ATTENUATION CHARACTERISTICS OF SEISMIC GROUND MOTION IN THE 1995 HYOGOKEN-NAMBU EARTHQUAKE

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ABSTRACT

The recorded ground motion of the 1995 Hyogoken-nambu Earthquake are used to study the attenuation characteristics of near-field ground motion. The peak ground accelerations and velocities are compared to the attenuation relations derived from far-field data recorded from 76 JMA stations. Although the near-field data used include non-JMA stations, the peak ground motion data have a relatively good fit to the far-field attenuation relations. Saturation of the peak ground motion near the fault was examined by introducing a distance saturation parameter to the attenuation relations and performing a non-linear least squares analysis on the Hyogoken-nambu Earthquake data. Since the data used are from a single event, the magnitude independence of the PGA cannot be determined. However, the fit of the recorded data in the near-field is improved. The resulting attenuation relations for the Hyogoken-nambu Earthquake are given by:

$$\log_{10} PGA = 0.322 + 0.477M_J - \log_{10}(r+3.8) - 0.00144r + 0.00311h$$

$$\log_{10} PGV = -1.576 + 0.628M_J - \log_{10}(r+7.0) - 0.00130r + 0.00222h$$

where PGA (cm/s^2) and PGV (cm/s) are the larger of the peak accelerations and velocities from two horizontal components, M_J is the JMA magnitude, r is the closest distance to the fault rupture, and h is the depth of the point in the fault rupture where r is measured.

1. INTRODUCTION

An earthquake with a magnitude of 7.2 in the Japan Meteorological Agency (JMA) scale occurred in the vicinity of Kobe on January 17, 1995. It is the most destructive earthquake in Japan since the 1923 event (AIJ, 1995; EERI, 1995). Kobe is one of the oldest and important economic hub

of the region and this disaster provided a preview of what might happen if a big earthquake strikes a metropolitan area like Tokyo.

There are several near source records from the Hyogoken-nambu Earthquake (also called the Great Hanshin Earthquake or simply as the Kobe Earthquake). One of these is the record from the JMA Kobe station. Although the epicentral distance is about 20 km, the activated fault runs very close to this station and the record can be considered as near-field. Since the earthquake occurred very close to a metropolitan area, several seismometers in the near-field were able to record the event. These near-field records are valuable because there are very few in Japan and they can help us understand the characteristics of near-field ground motion.

This study aims to evaluate previously developed attenuation relations (Molas and Yamazaki, 1995) in light of the Hyogoken-nambu Earthquake and to characterize the behavior of the near field records with respect to the far-field attenuation relations. Towards this end, it is necessary to briefly summarize the data, methods, and results of the previous attenuation study.

2. ATTENUATION RELATIONS FROM RECORDS OF THE JMA STATIONS

The acceleration time histories from the JMA stations under study were recorded by the new JMA-87 type seismometers. These digital seismometers have a flat sensitivity from 0.05 Hz to 10 Hz and can measure accelerations from $3x10^{-3}$ cm/s^2 to 980 cm/s^2 for periods from 1s to 10 min (JMA, 1991). Older SMAC-B2 seismometers have suppressed sensitivity in the high frequencies. Thus, correction procedures are needed for SMAC-B2 records (Kawashima et al., 1982, 1986). Records from JMA stations including events with depths of up to 200 km were used to develop attenuation relations for the peak ground acceleration (PGA) and peak ground velocity (PGV) for Japan (Molas and Yamazaki, 1995). Local-site effects (i.e., relative amplification given by station coefficients) of 76 JMA stations were also determined. However, near source data are lacking and the attenuation relations are deemed valid only for far-field ground motion.

Table 1 shows the summary of the data used in the previous study. Although the number of records is large, the number of stations is fixed (i.e., 76 JMA stations using the JMA-87 seismometers). The data used by Molas and Yamazaki does not include the Hyogoken-nambu Earthquake and many of the earthquakes are in eastern and northern Japan with few events in western and southern Japan. Thus, there are less records for the JMA stations in the west than in the east and north of Japan. The data set also lacks records in the near-field. Although the JMA Kushiro station is very close to the epicenter of the 1993 Kushiro-Oki earthquake (about 4 km), the source depth is about 100 km.

TABLE 1. SUMMARY OF DATA USED FOR THE ATTENUATION STUDY (MOLAS AND YAMAZAKI, 1995)

No. of records	2,166
No. of recording stations	76
Date recorded	August 1, 1988 to December 31, 1993
Instrument	JMA-87 type accelerometers
Recording Institution	Japan Meteorological Agency (JMA)
Magnitude range	4.0 to 7.8 (JMA scale)
Minimum intensity (larger of two horizontal components)	PGA ≥ 1.0cm/s/s
Depth range	1.0km to 200km

The PGA and PGV data were analyzed using a two-stage regression method (Joyner and Boore, 1981), which was found by Fukushima and Tanaka (1990) to be effective in eliminating the systematic error in regression resulting from the apparent correlation of the magnitude and slant distance. The effect of each recording station is considered in the regression instead of the commonly used soil-type classifications. However, the solution of the least squares regression for the first stage became singular. The regression is solved by an iterative partial regression technique (Molas and Yamazaki, 1995). The resulting attenuation relations (PGA in cm/s^2 and PGV in cm/s) are:

$$\log_{10} PGA = 0.206 + 0.4778M_J - \log_{10} r - 0.00144r + 0.00311h + c_i^a + 0.276P \quad (1)$$

$$\log_{10} PGV = -1.769 + 0.628M_J - \log_{10} r - 0.00130r + 0.00222h + c_i^v + 0.257P \quad (2)$$

where M_J is the JMA Magnitude, r is the shortest distance from the site to the fault plane, h is the depth of the point in the fault plane where r is measured, c_i is the station coefficient, and $P = 0$ for 50 percentile values (mean) or $P = 1$ for 84 percentile values. The resulting station coefficients for the 76 JMA stations in the study are given in Molas and Yamazaki (1995).

3. RECORDED GROUND MOTION OF THE HYOGOKEN-NAMBU EARTHQUAKE

Table 2 shows a summary of the ground motion recorded by JMA stations during the Hyogoken-nambu Earthquake. Figure 1 shows the locations of the JMA stations. The triangles represent the JMA stations whose records are used in this study (see Table 2) while the squares represent the remaining JMA stations. Some JMA stations whose records were not used in this study are closer to the epicenter than the stations whose records were used. This is most likely due to the low amplification rates (i.e., station coefficients) in the former. Although 42 stations recorded the acceleration time history of the earthquake, only the Kobe station can be considered as near-field. The JMA Kobe and Osaka stations have an epicentral distance of about 20 km and 50 km, respectively. As generally known, the use of epicentral or hypocentral distance in attenuation relations

is not so good especially for events with large fault dimensions. The distance, r, in this study is defined as the shortest distance from the site to the fault surface. To measure this distance, the activated fault geometry must be estimated.

TABLE 2. SUMMARY OF THE HYOGOKEN-NAMBU EARTHQUAKE DATA RECORDED BY JMA STATIONS

	Station Code	Station Name	Epicentral Distance, D(km)	Shortest Distance, r (km)	Depth h (km)	Recorded PGA (cm/s/s)	Site-adjusted PGA*	Recorded PGV (cm/s)	Site-adjusted PGV*
1	AJI	Ajiro	377.61	350.56	4 3	2.54	1.54	0.41	0.32
2	FKK	Fukuoka	440.75	434.69	1.7	2.95	1.81	0.66	0 37
3	FUK	Kawaguchiko	196.45	169.22	4.3	41.50	31.16	5.31	3.40
4	HIK	Hikone	136 29	106.36	4.3	146.89	101.36	15.02	7.14
5	HIR	Hiroshima	233.71	228.69	1.7	12 08	10.48	1.51	1.05
6	HMD	Hamada	269.69	266.34	1.7	2.81	5 77	1.02	3.10
7	IID	Iida	277.63	248.30	4.3	14.98	17.15	2.54	3.76
8	KAN	Kanazawa	266.20	239.03	4.3	25.55	19.27	6.06	2.95
9	KOB	Kobe	19.45	4.57	1.7	817.86	1207.48	89.50	112.63
10	KOF	Kofu	344 82	315.57	4.3	4.96	3.65	1.31	0.97
11	MAE	Maebashi	419.41	389.50	4.3	2.18	3.86	1 45	2.40
12	MAT	Matsushiro	362.75	332.90	4.3	1.15	3 72	0.62	2.88
13	MIS	Mishima	363.47	336.11	4 3	3.66	3.86	0.89	0.87
14	MIT	Mito	533.90	504 40	4.3	1.71	0.80	0.98	0.63
15	MRT	Murotomisaki	168.49	159.88	1.7	22.66	28.90	3.64	4 98
16	MTM	Matsumoto	325.89	295.96	4.3	4.18	10.02	1.50	3.00
17	MTS	Matsue	199.93	199.71	1.7	5.91	4.12	0.49	0.39
18	MTY	Matsuyama	221.19	214.32	1.7	20 48	15.45	2.57	1.66
19	MYZ	Miyazaki	446.99	438.78	1.7	3.28	5 68	0 80	0.99
20	MZH	Maizuru	98.88	78.31	4.3	66.93	64.57	5.05	4.53
21	NAG	Nagoya	190.45	161 47	4.3	15.54	14.70	3.23	3.19
22	NII	Niigata	517.63	488.54	4.3	2.14	2.11	2.11	1 36
23	OIT	Oita	347.03	339.88	1.7	9.61	9.97	2.21	1.69
24	OKA	Okayama	99.35	95.65	1.7	77.31	81.51	5.05	6.76
25	OMA	Omaezaki	294.44	269.56	4.3	6 09	9.21	1.48	2.54
26	ONA	Onahama	593.76	563.95	4.3	1.40	1 28	0 31	0.25
27	OSA	Osaka	48.75	24.27	4.3	80.85	105 18	18.45	14.88
28	SHJ	Shionomisaki	146.29	142.23	1.7	24.05	20.38	1.79	2.49
29	SHN	Shimonoseki	381.57	375 93	1.7	5.88	4.77	0.59	0.48
30	SHZ	Shizuoka	314.21	287.25	4.3	4.08	6.35	0.65	1.17
31	TAT	Tateyama	447.06	420.42	4.3	2.23	1.81	0.49	0.32
32	TKD	Takada	404 62	375.29	4.3	3.79	2.24	1.36	0.76
33	TKY	Takayama	268.05	238.41	4.3	9 06	15.08	1.49	3.04
34	TOK	Tokyo	449.66	420.98	4.3	2.61	1 55	1.33	0.87
35	TOT	Tottori	120.45	120.73	4.3	76.74	59.69	10.17	6.55
36	TOY	Toyama	307.86	279.36	4.3	14.34	19.38	4.90	7.43
37	TSU	Tsu	140.25	114 35	4.3	70.99	69.25	6.48	5 84
38	UTS	Utsunomiya	491.38	461.57	4.3	1.21	1.05	0.36	0.37
39	UWA	Uwajima	272.59	264.81	1.7	7.18	7.18	0.92	0.92
40	WAJ	Wajima	354.52	328.53	4.3	19.24	16.89	3.44	2.27
41	YOK	Yokohama	434.60	406.47	4.3	3.84	3.03	1.38	0.85
42	YON	Yonago	177.27	177.57	1.7	20 58	16 17	2.77	2.36

*Site-adjusted PGA and PGV were calculated based on the station coefficients determined by Molas and Yamazaki(1995).

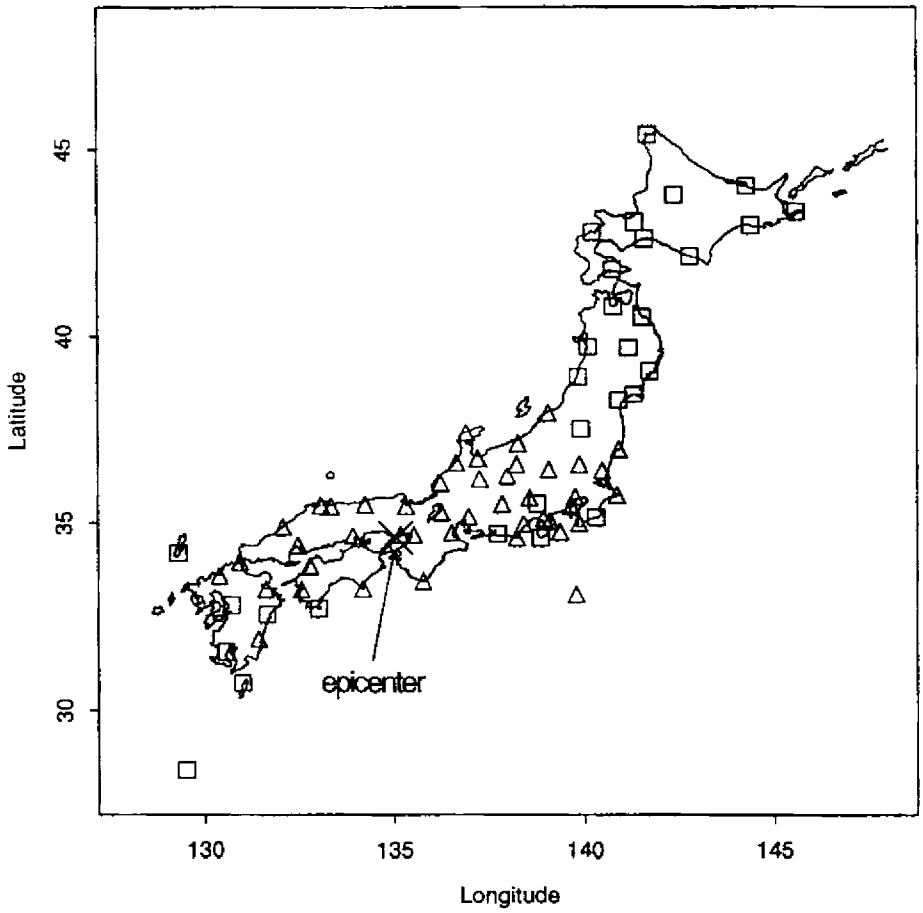

Figure 1. Location of JMA recording stations and epicenter (shown by X) of the Hyogoken-nambu Earthquake. Triangles show the stations used in this study

Kikuchi (1995) modelled the activated fault as three strike-slip faults approximately extending from the southwest to northeast direction (Figure 2a). The activated faults have a dip angle of 90 degrees with varying dimensions and depth. To compute the shortest distance from the JMA stations, we used a simplified fault geometry based on Kikuchi. Since there are no stations very close to fault 2 and this fault is relatively smaller compared to the other two, it was disregarded in lieu of extending the north-eastern fault (fault 3) to be almost continuous with the south western fault (fault 1). The adopted fault geometry is shown in Figure 2b. Although the activated fault model has three distinct faults, it is reasonable to assume that the recorded ground motions are superpositions of the ground motions from the three faults. Thus, we retained the JMA magnitude as 7.2. Table 2 lists the epicentral and shortest (slant) distances and the depth of the point in the fault that is closest to the JMA stations under consideration. The definition of distance, r, and depth, h, in this study is illustrated in Figure 3. In the case of the JMA Kobe station, although it is closer to the north-eastern fault horizontally, the shortest slant distance is from the south-western fault whose extent is closer to the surface. Figure 4 shows the recorded PGA and

PGV with respect to the closest distance. The station coefficients, c_i, used in this figure are taken as zero. This represents the mean response of the 76 JMA stations. It was observed that this mean response is generally lower than the mean response if the recording stations were not considered in the regression. This is caused by the fact that stations with high amplifications tend to have more records than those with less amplification. The apparent attenuation rate (by visual inspection) for the PGA seems a little higher than in Equation 1. For PGV, the attenuation rate seems to fit well although many data points are above the mean predicted line. The fitting of the data with respect to the predicted peak ground motion looks good even for near-field data even though the equations were developed from far-field data.

By taking into account the local site effect of each recording station, we can take out the effect of the different amplification of each site. Figure 5 shows the PGA and PGV adjusted for the local site effect (Molas and Yamazaki, 1995). The dotted line shows the one standard deviation of the predictive equations and takes into account the local site effects of the JMA stations. Although the fitting is improved for both the PGA and PGV, the distribution of the data points are similar to the uncorrected ones (Figure 4).

The importance of the definition of distance in the near-field has been recognized by many researchers (e.g., Boore and Joyner, 1982; Singh et al., 1989; Ohno et al., 1993) Ohno et al. proposed a redefinition of distance taking into consideration the fault geometry. After this redefinition, they showed that the attenuation characteristics of near-field records assume those of far-field records. As shown in Figures 4 and 5, by defining the distance, r, as the shortest distance from the site to the fault plane, the near-field record fit well with the attenuation relation. Since this is only one data point, however, it is premature to draw general conclusions.

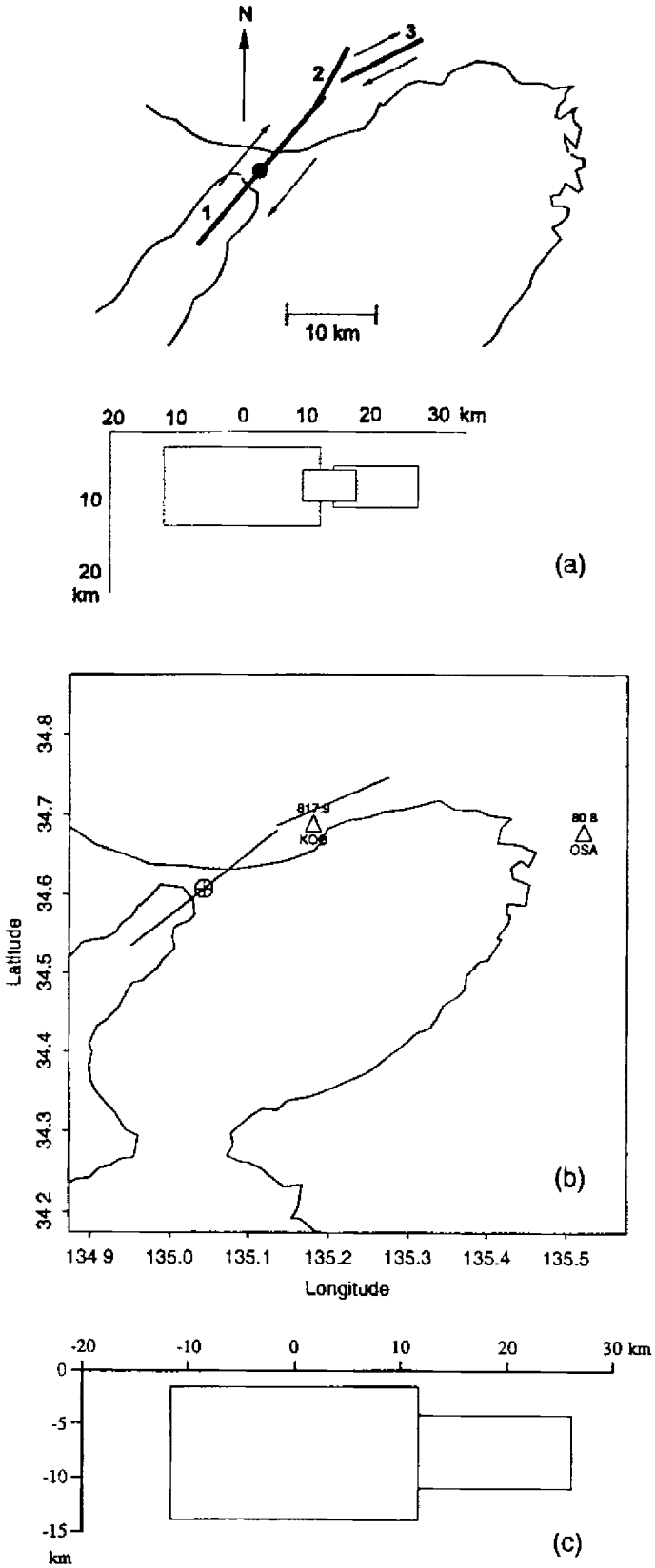

Figure 2. Fault model (a) proposed by Kikuchi (1995) and (b) modified fault used in this study. The vertical section of the modified fault model is shown in (c)

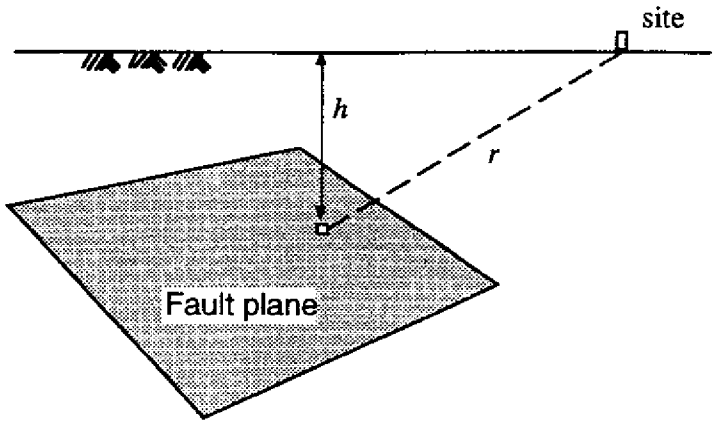

Figure 3. The distance term, r, and the depth term, h, are measured from the point in the fault plane where r is minimum. The fault plane is considered to be oriented in there-dimensional space. However, the fault model for the Hyogoken-nambu Earthquake is considered to be vertical.

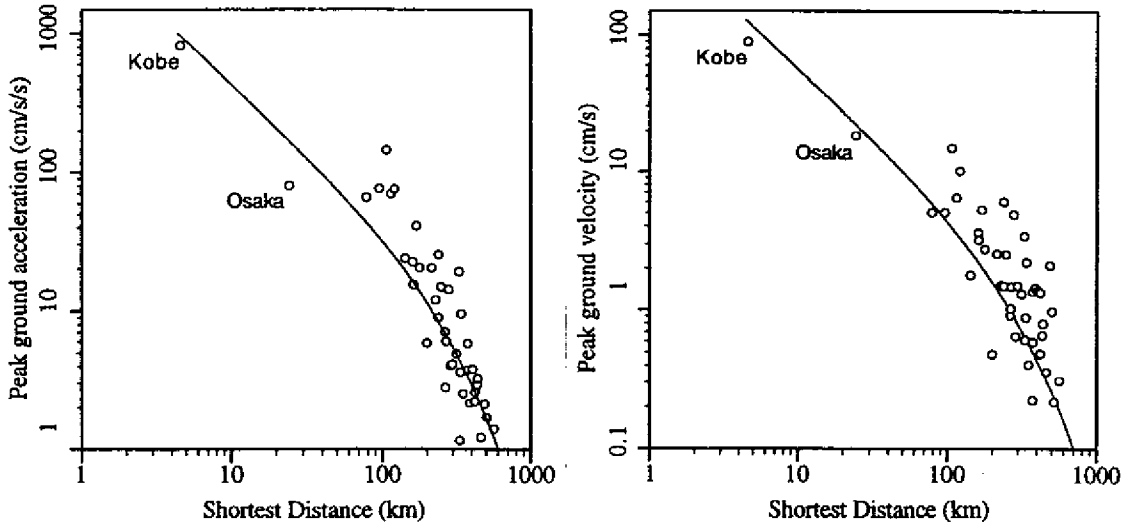

Figure 4. Attenuation of the recorded PGA(left) and PGV(right) of the Hyogoken-nambu Earthquake from the JMA stations. The solid lines are the predicted attenuation from Equation 1 (PGA) and Equation 2 (PGV), which were proposed by Molas and Yamazaki (1995). Station coefficients for the PGA and PGV in this figure were taken to be zero (which represents the mean response of the 76 JMA stations studied by Molas and Yamazaki.

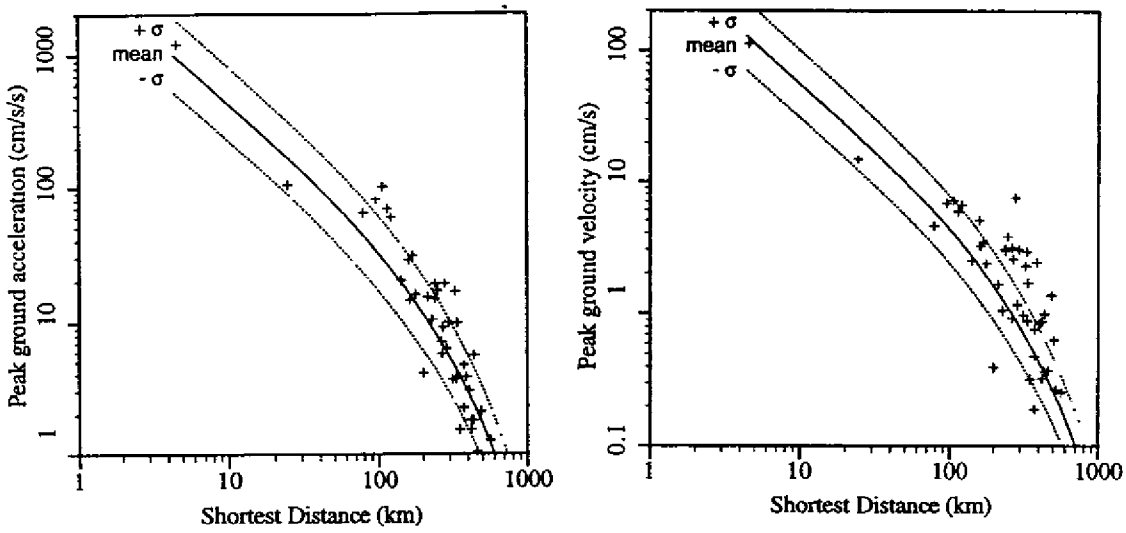

Figure 5. Site-adjusted PGA(left) and PGV(right) of the Hyogoken-nambu Earthquake from the JMA stations. The station coefficients of the JMA stations determined by Molas and Yamazaki (1995) were used to consider the amplification characteristics of each station.

4. EFFECT OF THE HYOGOKEN-NAMBU EARTHQUAKE DATA ON THE ATTENUATION EQUATIONS

There are a lot of good near-field records for this earthquake, which are rather rare in Japan. It is therefore interesting to investigate how the near-field data affects the attenuation relations derived from far-field data. Unfortunately, at this moment, only the JMA records are possible to integrate into the original data set. Using the original data selection criteria (Molas and Yamazaki, 1995), 42 records are selected. However, the record at Uwajima is further excluded because there is no other record from this JMA station. The resulting data set therefore has 2,207 records from 388 events and 76 stations.

The results of the iterative partial regression for PGA and PGV are

$$\log_{10} PGA = 0.184 + 0.482\, M_J - \log_{10} r - 0.00149 r + 0.00315 h + c_i^a + 0.278 P \quad (3)$$

$$\log_{10} PGV = -1.781 + 0.631 M_J - \log_{10} r - 0.00127 r + 0.00211 h + c_i^v + 0.259 P \quad (4)$$

where the variables are defined as in Equation 1. There is little difference compared to the original attenuation relation. Figure 6 shows the predicted attenuation curves of the original and new attenuation relations for the Hyohoken-nambu Earthquake (M = 7.2, h = 4.3 km) and the confidence limits based on one standard deviation. The attenuation curves are very close to each other. This is to be expected since the influence of the new

data is small compared with the large number of data used in the original data set. The relatively good fit of the Hyogoken-nambu Earthquake data to the original predictive curves means that the improvement of the regression fit by including the new data will be small. In the case of the near-field record in the JMA Kobe station, the predicted PGA from the original attenuation equation is close to the recorded and adjusted PGA. Thus, the effect on the regression is also small.

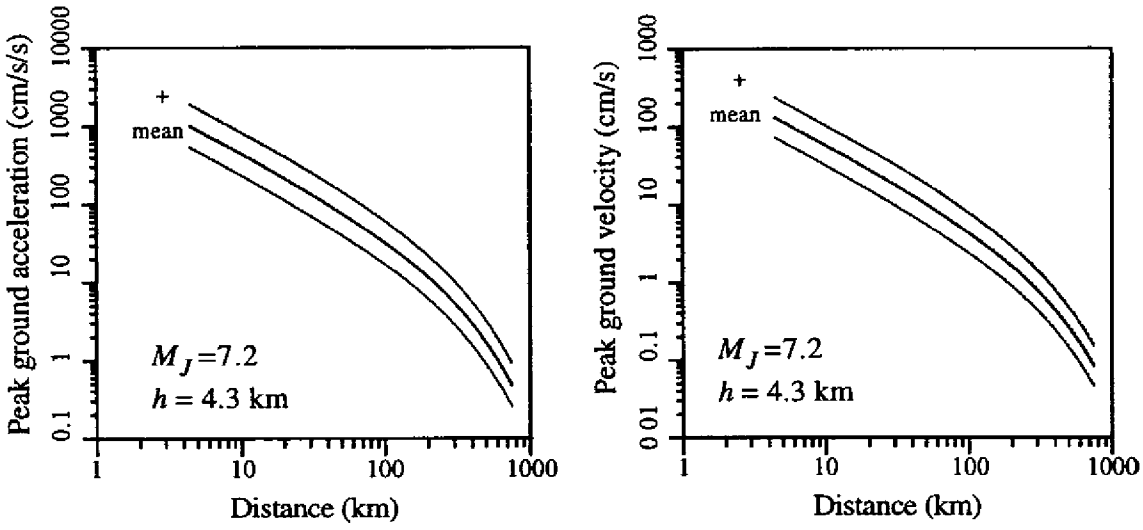

Figure 6. Mean and one standard deviation curves for Equation 1 (solid lines) and computed attenuation relation considering the data of the Hyogoken-nambu Earthquake (dotted lines)

5. OTHER NEAR-FIELD RECORDS

Several organizations collected near-field data from the Hyogoken-nambu Earthquake. Near-field data are few in Japan because many events occur offshore and may be deep. The non-JMA near-field data used in this study were collected from various publications which reported on the Hyogoken-nambu Earthquake. We selected data that were recorded on free-field conditions and further excluded those that were recorded by the SMAC-B2 instrument. Table 3 summarizes the non-JMA data used in this study. Most of these data have a shortest distance, r, less than 100 km. The locations of the data close to the fault are given in Figure 7. This figure also shows the relative PGA and PGV of the near-field records and clearly shows that the largest peak ground motions occur along the activated fault. Figure 8 shows the plot of these data with the JMA data with respect to the shortest distance. The JMA data in this figure are the recorded PGA and PGV without correcting for the station effect. Since the station coefficients of the non-JMA stations are unknown, corrections are not possible. The

figure shows that non-JMA recorded PGAs and PGVs have a good fit with Equation 1 and 2, respectively. Figure 8 also shows the confidence limits of one standard deviation. It must be noted that these standard deviations are based on the fact that the station effects are explicitly determined and therefore does not contain the station-to-station component of the variance. For non-corrected data, the correct confidence limits should include the station-to-station component, therefore the confidence limits should be a bit wider than those in Figure 8. These limits are used in Figure 8 as a reference only. Most of the non-JMA data are within one standard deviation from the mean although there are more data points above the mean line than under it. This trend might be specific to the Hyogoken-nambu Earthquake.

In our previous study, we did not consider the effect of near-source data in the attenuation relations because there are no near-field records from the JMA stations that we studied. The predicted attenuation curves in Figure 8 show a rather straight line as the distance approaches zero. This is mainly due to the geometric spreading term of the attenuation relations. It has been shown theoretically and statistically that there exist a limit on the ground motion very near the fault rupture due to the limit on the energy that the earth's material can release due to its finite strength. Several attenuation relations which consider the near-field assume a magnitude-dependent distance parameter which limits the predicted peak ground motion in the near-field. This is usually achieved by making the distance parameter approach a finite value instead of zero at sites close to the fault. From Figure 8, it is apparent that the data with distances less than 10 km will have a much better fit if the attenuation curves become flat at distances less than 10 km, especially the data with a distance of about 5 km. The depth of the north-eastern fault (4.3 km) is highly influential in this range.

However, this observation is based on one event only and we need more data to be able to precisely predict ground motion in the near-field. The results of the previous study show that the local-site effect is very important in attenuation relations. The use of simple soil-type classification does not provide adequate information on the amplification of a single site and this can lead to large errors, especially if used in hazard and risk analyses which are based on single sites. It is still unclear how the site effects of the non-JMA stations used in this study will affect the attenuation relation in the near-field.

TABLE3. SUMMARY OF NON-JMA DATA OF THE HYOGOKEN-NAMBUEARTHQUAKE USED IN THISSTUDY

Station code	Station Location	Latitude (deg)	Longitude (deg)	Shortest Distance, r(km)	Depth, h(km)	PGA (cm/s/s)	PGV (cm/s)
KansaiElectricPowerCo.							
A-1	Miyazu Energy Res. Inst	35.554	135.256	89.98	4.30	69.9	
A-2	Yamazaki Experiment Center	35.060	134.603	64.12	4.30	131.3	
A-3	West Kyoto Substation	34.967	135.622	40.33	4.30	129.3	
A-4	Shin-Kobe Substation	34 731	135.250	4.34	4.30	584.3	
A-5	Takasago Power Station	34 753	134.783	28.24	1.70	198.0	
A-6	Ako Power Station	34.735	134.379	56.96	1.70	103.6	
A-7	General Technical Res. Inst.	34.743	135.442	15.91	4.30	506.6	
A-8	Amagasaki-3 Power Station	34.690	135.391	13.13	4.30	353.6	
A-9	Nanko Power Station	34.614	135.408	19.71	4.30	125.8	
A-10	Yao Substation	34.603	135.611	35.02	4 30	148.0	
A-11	Shinki Substation	34 594	135.650	38.60	4.30	46.1	
A-12	Minami-Osaka Substation	34.464	135.475	36.74	4.30	146.0	
A-13	Kainanko Substation	34.150	135.192	48.16	1.70	128.2	
A-14	Gobo Power Station	33.850	135.150	78.33	1.70	74.0	
A-15	Yusaki Substation	33.672	135.350	102 76	1.70	18.5	
Osaka Gas							
B-1	East Supply Department	34 668	135.619	32.99	4.30		23.0
B-2	Fujiidera Governor Station	34.564	135.609	37.04	4.30		12.7
B-3	Kyoto Supply Station	34.992	135.741	50.79	4.30		13.5
B-4	Soyama Supply Station	34.496	135.544	37.48	4.30		11.0
B-5	Matsue Supply Station	34.240	135.141	37.16	1.70		21.8
B-6	Iwasaki Supply Station	34.665	135.481	21 39	4.30		24.0
B-7	Fukiai Supply Station	34.695	135.211	4.91	4.30	802.0	
B-8	Shijo-Nawate Supply Station	34.739	135 632	33.00	4.30	256 5	
B-9	Fushimi Supply Station	34.926	135.743	47.46	4 30	178 0	17.6
B-10	Nakanoshima Supply Station	34.236	135.185	39.62	1.70	106.5	15.1
Takenaka Corporation							
C-1	Osaka, Kita-ward	34.703	135.505	22.07	4.30	267.4	
C-2	Osaka,Kita-ward	34.698	135.519	23.47	4.30	50.3	
Research Center for Earthquake Prediction,Disaster Prevention Research Institute, Kyoto University							
D-1	Abusan	34.860	135.574	30.41	4.3		10.4
D-2	Asai	35.477	136.324	125.55	4.30		2.5
D-3	Oya	35.322	134.666	82.81	4.30		3.9
D-4	Kume	35.089	133.849	118.13	1.70		3.4
D-5	Wachi	35.282	135.401	60.87	4.30		31.7
Ministry of Transport, Ports and Harbors Research Institute							
E-1	Kobe Port	34 686	135 209	5.33	4.30	502.0	
E-2	Amagazaki Port	34 712	135 404	13.20	4.30	471.7	
Kobe City Government							
F-1	Port Island	34.670	135.208	6.38	4.30	341.2	87.3
Shiga Prefectural Government							
G-1	Ashibiya	35.209	135.851	73.70	4.30	37.0	6.2
G-2	Torahime	35.416	136.265	117.09	4.30	70.0	6.9
G-3	Mizuguchi	34.968	136.170	85.55	4.30	43.0	4.1
G-4	Osakaya	34.998	135 861	60 59	4.30	45.0	6.6
G-5	Kusatsu	35.011	135 958	69 14	4.30	145 0	11.6
G-6	Imazu	35 403	136 035	100 77	4.30	47.0	4 2

JR Railway Technical Research Institute (Nakamura et al., 1995)							
H-1	Nishi-Akashi	34.6640	134.964	9.73	1.70	397.0	39.2
H-2	Takaton	34.6490	135.139	3.24	1.70	666.0	138.0
H-3	Shin-Kobe	34.7040	135.200	4.42	4.30	530.0	
H-4	Kakogawa	34.7640	134.843	25.34	1.70	313.0	27.9
H-5	Himeji	34.8225	134.694	39.51	1.70	125.0	
H-6	Takarazuka	34.8090	135.344	10.33	4.30	694.0	75.0
H-7	Higashi-Kishiwada	34.4450	135.388	34.84	4.30	144.0	
H-8	Wakayama	34.2240	135.199	41.39	1.70	143.0	
H-9	Shin-Osaka Station	34.7060	135.506	22.11	4.30	228.0	45.3
H-10	Shin-Osaka Substation	34.7370	135.516	22.55	4.30	229.0	34.4
H-11	Aioi	34.8150	134.476	53.59	1 70	62.0	
H-12	Sasayamaguchi	35.0530	135.180	35.40	4.30	177.0	
H-13	Ikuno	35.1666	134.793	62.09	4.30	53.0	
H-14	Shin-Takatsuki	34.8590	135.654	37.13	4.30	297.0	
H-15	Sonobe	35.1000	135 487	44.04	4.30	163.0	
H-16	Iri	34 7510	134.208	72.23	1.70	97.0	
H-17	Nara	34.6770	135.821	50.81	4.30	112.0	
H-18	Fukuchiyama	35.2930	135.121	62.52	4.30	107.0	
H-19	Gobo	33.9040	135.162	72.79	1.70	132.0	
H-20	Kansai Int'l Airport	34.4334	135.244	26.77	1.70	117.0	
The Committee of Earthquake Observation and Research in the Kansai Area (CEORKA)							
I-1	Kobe University	34.725	135.240	4.31	4.30		55.1
I-2	Fukushima	34 687	135.474	19.08	4.30		31.0
I-3	Morikouchi	34.680	135.572	27.76	4.30		27.1
I-4	Yae	34.680	135.612	31.29	4.30		21.8
I-5	Chihaya-Asakasa	34.4390	135.659	49.36	4.30		5.2
I-6	Sakai	34.564	135.469	26.41	4.30		15.9
I-7	Tadaoka	34.480	135.408	31.30	4.30		24.4
I-8	Abeno	34.636	135.519	25.02	4.30		24.9
Ministry of Construction							
J-1	Kakogawa Dike	34.7725	134.8386	27.30	1.70	211.0	
J-2	Amagasaki Bridge	34.7264	135.4206	13.54	4.30	294.0	
J-3	Kinokawa River	34.2256	135.1533	38 09	1.70	129.0	
J-4	Yodogawa River (Oyodo)	34.7056	135.4861	19.60	4.30	224.0	
J-5	Yodogawa Dike	34.7194	135.5167	22.08	4.30	138.0	
J-6	Yamatogawa River	34.5861	135.5881	33.18	4.30	199.0	
J-7	Yoshinogawa River (Tokushima)	34.0864	134.5575	61.36	1.70	110 0	
J-8	Yoshinogawa River (Ishii)	34.0983	134.4547	66.50	1.70	90.0	
J-9	Anogase Dam	34.8781	135.8306	52.69	4.30	107 0	
J-10	Naruto	34 2340	134.6410	43.92	1.70	136 00	
Hanshin Expressway Corporation							
K-1	Higashi-Kobe Bridge	34.7065	135.296	6 52	4.30	326.0	
K-2	Inagawa	34.8360	135.427	17 65	4.30	421.0	
K-3	Kanjyo Yotsubashi	34.6670	135.488	21 91	4.30	324.0	
K-4	Matsunohama	34.5000	135.413	30.54	4.30	169.0	

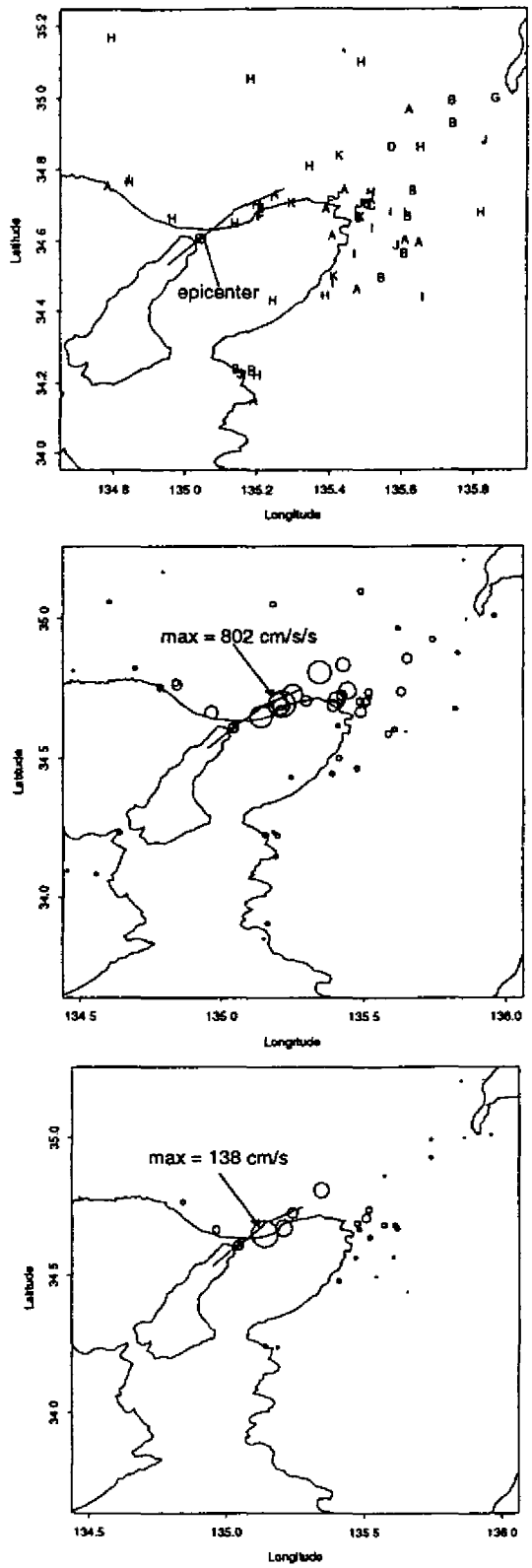

Figure 7. Location of non-JMA near-field data (top) and the distribution of the peak ground acceleration (middle) and the peak ground velocity (bottom) in the near-field.

6. MODIFIED ATTENUATION RELATION IN THE NEAR-FIELD

In the light of the preceding observations, it is possible to use the near-field data of the Hyogoken-nambu Earthquake to introduce modifications to Equations (1) and (2) for use in the near-field. However, since the data available is limited to one earthquake only, the modifications should be used with careful consideration of this fact.

The attenuation characteristics in the near-field has been studied by Campbell (1981) using data from the US supplemented by worldwide data. Based on the theoretical considerations, Campbell used the attenuation relation of the form:

$$PGA = a\,exp(bM)[R + C(M)]^{-d} \tag{5}$$

where

$$C(M) = c_1\,exp(c_2 M) \tag{6}$$

This form is supported by geological and seismological studies. The term c_1 is related to the distance saturation while c_2 is related to the magnitude saturation. The magnitude saturation term of $C(M)$ is related to the shape of predictive equations in the near field. If total magnitude independence of the PGA is assumed, the PGA at the fault surface is the same regardless of the magnitude of the event. Studies have shown that the PGA near the fault rupture is magnitude independent. To satisfy this condition in the attenuation relations, the following constraint is imposed:

$$c_2 = b/d \tag{7}$$

In the case of Japan, Fukushima and Tanaka (1990) supplemented the Japanese data with near-field data of Campbell (1981). They constrained their regression model such that the peak ground acceleration near the fault rupture is magnitude-independent. Kamiyama et al. (1994) used a semi-empirical model to obtain a magnitude-independent peak ground acceleration and magnitude-dependent peak ground velocity and displacement near the fault rupture.

Since the near-field data for this study is limited to one earthquake, it is not possible to verify if the data supports magnitude-independence. However, we believe that there are enough arguments to support magnitude independence of peak ground acceleration near the fault rupture. Therefore, in the near-field, Equations (1) and (2) are modified to reflect distance and magnitude saturation as

$$\log_{10} PGA = 0.206 + 0.477M_J - \log_{10}(r + C^{*}(M)) - 0.00144r + 0.00311h \tag{8}$$

$$\log_{10} PGV = -1.769 + 0.628\,M_J - \log_{10}(r + C^{*}(M)) - 0.00130r + 0.00222h \tag{9}$$

where

$$C(M) = d_1 10^{d_2 M} \tag{10}$$

Similar to Fukushima and Tanaka (1990), we applied the distance adjustment only for the geometric spreading term. This is because in the near-field, anelastic attenuation is negligible relative to geometric spreading. If total magnitude-independence of the peak ground acceleration is assumed, d_2 is set equal to the magnitude scaling parameter (i.e., d_2 = 0.477). However, since the near-source data used is from a single event, we limit our determination of the near-field saturation to that of $C^a(M)$ and $C^v(M)$. These values are assumed to be constant at this time. To estimate $C(M)$, we performed a non-linear least square analysis of the Hyogoken-nambu Earthquake data (JMA and non-JMA). This is done by the GOLDEN search algorithm (Press, et al., 1992) to iteratively find $C(M)$ such that the sum of squares of the errors are minimized. The error is defined as the difference between the predicted ground motions by Equations (8) and (9) for a trial value of $C(M)$ and the corresponding recorded peak ground motion. This method implicitly assumes that the attenuation rates and depth terms of Equations 1 and 2 apply for the Hyogoken-nambu Earthquake records. Since the source depth are small for this event, the second assumption does not have much influence in the least squares analysis. The parameter $C(M)$ was found to be 0.82 km for PGA and 0.55 km for PGV. The $C(M)$'s determined from the leastsquares analysis seem small.

However, it is noted that the best fit attenuation of ground motion for an individual earthquake is very likely different from the best fit line determined from a set of earthquakes. One source of this difference is referred to as the earthquake-to-earthquake component of the variability (or error), ε_e (Joyner and Boore, 1993). If this component is considered, the regression equations become

$$log_{10} PGA = 0.206 + 0.477 M_J - log_{10} (r + C^a(M)) - 0\ 00144r + 0.00311h + \varepsilon_e^a \tag{11}$$

$$log_{10} PGV = -1.769 + 0.628\ M_J - log_{10} (r + C^v(M)) - 0.00130r + 0.00222h + \varepsilon_e^a \tag{12}$$

A trial value of $C(M)$ is assumed and then ε_e is determined such that the mean of the error (not including ε_e) is zero. The resulting sum of the squares of errors is then used as the parameter to minimize by the GOLDEN search algorithm. $C(M)$ was found to be 3.8 km for PGA and 7.0 km for PGV while ε_e is 0.116 and 0.193 for the PGA and PGV, respectively. Molas and Yamazaki (1995) gives the standard deviation of the earthquake-to-earthquake component of the error as 0.122 and 0.103 for PGA and PGV, respectively. This means that ε_e lies within one standard deviation for PGA but about 1.9 times the standard deviation for PGV. This implies that the

peak ground velocities generated by the Hyogoken-nambu Earthquake is significantly greater than the events used by Molas and Yamazaki (1995).

It must be noted, however, that the error was measured against Equations 11 and 12 with a station coefficient of zero. This represents the mean response of the 76 JMA stations considering the local site effect. The mean response of the non-JMA recording stations may be significantly different than for the JMA stations. If this fact is considered, ε_e as determined by the procedure described above may be lower for both the PGA and PGV.

The resulting attenuation curves are shown in Figure 9. Although h is either 1.7 kin or 4.3 km for the recorded data, the curves were drawn assuming that $h = 0$. Since h is small, the contribution of the depth term to the predicted peak ground motion is negligible. It can be seen from Figure 9 that the results of the minimization analyses are not so different from the original attenuation relations if the earthquake-to-earthquake component of the error is not considered. If ε_e is considered, the distance saturation effect of the data is more pronounced, especially for PGV.

In the case of $C(M)$, we can compare it with other studies if the magnitude of the Hyogoken-nambu Earthquake is used as a reference. Campbell (1981) determined a $C(M)$ for PGA of 7 km for unconstrained magnitude independence and 21.3 km for a magnitude independent PGA at the near-field (assuming a Richter Magnitude of 6.8). Fukushima and Tanaka assumed magnitude independence of PGA and determined a $C(M)$ of 28.1 km. Kamiyama et al. (1994) also assumed magnitude independence of PGA and determined a $C(M)$ of 38.3 km. Although Kamiyama et al. assumed magnitude dependence for the PGV and the PGD, they used the same $C(M)$ as in the PGA. The distance saturation determined in this study is comparable to the unconstrained model of Campbell (1981). At present, it is difficult to assess the magnitude independence of the distance saturation for the recorded ground motion of the Hyogoken-nambu Earthquake.

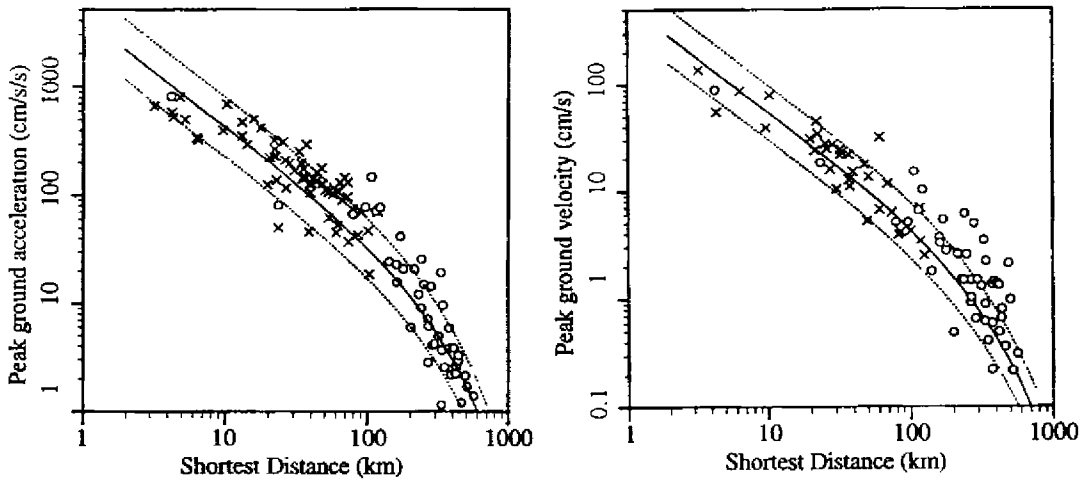

Figure 8. Plot of the recorded PGA(left) and PGV(right) for the JMA stations(circles) and other free-field (non-JMA) recording stations(x's) The solid line shows the predicted mean PGA and PGV using Equations 1 and 2, respectively, while the dotted lines give the one-standard deviation limits. However, it must be noted that the standard deviations of Equations 1 and 2 are based on the regressions which consider the local site effect of the JMA stations. The standard deviations (or variance) should include the station-to-station component of the variance, which were not explicitly estimated by Molas and Yamazaki(1995).

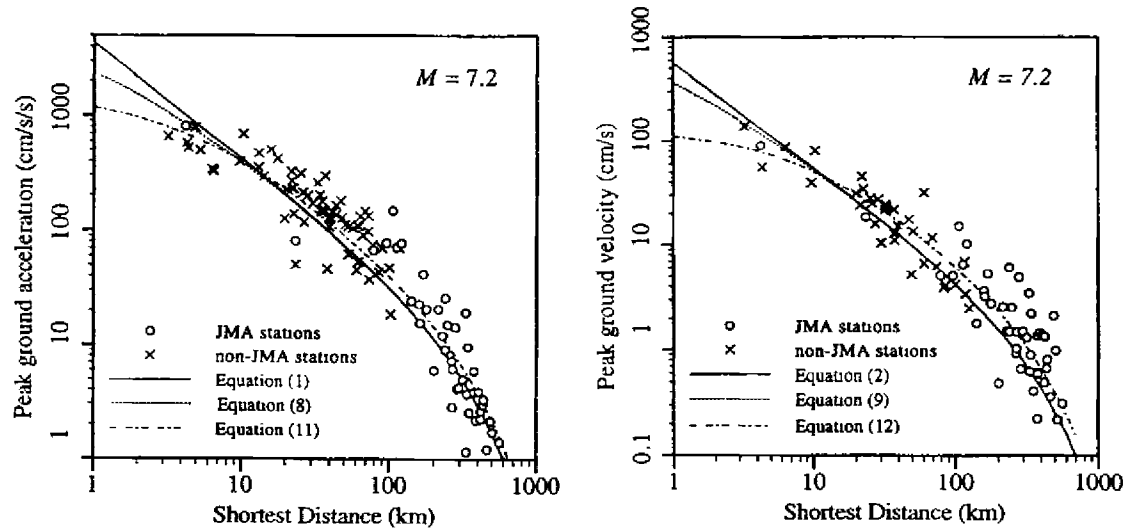

Figure 9. Modified attenuation curves for PGA(left) and PGV (right) considering the distance saturation effect in the near field. Equations 8 and 9 (dotted lines) show the distance saturation by adding a distance saturation term to the distance term of the geometric spreading term. The distance saturation term is then determined by least squares. Equations 11 and 12 additionally considers the random scaling of an individual earthquake with respect to the mean prediction in the least squares procedure to determine the distance saturation.

7. CONCLUSIONS

The earthquake ground motion data recorded during the Hyogoken-nambu Earthquake are examined and compared with the results of an attenuation study based on earthquakes before the Hyogoken-nambu Earthquake. Since the previous study is based on data from JMA stations recorded by the new JMA-87 type seismometers, the records from these stations are compared with the predicted attenuation curves. It is found that the recorded data have a relatively good fit. The fit is improved if the recorded data are corrected for local-site effects determined from the previous study. The near-field data also fit the predicted attenuation even though the equations were derived using far-field data. However, the data are still inadequate for a more definite conclusion.

Since there are several other near-field data for the Hyogoken-nambu Earthquake, the attenuation is also compared to the predictive equations. It is found that the near-field non-JMA data also have good fit with the attenuation relations based on far-field data. It is apparent that the fit will improve if the attenuation relations constrain the predicted PGAs and PGVs at the near-field to a finite-value. The attenuation relations developed from far-field data were modified by redefining the distance parameter for the geometric spreading term. Although magnitude independence of the PGA in the near-field is desirable, it is not possible to determine such characteristics from the data used in this study. The distance parameter was assumed to be a constant and determined such that the sum of squares of the errors are minimized. The resulting attenuation curves have improved fit in the near-field.

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