}A(\Delta) - \log_{10}A_0(\Delta) + C \qquad (1.1)$$

where, $A(\Delta)$ is the maximum signal amplitude in millimeters after simulating synthetic Wood-Anderson seismogram at the epicentral distance (Δ) in kilometers and $\log_{10}A_0(\Delta)$ is strongly related to the attenuation due to local geology. To measure $A(\Delta)$, one half of peak-to-peak maximum amplitude in millimeters in used. C is a coefficient for the empirical formula which is strongly dependent upon the local geological structure. Amplitude decay of the signal, obtained empirically from the slope of the maximum amplitude *versus* epicentral distance, is due to attenuation factors, anelasticity, scattering, and geometrical spreading governed by local geology.

To calculate the empirical formula, observed amplitudes, $A(\Delta)$, of approximately 200 synthetic vertical, N-S, and E-W component Wood-Anderson seismograms were used. Those data were measured from events in the epicentral distance ranging approximately from 50 km to 1000 km and were chosen from local events with magnitude ranging from about 2.5 to 5.0 published by KMA (Korea Meteorological Agency) and ISC (International Seismological Center) and were recorded at 4 stations (INCN, SSE, BJT, and MDJ). More data like KSRS and local stations of Korea will be added in future.

2. Procedure

To measure maximum amplitude in 3-C (N-S, E-W, vertical) for calculation of local magnitude (M_L), Wood-Anderson seismograms should be simulated from recording signals recorded at each station.

The recording signal (f), obtained at each station, can be expressed by convolving 3 factors, source (s), ground motion (g), and instrument response (i), as functions of time (t)

$$f(t) = s(t) \cdot g(t) \cdot i(t). \qquad (2.1)$$

If correct information on corresponding instrument response (i) is available, the ground motion (g) will be extracted from the recording signal (f) by deconvolving with corresponding instrument response in the frequency domain

$$G(\omega) = F(\omega)/I(\omega) \qquad (2.2)$$

where, $F(\omega)$ and $I(\omega)$ are obtained by performing the Fourier Transform of $f(t)$ and $i(t)$, respectively. $G(\omega)$ is equal to the convolution of the source (s) and ground motion (g) in the frequency domain. For instrument response (I), filtering, gain, and sensitivity as well as sensor response should be included. As the last step to synthesize the Wood-Anderson seismogram, the standard Wood-Anderson torsion instrument response (natural period of 0.8 s, damping constant of 0.8, and static magnification of 2800; Richter, 1935) is convolved with the signal resulting after deconvolution of the recording instrument response.

The transformation of the original signal $f(t)$ to the synthetic Wood-Anderson seismogram $f_{WA}(t)$ can be summarized as follows:

1) Deconvolution of the original signal with instrument response.

2) Convolution of the W-A instrument response after (1).

3) Inverse FFT after (2).

Table I. Events list used for this research.

Date Y M D	Lat. °N	Long. °E	$h(b)$ (km)	Magnification (M_b)	Reference
			1994		
94-02-12	36.4	127.3	0	3.5	KMA
94-03-04	37.53	118.81	8	3.5	ISC
94-04-21	35.85	131.07	25	5.1	ISC
94-04-23	35.88	131.12	26	5.1	ISC
94-04-23	35.82	131.11	26	4.5	ISC
94-07-25	34.98	124.47	21	5.0	ISC
94-09-12	40.53	122.10	12	4.2	ISC
94-10-14	38.8	125.6	0	3.5	KMA
94-10-22	41.70	120.37	20	4.5	ISC
94-11-07	35.07	121.80	15	4.0	ISC
94-12-01	37.9	123.8	0	3.6	KMA
			1995		
95-02-01	40.90	122.50	39	3.9	ISC
95-02-22	39.53	118.39	15	3.4	ISC
95-04-15	40.92	122.47	26	4.6	ISC
95-05-20	32.59	121.60	33	3.4	ISC
95-07-24	38.03	124.30	12	5.2	ISC
95-08-11	38.03	124.40	16	3.9	ISC
95-09-07	36.60	133.20	33	3.9	ISC
95-09-20	34.92	118.10	36	4.7	ISC
95-10-05	39.73	118.53	13	4.6	ISC
95-10-06	37.20	130.00	55	4.3	ISC
95-10-07	35.6	129.7	0	3.5	KMA
95-10-07	35.62	130.08	44	4.0	ISC
95-12-21	44.80	120.70	18	3.9	ISC
			1996		
96-01-01	37.9	129.6	0	4.2	KMA
96-01-19	35.31	124.2	22	3.9	ISC
96-01-23	37.50	129.61	57	4.2	ISC
96-02-08	39.2	126.4	0	3.1	KMA
96-04-08	39.7	118.4	5	3.6	ISC
96-04-13	35.9	127.9	0	3.1	KMA
96-05-05	42.8	117.2	33	3.3	ISC
96-05-16	34.4	125.5	0	3.5	KMA
96-07-17	41.95	120.51	16	4.7	ISC
96-07-22	40.74	122.5	15	3.8	ISC
96-07-27	38.6	121.9	6	3.5	ISC
96-08-13	38.4	120.0	33	3.7	ISC
96-08-14	36.7	128.0	0	3.0	KMA

Table I *(continued)*. ISC (I

Date Y M D	Lat. °N	Long. °E	*h*(*b*) (km)	Magnification (M_b)	Reference
1996					
96-09-14	38.72	125.93	19	4.1	ISC
96-10-15	36.1	128.3	0	3.3	KMA
96-11-10	36.7	125.4	0	3.5	KMA
96-11-16	38.89	127.4	15	3.8	ISC
96-11-17	33.4	121.1	33	3.8	ISC
96-12-09	39.18	118.4	12	3.6	ISC
96-12-12	39.8	118.0	22	3.2	ISC
96-12-13	37.19	128.75	10	4.7	ISC
96-12-13	37.2	128.8	0	3.0	KMA
96-12-14	37.2	128.6	0	2.7	KMA
96-12-15	37.3	128.6	0	2.5	KMA
96-12-15	40.24	116.69	10	4.5	ISC
96-12-16	40.0	116.68	14	3.7	ISC
96-12-18	37.3	128.6	0	2.7	KMA
96-12-20	37.3	128.8	0	2.8	KMA
1997					
97-01-14	35.19	121.19	38	3.8	ISC
97-01-14	38.3	128.7	33	3.2	KMA
97-02-06	38.7	118.12	11	3.8	ISC
97-02-18	39.83	116.0	15	3.4	ISC
97-02-28	39.22	118.9	18	3.4	ISC
97-03-31	33.581	121.249	33	4.2	PDE
97-04-12	38.314	120.526	33	4.5	PDE
97-05-09	35.1	126.0	0	3.2	KMA
97-05-09	35.1	126.0	0	3.0	KMA
97-05-21	36.0	126.8	0	3.5	KMA
97-05-25	40.938	115.235	33	4.2	PDE
97-06-11	41.384	122.741	33	?	PDE
97-06-25	33.628	122.079	10	?	PDE
97-06-25	35.820	129.189	10	4.7	PDE
97-07-27	33.560	122.193	10	4.8	PDE
97-08-09	35.142	124.730	10	?	PDE
97-09-05	37.375	134.371	26	4.6	PDE
97-09-18	38.075	121.196	33	4.8	PDE
97-10-07	41.928	121.074	33	?	PDE
97-10-11	35.9	128.7	0	3.2	KMA
97-10-18	37.3	128.8	0	3.0	KMA
97-11-10	37.8	125.4	0	3.0	KMA

Table I (*continued*).

Date Y M D	Lat. °N	Long. °E	*h*(*b*) (km)	Magnification (M_b)	Reference
			1998		
98-01-10	41.083	114.500	30	5.8	PDE
98-01-10	41.244	114.458	33	?	PDE
98-01-10	41.012	114.578	33	?	PDE
98-01-17	35.540	130.025	33	?	PDE
98-01-22	41.357	115.380	33	3.6	PDE
98-01-29	40.191	123.225	10	3.6	PDE
98-02-08	39.332	122.275	33	?	PDE
98-02-10	37.711	123.507	10	4.3	PDE
98-04-14	39.692	118.649	33	4.6	PDE
98-06-02	41.140	114.497	10	4.8	PDE
98-06-02	41.234	114.648	33	4.5	PDE
98-06-08	38.5	124.3	0	3.7	KMA
98.06.08	36.7	125.2	0	2.8	KMA
98-07-14	41.221	114.368	33	?	PDE
98-07-27	41.250	114.886	33	?	PDE
98-07-27	41.216	114.644	33	4.3	PDE
98-08-13	41.151	114.522	33	4.3	PDE
98-08-15	38.439	119.163	33	?	PDE
98-08-30	32.704	121.604	33	?	PDE
98-09-03	36.442	125.683	10	?	PDE
98-09-06	40.754	120.164	33	4.1	PDE
98-09-13	36.096	127.204	10	?	PDE
98-12-19	43.445	116.417	10	?	PDE
			1999		
99-01-11	38.30	128.70	10	4.2	PDE
99-01-12	38.30	128.60	10	2.9	PDE
99-01-29	44.657	115.705	10	4.9	PDE
99-02-23	37.031	125.828	33	3.3	PDE
99-03-05	40.50	126.30	33	3.5	PDE
99-03-11	41.131	114.658	33	5.1	PDE
99-03-12	41.330	114.809	10	4.2	PDE
99-03-13	41.257	114.763	33	?	PDE
99-03-19	41.298	114.483	10	?	PDE
99-03-24	33.826	120.550	33	3.6	PDE
99-04-07	37.20	128.90	33	3.3	PDE
99-04-07	37.20	128.90	33	2.9	PDE
99-04-07	37.20	128.90	33	2.6	PDE
99-04-09	37.20	128.90	33	2.8	PDE
99-04-23	36.00	129.30	33	3.2	PDE
99-05-12	40.390	118.839	33	?	PDE
99-05-15	39.571	113.574	10	4.4	PDE

3. Data analysis

In this research, about 200 data were chosen from 96 events, with epicentral distance, ranging approximately from 50 km to 1000 km, which occurred near and in the Korean Peninsula from 1994 to 1999 as shown in table I and recorded at INCN, SSE, BJT, and MDJ, all of which 3-C FDSN (Federation of Digital Broadband Seismograph Network) stations. The area covered by the wave paths from event sources to the stations includes the eastern part of China, the Yellow Sea, and the northern part of North Korea as well as the Korean Peninsula (fig. 2).

Seismometers of INCN which is located in the Western Korean Peninsula and have been operating since 1995 are the broadband STS-1 and STS-2 produced by Streckeisen.

The SSE station, which is one of IMS (International Monitoring System) auxiliary seismic stations of CTBT (Comprehensive Nuclear-Test Ban Treaty) is located in Shanghai, China, in a southwestern direction from the Korean Peninsula. The broadband seismometer of SSE which has been operating since 1986 in the Streckeisen STS-1.

The BJT station, which is functioning as an IMS auxiliary station and has been activated as an FDSN seismic station since 1994, is located in Beijing in a northwestern direction from the Korean Peninsula. The MDJ station located in a northeastern direction from Korea has been working as an important seismic station in East Asia since 1986. The broadband seismometers of BJT and MDJ are also Streckeisen STS-1.

The STS-1 and STS-2 manufactured by Streckeisen are known to be designed for installation with ease and simplicity, for operation in a wide temperature range, and for transport with convenience. The resolving minimum earth noise

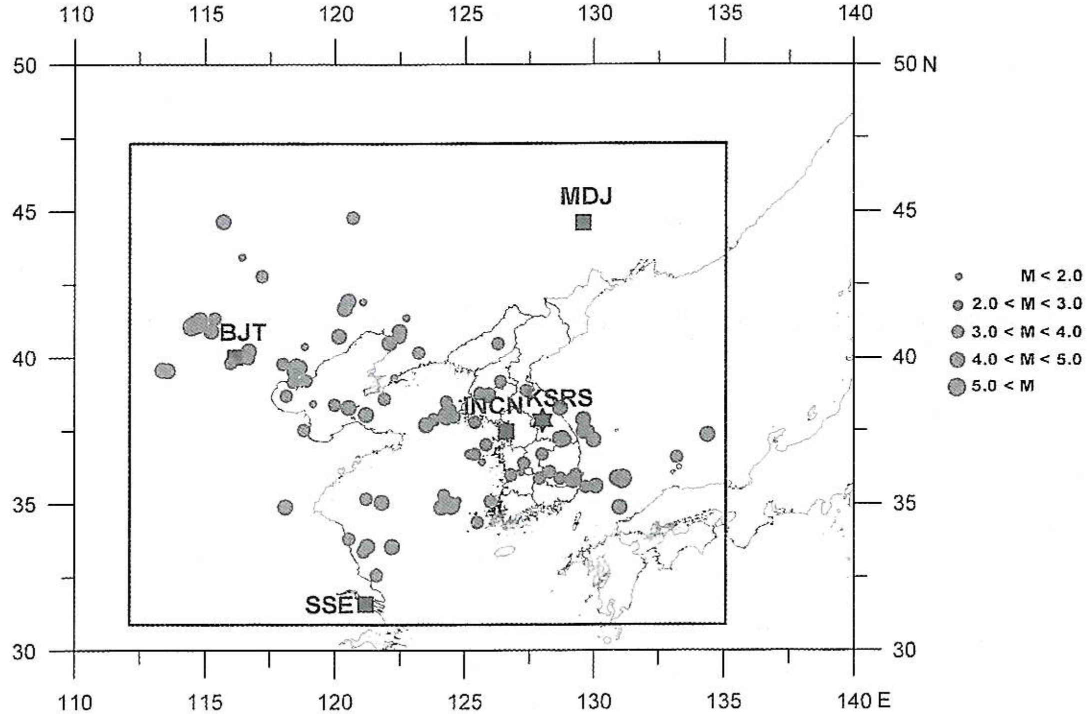

Fig. 2. Location map of epicenters and seismic stations used for this study.

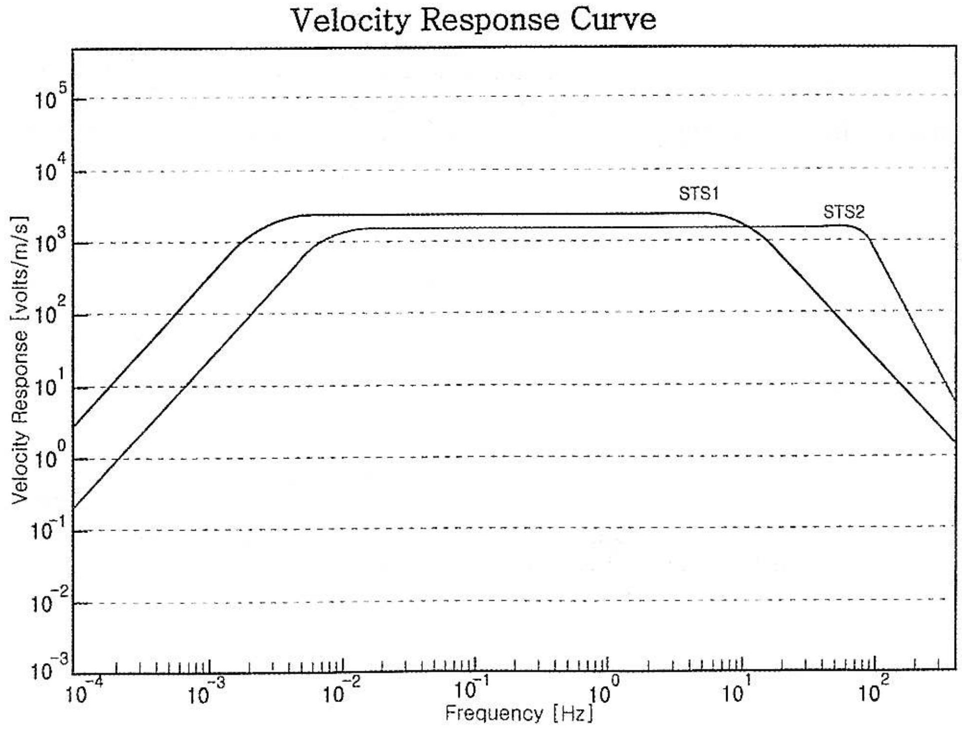

Fig. 3. Instrument response curve for the seismometer recording the data.

level of those sensors exceeds that of other instruments over the same frequency range. Signal output is proportional to ground velocity over a relatively broad frequency band using an electronic force feedback sensor. Generally, according to the instrument response curve, the instrument shows flat response at a frequency band from 0.01 Hz to 10 Hz (fig. 3). The sampling rates of 20, 40, 50 or 100 samples per second were used. When performing deconvolution with instrument response, the sensor response of STS-1 or STS-2, gain constant, sensitivity, and filtering, such as FIR (Finite Impulse Response) filters, were considered. On the synthetic Wood-Anderson seismogram, $f_{WA}(t)$, one half of the maximum amplitude is measured to determine local magnitude (M_L), horizontally and vertically, respectively. To obtain the empirical curve for estimating M_L, the constraint that magnitude of 3 is equal to that of events with epicentral distance of 100 km and measured amplitude at Wood-Anderson recording of 0.001 m as Richter (1935) was applied in the fit of the observed magnitudes.

The attenuation curve can be obtained by subtracting $\log_{10}A(\Delta)$ from both sides of eq. (1.1) as follows:

$$M_L - \log_{10}A(\Delta) = -\log_{10}A_0(\Delta) + C. \quad (3.1)$$

The left-hand side of eq. (3.1) can be obtained normalizing the amplitudes measured from synthetic Wood-Anderson seismograms by the published magnitude data.

4. Results and discussion

The coefficients of the empirical formula for the attenuation curve, $\log_{10}A_0(\Delta)$, were deter-

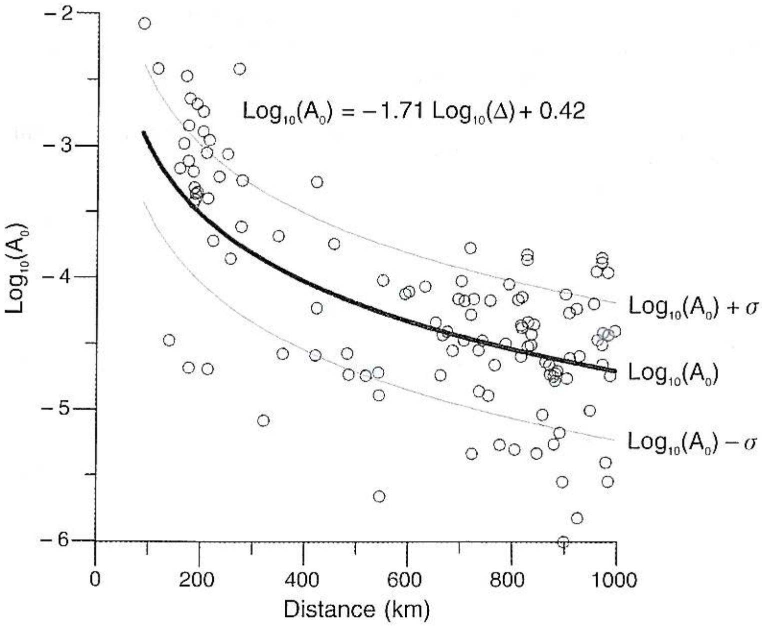

Fig. 4. Attenuation curve for horizontal components by least-square fitting after measuring amplitude from synthetic W-A seismograms.

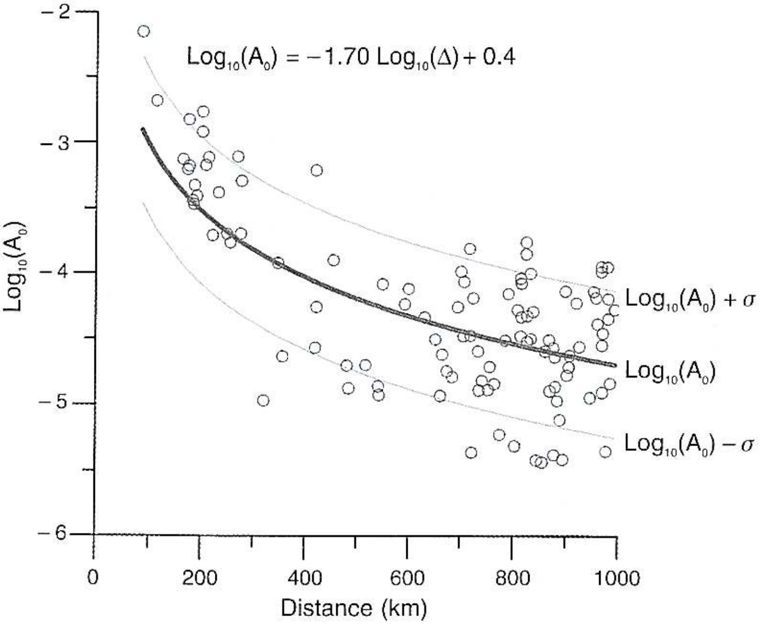

Fig. 5. Attenuation curve for vertical components by least-square fitting after measuring amplitude from synthetic W-A seismograms.

mined by a least-square fitting of the amplitudes from synthetic Wood-Anderson seismograms as shown in figs. 4 and 5. In the epicentral distance ranging from 50 km to 100 km, few data were used. After the least-square fitting, the attenuation curve for horizontal components (E-W, N-S) was calculated, with standard deviation (σ) of 0.52, as

$$-1.71\log_{10}(\Delta)+0.42=-\log_{10}A_0(\Delta)+C. \quad (4.1)$$

The attenuation curve for the vertical component was calculated, with standard deviation (σ) of 0.56, as

$$-1.70\log_{10}(\Delta)+0.4=-\log_{10}A_0(\Delta)+C. \quad (4.2)$$

The small amount of data for this research seems to cause a relatively high standard deviation both in horizontal and vertical components.

As shown in fig. 6, we arrive at to the preliminary conclusion that the attenuation of the studied area including the Korean Peninsula, the Yellow Sea, South Manchuria, and the east coast of China is weaker than that of South California (Kanamori *et al.*, 1993) but stronger than that of the East United States (Kim, 1998).

In eqs. (4.1) and (4.2), C is the station correction term that will be determined by inversion with the empirical attenuation curve and observed magnitude of events. Now that the number of event-station pairs is limited, the inversion for station correction is unstable. As many data as possible need to be collected for the inversion to provide a stable correction in future.

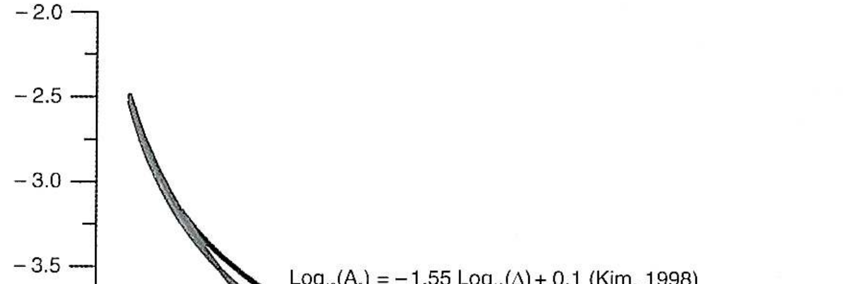

Fig. 6. Comparison between the horizontal attenuation curves of this study, of South California (Kanamori *et al.*, 1993) and East United States (Kim, 1998).

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