NORSAR

Reduction of Natural Disasters in Central America
Earthquake Preparedness and Hazard Mitigation
Seismic Zonation and Earthquake Hazard Assessment

Technical Report No. 2-17

Spectral Strong Motion Attenuation in Central America

by

Alvaro Climent[1], Waldo Taylor[1], Mauricio Ciudad Real[2], Wilfried Strauch[3], Guillermo Santana[4], Mario Villagran[5], Anders Dahle[6] and Hilmar Bungum[6]

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Summary

A bayesian regression analysis of response spectral ordinates based on 218 digitized strong ground motion accelerograms (largest horizontal component) from Central America, augmented by 62 similar, high-magnitude observations from Guerrero, Mexico, has been performed using the simple linearized ground motion model:

$$\ln A = c_1 + c_2 M + c_3 \ln r + c_4 r + c_5 S + \ln \varepsilon \quad (1)$$

where M is moment magnitude, r is hypocentral distance, S is zero for rock sites and 1 for soil sites and $\ln\varepsilon$ is a normally distributed error term with zero mean and standard deviation σ i.e. $\ln\varepsilon = N(0, \sigma)$.

For pseudo-relative velocity (PSV) in m/s, the following coefficients have been found for the mean value of the largest component of horizontal ground motion at 5% damping:

f(Hz)	c_1	c_2	c_3	c_4	c_5	σ
0.25	-7.441	1.007	-0.601	-0.00040	0.496	0.73
0.50	-7.348	1.128	-0.728	-0.00053	0.536	0.79
1.00	-6.744	1.081	-0.756	-0.00077	0.588	0.82
2.00	-5.862	0.917	-0.726	-0.00107	0.566	0.82
5.00	-4.876	0.642	-0.642	-0.00156	0.470	0.82
10.00	-4.726	0.483	-0.581	-0.00199	0.381	0.80
20.00	-5.487	0.447	-0.550	-0.00246	0.309	0.78
40.00	-7.214	0.553	-0.537	-0.00302	0.327	0.75

Correspondingly for peak ground acceleration (PGA) in m/s^2:

f(Hz)	c_1	c_2	c_3	c_4	c_5	σ
40.00	-1.687	0.553	-0.537	-0.00302	0.327	0.75

1 Introduction

This report presents the first comprehensive regression analysis of strong motion data from Central America and Mexico, compiled in a common data base format during the four year project "Reduction of Natural Disasters in Central America. Earthquake Preparedness and Hazard Mitigation. Seismic Zonation and Earthquake Hazard Assessment". The results should be regarded as tentative in the sense that the data and analysis presented herein remain open and subject to comprehensive review and discussion by interested parties, which most may lead to the need for an updating of various key parameters. It is also likely that different approaches to data selection and analysis will be tried later, and that various regional subsets of data will be subjected to more detailed analysis.

The analysis presented here is performed for response spectral pseudo-relative velocity (PSV), including also the PSV at 40 Hz which defines the peak ground acceleration (PGA), for the largest horizontal component of ground motion at 5 % of critical damping. The response spectral ordinates for the regression analysis were computed according to the step-by-step method (Nigam and Jennings, 1969), following instrument correction and band-pass filtering between 0.2 and 25 Hz, using the procedure described by Sunder and Connor (1982).

The results are presented for eight frequencies (including PGA at 40 Hz) between 0.25 and 40 Hz. The regression analysis was actually performed for additional frequencies, in order to achieve a sufficient basis for computing smoothed coefficients. The final results are thus presented in terms of smoothed coefficients, except for the extreme frequencies (highest and lowest at 0.25 and 40.0 Hz respectively) where the un-smoothed results are preserved.

2 Data Background

2.1 General

The data selected for analysis are based on strong-motion records from the Central American data base established during this project and documented in detail by Taylor (1992), Taylor et al. (1994), Santos(1992), and Segura et al. (1994).

In order to strengthen the magnitude-distance distribution of the data at larger magnitudes, some records for earthquakes above Mw 6.5 from Guerrero, Mexico have been included in the analysis.

The data used in the regression amounts to 280 records, originating from a number of sources, as shown in Table 2.1. There are 72 different earthquakes represented in the data and around one hundred recording stations.

Number of records	Country	Institution providing the data
102	Costa Rica	University of Costa Rica (UCR), San Jose, Costa Rica
62	Mexico	University of Mexico (UNAM), Mexico City, Mexico
55	Costa Rica	Instituto Costrarricense de Electricidad (ICE), San Jose, Costa Rica
34	Nicaragua	Instituto Nicaragüense de Estudios Territoriales (INETER), Managua, Nicaragua
19	El Salvador	Centro de Investigaciones Geotecnicas (CIG), San Salvador, El Salvador
8	Nicaragua, El Salvador	United States Geological Survey (USGS) Boulder, Colorado

Table 2.1 Number of records contributing to the analysis by country and by agency providing the data.

The earthquakes are classified as subduction zone (SU) or shallow crustal (SC) events. As shown and discussed in more detail in Section 5, the observations do not unequivocally call for separate grouping of subduction and shallow crustal events.

The recording sites are classified as rock or soil sites, and this is an active parameter used in the regression analysis. There are 92 rock site recordings (about 1/3 of the data set). In three cases, the site conditions remain undetermined and are classified as unknown (UNKN). In the actual analysis, these few records have been considered as deriving from soil sites, which then comprise a total of 188 recordings (2/3 of the data set).

The distribution of the records of Table 2.2 with respect to magnitude and epicentral distance is shown in Fig. 2.1. The correlation coefficient of the distribution is 0.45, representing a moderate dependence between magnitude and distance. As a first approximation in this initial analysis, therefore, a simple one-step regression was applied (for a more detailed discussion of one-step vs. two-step approaches, see Dahle et al., 1991).

The location of epicenters and recording sites for the strong motion data are shown in Fig. 2.2. It should be emphasized that the Guerrero (Mexico) data comprise 62 of 280 records, amounting to about 22% of the data, and mainly representing large magnitudes and earthquakes recorded at large distances.

Throughout this analysis only the largest horizontal component of motion has been used, selected from a data base of 280 3-component recordings. The total Central American data base consists of 1040 single component recordings (Taylor et al., 1994), giving theoretically almost 350 3-component records. The selection of fewer recordings in this analysis is caused by; i) existence of duplicate recordings (El Salvador data from CIG and NGDC) and ii) Guerrero, Mexico data only above magnitude 6.5 were used.

2.2 Magnitudes and Locations

The magnitude distribution (Fig 2.3) shows that magnitudes around 5-6 and 8 are well represented. The important high magnitude coverage is obtained by the inclusion of the Guerrero (Mexico) data. For more details concerning the determination of source parameters for the selected events we refer to Taylor et. al. (1994) and Segura et al. (1994).

Magnitudes M_w were established for the Central American data either directly from Harvard moment tensor solutions whenever available, or by regression equations developed by Rojas et al. (1993 b) for different magnitude types versus M_w.

The work by Rojas et al. (1993 a) contains several alternative locations and magnitudes for particular earthquakes. A special catalogue linking the preferred location and magnitude to the strong motion data was established and entered into the headers of the strong motion data files before we commenced the processing and analysis. The order of priority of the magnitudes used for conversion to M_W, were M_S (surface wave), m_b (body wave), M_D(local), respectively.

For the Guerrero (Mexico) data the moment magnitudes were taken from Ordaz and Singh (1992).

2.3 Hypocentral Distance and Focal Depth

The hypocentral distance distribution (Fig 2.3) shows that distances less than about 150 km are most common, but that hypocentral distances from 6-500 km are represented.

The focal depth distribution (Fig 2.4) reveals a concentration of shallow earthquakes, although subduction earthquakes up to about 100 km focal depth are also represented.

Year	M	D	H	m	Elat (deg)	Elon (deg)	Dt (km)	Ev	Edist (km)	Slat (deg)	Slon (deg)	Stype	M_w
1990	12	22	17	27	9.911	-84.313	4.8	SC	25.9	9.938	-84.078	SOIL	6.0
1990	12	22	17	27	9.911	-84.313	4.8	SC	16.2	10.021	-84.216	SOIL	6.0
1990	12	22	17	27	9.911	-84.313	4.8	SC	56.2	9.842	-83.805	ROCK	6.0
1990	12	22	17	27	9.911	-84.313	4.8	SC	42.8	9.866	-83.925	SOIL	6.0
1990	12	22	17	27	9.911	-84.313	4.8	SC	30.5	9.870	-84.038	ROCK	6.0
1990	12	22	17	27	9.911	-84.313	4.8	SC	23.4	9.916	-84.099	SOIL	6.0
1990	12	22	17	27	9.911	-84.313	4.8	SC	26.2	9.938	-84.075	SOIL	6.0
1990	12	22	17	27	9.911	-84.313	4.8	SC	48.5	9.976	-84.751	SOIL	6.0
1990	12	22	17	27	9.911	-84.313	4.8	SC	23.0	9.940	-84.105	SOIL	6.0
1990	12	22	17	27	9.911	-84.313	4.8	SC	27.0	10.088	-84.482	SOIL	6.0
1991	4	22	21	56	9.633	-83.148	23.5	SC	107.4	9.938	-84.078	SOIL	7.6
1991	4	22	21	56	9.633	-83.148	23.5	SC	124.7	10.021	-84.216	SOIL	7.6
1991	4	22	21	56	9.633	-83.148	23.5	SC	75.7	9.842	-83.805	ROCK	7.6
1991	4	22	21	56	9.633	-83.148	23.5	SC	104.9	9.937	-84.054	SOIL	7.6
1991	4	22	21	56	9.633	-83.148	23.5	SC	88.7	9.866	-83.922	SOIL	7.6
1991	4	22	21	56	9.633	-83.148	23.5	SC	101.0	9.870	-84.038	ROCK	7.6
1991	4	22	21	56	9.633	-83.148	23.5	SC	108.9	9.916	-84.099	SOIL	7.6
1991	4	22	21	56	9.633	-83.148	23.5	SC	67.8	9.374	-83.708	SOIL	7.6
1991	4	22	21	56	9.633	-83.148	23.5	SC	130.0	9.848	-84.314	SOIL	7.6
1988	3	11	03	44	8.890	-83.110	51.3	SU	139.2	9.859	-83.913	SOIL	6.0
1987	7	15	11	36	9.470	-84.190	36.5	SU	52.8	9.859	-83.913	SOIL	5.2
1988	10	23	16	01	9.890	-83.910	9.0	SC	3.5	9.859	-83.913	SOIL	3.7
1989	2	26	12	21	9.660	-84.190	28.0	SU	37.6	9.859	-83.913	SOIL	5.4
1988	1	31	23	31	9.770	-83.630	9.0	SC	32.5	9.859	-83.913	SOIL	5.0
1987	7	15	11	36	9.470	-84.190	36.5	SU	52.9	9.866	-83.922	SOIL	5.2
1987	7	15	14	31	9.540	-84.160	40.4	SU	44.7	9.866	-83.922	SOIL	5.0
1987	7	15	11	36	9.470	-84.190	36.5	SU	50.6	9.916	-84.099	SOIL	5.2
1987	7	15	14	31	9.540	-84.160	40.4	SU	42.3	9.916	-84.099	SOIL	5.0
1988	1	31	23	31	9.770	-83.630	9.0	SC	20.8	9.842	-83.805	ROCK	5.0
1988	3	11	03	44	8.890	-83.110	51.3	SU	174.7	10.021	-84.216	SOIL	6.0
1988	3	11	03	44	8.890	-83.110	51.3	SU	28.1	8.645	-83.172	ROCK	6.0
1988	10	23	16	01	9.890	-83.910	9.0	SC	3.0	9.866	-83.922	SOIL	3.7
1988	5	23	15	26	8.560	-83.280	5.1	SC	15.2	8.645	-83.172	ROCK	4.2
1989	1	24	23	24	8.660	-82.880	29.7	SU	32.1	8.645	-83.172	ROCK	4.9
1989	2	26	12	21	9.660	-84.190	28.0	SU	40.2	10.021	-84.216	SOIL	5.4
1990	4	28	01	23	8.680	-83.630	27.9	SU	50.5	8.645	-83.172	ROCK	6.4
1990	12	22	17	28	9.856	-84.314	4.7	SC	27.4	9.937	-84.077	SOIL	5.5
1990	12	22	17	28	9.856	-84.314	4.7	SC	21.2	10.021	-84.216	SOIL	5.5
1990	12	22	17	28	9.856	-84.314	4.7	SC	42.5	9.866	-83.925	SOIL	5.5
1990	12	22	17	28	9.856	-84.314	4.7	SC	30.2	9.870	-84.038	ROCK	5.5
1990	12	22	17	28	9.856	-84.314	4.7	SC	24.4	9.916	-84.099	SOIL	5.5
1990	12	22	17	28	9.856	-84.314	4.7	SC	49.8	9.977	-84.751	SOIL	5.5
1990	12	22	17	28	9.856	-84.314	4.7	SC	39.6	9.910	-83.956	SOIL	5.5
1990	12	22	17	28	9.856	-84.314	4.7	SC	31.7	10.088	-84.482	SOIL	5.5
1990	6	08	00	31	9.850	-84.350	8.9	SC	24.0	10.021	-84.216	SOIL	5.3
1990	6	09	00	34	9.900	-84.310	9.5	SC	16.9	10.021	-84.216	SOIL	5.3
1990	6	16	02	22	9.870	-84.320	7.0	SC	20.3	10.021	-84.216	SOIL	4.8

Table 2.2. Cont. ...

Year	M	D	H	m	Elat (deg)	Elon (deg)	Dt (km)	Ev	Edist (km)	Slat (deg)	Slon (deg)	Stype	M_w
1990	6	30	14	51	9.820	-84.380	4.8	SC	28.7	10.021	-84.216	SOIL	5.5
1990	6	30	14	55	9.900	-84.350	5.0	SC	19.9	10.021	-84.216	SOIL	5.1
1990	6	30	14	59	9.920	-84.300	19.5	SC	14.5	10.021	-84.216	SOIL	5.1
1990	6	30	14	51	9.820	-84.380	4.8	SC	32.6	9.916	-84.099	SOIL	5.5
1990	3	25	13	16	9.550	-84.950	16.2	SC	104.9	9.937	-84.077	SOIL	7.1
1990	3	25	13	22	9.620	-84.928	16.9	SC	99.7	9.937	-84.077	SOIL	7.3
1990	3	25	13	16	9.550	-84.950	16.2	SC	96.0	10.021	-84.216	SOIL	7.1
1990	3	25	13	22	9.620	-84.928	16.9	SC	89.9	10.021	-84.216	SOIL	7.3
1990	3	25	13	22	9.620	-84.928	16.9	SC	113.6	9.866	-83.922	SOIL	7.3
1990	3	25	13	22	9.620	-84.928	6.5	SC	103.9	9.939	-84.037	SOIL	7.3
1990	3	25	13	22	9.620	-84.928	16.9	SC	101.4	9.870	-84.038	ROCK	7.3
1990	3	25	13	22	9.620	-84.928	16.9	SC	96.6	9.916	-84.099	SOIL	7.3
1990	3	25	13	16	9.550	-84.950	16.2	SC	52.0	9.976	-84.755	SOIL	7.1
1990	3	25	13	22	9.620	-84.928	16.9	SC	43.9	9.976	-84.755	SOIL	7.3
1990	3	25	13	22	9.620	-84.928	16.9	SC	86.2	9.431	-84.166	ROCK	7.3
1990	3	25	13	22	9.620	-84.928	16.9	SC	97.0	9.940	-84.105	SOIL	7.3
1990	3	25	13	16	9.550	-84.950	16.2	SC	78.8	10.088	-84.482	SOIL	7.1
1990	3	25	13	22	9.620	-84.928	16.9	SC	71.4	10.088	-84.482	SOIL	7.3
1991	4	22	22	08	9.820	-83.505	10.0	SC	64.0	9.937	-84.077	SOIL	5.9
1991	4	22	22	19	9.915	-83.413	10.0	SC	72.8	9.937	-84.077	SOIL	5.9
1991	4	22	22	07	10.005	-83.377	10.0	SC	91.9	10.021	-84.216	SOIL	5.7
1991	4	22	22	08	9.820	-83.505	10.0	SC	81.0	10.021	-84.216	SOIL	5.9
1991	4	22	22	07	10.005	-83.377	10.0	SC	50.3	9.842	-83.805	ROCK	5.7
1991	4	22	22	19	9.915	-83.413	10.0	SC	43.7	9.842	-83.805	ROCK	5.9
1991	4	22	22	07	10.005	-83.377	10.0	SC	74.5	9.937	-84.054	SOIL	5.7
1991	4	22	22	07	10.005	-83.377	10.0	SC	61.7	9.866	-83.922	SOIL	5.7
1991	4	22	22	19	9.915	-83.413	10.0	SC	56.0	9.866	-83.922	SOIL	5.9
1991	4	22	21	56	9.633	-83.148	23.5	SC	109.9	8.645	-83.172	ROCK	7.6
1991	4	22	22	08	9.820	-83.505	10.0	SC	65.9	9.916	-84.099	SOIL	5.9
1991	4	22	23	13	9.466	-83.304	10.0	SC	45.4	9.373	-83.707	SOIL	5.1
1991	4	22	22	07	10.005	-83.377	10.0	SC	104.1	9.848	-84.314	SOIL	5.7
1991	4	22	21	56	9.633	-83.148	23.5	SC	113.9	9.431	-84.166	ROCK	7.6
1991	4	22	21	56	9.633	-83.148	23.5	SC	154.5	10.088	-84.482	SOIL	7.6
1991	4	24	19	12	9.440	-83.520	12.7	SC	54.5	9.842	-83.805	ROCK	6.1
1991	4	24	19	12	9.440	-83.520	12.7	SC	21.8	9.373	-83.707	SOIL	6.1
1991	2	16	13	24	9.990	-84.100	19.5	SC	13.2	10.021	-84.216	SOIL	3.3
1991	8	02	04	14	9.740	-84.050	6.9	SC	20.3	9.916	-84.099	SOIL	4.7
1991	8	06	10	55	9.740	-84.030	17.7	SC	18.3	9.866	-83.922	SOIL	4.7
1991	8	06	10	55	9.740	-84.030	17.7	SC	21.0	9.916	-84.099	SOIL	4.7
1991	8	09	09	33	9.771	-84.038	5.3	SC	34.0	10.021	-84.216	SOIL	5.3
1991	8	09	09	33	9.771	-84.038	5.3	SC	26.7	9.842	-83.805	ROCK	5.3
1991	08	09	09	33	9.771	-84.038	5.3	SC	16.5	9.866	-83.922	SOIL	5.3
1991	8	09	09	33	9.771	-84.038	5.3	SC	17.5	9.916	-84.099	SOIL	5.3
1991	8	09	17	53	9.810	-84.000	5.2	SC	16.0	9.916	-84.099	SOIL	4.7
1991	8	09	18	00	9.760	-84.000	7.0	SC	20.5	9.916	-84.099	SOIL	4.8
1990	8	09	09	33	9.771	-84.038	5.3	SC	17.9	9.910	-83.956	SOIL	5.3
1992	3	07	01	53	10.030	-84.350	85.0	SU	14.7	10.021	-84.216	SOIL	6.6
1992	3	07	01	53	10.030	-84.350	85.0	SU	63.2	9.842	-83.805	ROCK	6.6

Table 2.2. Cont. ...

Year	M	D	H	m	Elat (deg)	Elon (deg)	Dt (km)	Ev	Edist (km)	Slat (deg)	Slon (deg)	Stype	M_w
1992	3	07	01	53	10.030	-84.350	85.0	SU	50.3	9.866	-83.922	SOIL	6.6
1992	3	07	01	53	10.030	-84.350	85.0	SU	29.8	9.916	-84.099	SOIL	6.6
1992	3	07	01	53	10.030	-84.350	85.0	SU	20.6	9.848	-84.314	SOIL	6.6
1992	3	07	01	53	10.030	-84.350	85.0	SU	45.0	9.940	-84.751	SOIL	6.6
1992	11	03	11	46	9.920	-84.140	4.3	SC	14.0	10.021	-84.216	SOIL	4.3
1992	11	03	11	46	9.920	-84.140	4.3	SC	4.5	9.916	-84.099	SOIL	4.3
1992	9	14	08	34	10.167	-84.188	2.9	SC	19.0	10.021	-84.216	SOIL	4.8
1987	7	15	11	36	9.470	-84.190	36.5	SU	54.5	9.940	-84.330	SOIL	5.2
1987	7	15	14	31	9.540	-84.160	40.4	SU	48.2	9.940	-84.330	SOIL	5.0
1987	7	15	11	36	9.470	-84.190	36.5	SU	54.5	9.940	-84.330	ROCK	5.2
1987	7	15	14	31	9.540	-84.160	40.4	SU	48.2	9.940	-84.330	ROCK	5.0
1987	8	27	16	52	9.600	-84.090	43.5	SU	24.6	9.820	-84.110	SOIL	4.6
1987	8	27	17	53	9.420	-84.210	30.0	SU	45.8	9.820	-84.110	SOIL	3.7
1987	09	20	03	03	9.690	-84.400	55.0	SU	34.9	9.820	-84.110	SOIL	4.5
1988	1	31	23	31	9.770	-83.630	9.0	SC	52.9	9.820	-84.110	SOIL	5.0
1988	1	31	23	40	9.770	-83.630	17.0	SC	52.9	9.820	-84.110	SOIL	4.1
1988	3	11	03	44	8.890	-83.110	51.3	SU	25.1	8.950	-83.330	ROCK	6.0
1988	3	11	03	44	8.890	-83.110	51.3	SU	150.8	9.820	-84.110	SOIL	6.0
1988	3	23	07	39	9.850	-84.190	69.0	SU	9.4	9.820	-84.110	SOIL	5.0
1989	2	26	12	21	9.660	-84.190	28.0	SU	34.7	9.940	-84.330	SOIL	5.4
1989	2	26	12	21	9.660	-84.190	28.0	SU	34.7	9.940	-84.330	ROCK	5.4
1990	4	28	01	23	8.680	-83.630	27.9	SU	44.6	8.950	-83.330	SOIL	6.4
1990	6	01	03	28	9.880	-84.310	4.8	SC	7.0	9.940	-84.330	SOIL	4.5
1990	6	08	00	31	9.850	-84.350	8.9	SC	10.2	9.940	-84.330	SOIL	5.3
1990	6	08	00	31	9.850	-84.350	9.0	SC	10.2	9.940	-84.330	ROCK	5.3
1990	6	08	13	46	9.900	-84.280	7.0	SC	7.1	9.940	-84.330	ROCK	4.8
1993	6	09	00	34	9.900	-84.310	9.5	SC	5.0	9.940	-84.330	SOIL	5.3
1990	6	09	00	34	9.900	-84.310	9.5	SC	5.0	9.940	-84.330	ROCK	5.3
1990	6	16	02	22	9.870	-84.320	7.0	SC	7.9	9.940	-84.330	ROCK	4.8
1990	6	18	09	09	9.880	-84.340	13.5	SC	6.8	9.940	-84.330	ROCK	4.0
1990	6	30	14	51	9.820	-84.380	4.8	SC	14.4	9.940	-84.330	ROCK	5.5
1990	3	25	13	22	9.620	-84.928	16.9	SC	123.4	10.700	-85.190	SOIL	7.3
1990	3	25	13	16	9.550	-84.950	16.2	SC	80.6	9.940	-84.330	SOIL	7.1
1990	3	25	13	22	9.620	-84.928	16.9	SC	74.6	9.940	-84.330	SOIL	7.3
1990	3	25	13	22	9.620	-84.928	16.9	SC	104.4	9.470	-83.990	SOIL	7.3
1990	3	25	13	22	9.620	-84.928	16.9	SC	97.4	10.480	-84.760	SOIL	7.3
1990	5	29	19	56	9.860	-84.260	15.0	SC	11.7	9.940	-84.330	SOIL	5.0
1990	5	30	22	05	9.850	-84.270	13.9	SC	12.0	9.940	-84.330	SOIL	5.1
1990	5	31	08	59	9.880	-84.310	3.9	SC	7.0	9.940	-84.330	SOIL	4.3
1990	12	22	17	27	9.911	-84.313	4.8	SC	37.9	10.250	-84.280	ROCK	6.0
1991	3	16	06	02	9.720	-85.665	30.0	SU	103.3	10.460	-85.100	SOIL	6.3
1991	4	22	21	56	9.633	-83.148	23.5	SC	133.8	9.940	-84.330	SOIL	7.6
1991	4	22	21	56	9.633	-83.148	23.5	SC	133.8	9.940	-84.330	ROCK	7.6
1991	4	22	21	56	9.633	-83.148	23.5	SC	141.7	10.250	-84.280	ROCK	7.6
1991	4	27	05	42	10.060	-83.320	22.2	SC	36.5	9.940	-83.630	SOIL	5.3
1991	4	27	05	42	10.060	-83.320	22.2	SC	19.8	10.040	-83.500	SOIL	5.3
1991	8	09	17	53	9.810	-84.000	5.2	SC	7.9	9.740	-84.010	ROCK	4.7
1991	8	09	18	00	9.760	-84.000	7.0	SC	2.5	9.740	-84.010	ROCK	4.8

Table 2.2. Cont. ...

Year	M	D	H	m	Elat (deg)	Elon (deg)	Dt (km)	Ev	Edist (km)	Slat (deg)	Slon (deg)	Stype	M_w
1991	11	10	08	20	9.870	-83.420	11.9	SC	24.3	9.940	-83.630	SOIL	5.3
1991	11	10	08	20	9.870	-83.420	11.9	SC	20.8	10.040	-83.500	ROCK	5.3
1992	3	07	01	53	10.030	-84.350	85.0	SU	118.3	10.700	-85.190	SOIL	6.6
1992	3	07	01	53	10.030	-84.350	85.0	SU	49.3	9.740	-84.010	ROCK	6.6
1992	3	07	01	53	10.030	-84.350	85.0	SU	10.2	9.940	-84.330	ROCK	6.6
1992	3	07	01	53	10.030	-84.350	85.0	SU	73.7	9.470	-83.990	SOIL	6.6
1992	3	07	01	53	10.030	-84.350	85.0	SU	95.0	10.460	-85.100	SOIL	6.6
1992	11	03	11	46	9.920	-84.140	4.3	SC	20.9	9.940	-84.330	SOIL	4.3
1993	7	08	23	18	9.750	-83.690	13.6	SC	22.1	9.940	-83.630	SOIL	5.3
1993	7	10	20	40	9.760	-83.680	13.2	SC	20.5	9.940	-83.630	SOIL	5.8
1993	7	10	21	11	9.760	-83.660	13.3	SC	20.0	9.940	-83.630	SOIL	3.9
1993	7	13	15	10	9.720	-83.660	14.4	SC	22.3	9.940	-83.630	SOIL	5.2
1991	4	22	21	56	9.633	-83.148	23.5	SC	59.5	10.040	-83.500	SOIL	7.6
1990	12	22	17	27	9.911	-84.313	4.8	SC	3.7	9.940	-84.330	ROCK	6.0
1972	1	5	5	55	12.280	-86.230	33.0	SC	18.4	12.140	-86.320	SOIL	4.5
1972	1	5	5	55	12.280	-86.230	33.0	SC	19.4	12.11	-86.27	SOIL	4.5
1972	12	23	07	17	12.130	-86.300	5.0	SC	2.4	12.140	-86.320	SOIL	5.4
1972	12	23	06	29	12.150	-86.270	5.0	SC	5.5	12.140	-86.320	SOIL	6.4
1972	12	23	07	19	12.160	-86.300	5.0	SC	3.1	12.140	-86.320	SOIL	5.7
1967	11	18	22	43	13.050	-89.420	70.0	SU	74.1	13.680	-89.198	UNKN	5.9
1968	01	04	10	04	12.100	-86.300	5.0	SC	6.4	12.150	-86.270	SOIL	4.9
1973	03	31	20	13	12.100	-86.300	5.0	SC	3.4	12.110	-86.270	SOIL	4.6
1978	4	12	16	51	12.490	-87.895	58.2	SU	83.9	12.330	-87.140	SOIL	5.5
1978	5	31	01	07	12.335	-87.610	55.5	SU	162.8	12.110	-86.130	SOIL	6.5
1978	5	31	01	07	12.335	-87.610	55.5	SU	146.9	12.160	-86.270	SOIL	6.5
1978	5	31	01	07	12.335	-87.610	55.5	SU	162.5	11.850	-86.200	SOIL	6.5
1978	5	31	01	07	12.335	-87.610	55.5	SU	78.0	12.440	-86.900	SOIL	6.5
1978	5	31	01	07	12.335	-87.610	55.5	SU	51.1	12.330	-87.140	SOIL	6.5
1978	5	31	01	07	12.335	-87.610	55.5	SU	50.4	12.480	-87.170	SOIL	6.5
1980	6	06	20	35	12.445	-87.882	46.0	SU	84.7	12.610	-87.120	SOIL	5.3
1980	7	13	23	37	9.186	-84.085	41.0	SU	315.5	11.430	-85.850	SOIL	4.7
1983	7	18	12	52	12.270	-87.830	63.0	SU	170.0	12.160	-86.270	SOIL	6.5
1983	7	18	12	52	12.270	-87.830	63.0	SU	167.0	12.130	-86.300	SOIL	6.5
1978	7	20	09	34	11.975	-86.894	72.0	SU	84.4	12.110	-86.130	SOIL	5.5
1978	7	20	09	34	11.975	-86.894	72.0	SU	70.9	12.160	-86.270	SOIL	5.5
1978	7	20	09	34	11.975	-86.894	72.0	SU	76.8	11.850	-86.200	SOIL	5.5
1978	7	20	09	34	11.975	-86.894	72.0	SU	51.7	12.440	-86.900	SOIL	5.5
1978	7	20	09	34	11.975	-86.894	72.0	SU	47.7	12.330	-87.140	SOIL	5.5
1978	7	20	09	34	11.975	-86.894	72.0	SU	74.8	12.610	-87.120	SOIL	5.5
1978	7	20	09	34	11.975	-86.894	72.0	SU	128.8	11.430	-85.850	SOIL	5.5
1978	7	20	09	34	11.975	-86.894	72.0	SU	66.9	12.130	-86.300	SOIL	5.5
1978	7	20	09	34	11.975	-86.894	72.0	SU	76.9	12.150	-86.210	SOIL	5.5
1978	7	20	09	34	11.975	-86.894	72.0	SU	71.6	12.110	-86.250	SOIL	5.5
1978	7	20	09	34	11.975	-86.894	72.0	SU	70.3	12.140	-86.270	SOIL	5.5
1978	7	20	09	34	11.975	-86.894	72.0	SU	63.7	12.480	-87.170	SOIL	5.5
1980	8	01	08	16	12.364	-87.877	51.9	SU	80.1	12.330	-87.140	SOIL	5.6
1980	08	01	08	16	12.364	-87.877	51.9	SU	86.6	12.610	-87.120	SOIL	5.6
1977	09	03	22	33	12.332	-87.729	51.2	SU	64.0	12.330	-87.140	SOIL	5.7

Table 2.2. Cont. ...

Year	M	D	H	m	Elat (deg)	Elon (deg)	Dt (km)	Ev	Edist (km)	Slat (deg)	Slon (deg)	Stype	M_w
1977	09	03	22	33	12.332	-87.729	51.2	SU	73.0	12.610	-87.120	SOIL	5.7
1977	09	30	07	10	10.890	-86.150	70.0	SU	68.4	11.430	-85.850	SOIL	5.8
1979	10	01	12	14	11.967	-86.063	4.9	SC	4.0	11.970	-86.100	SOIL	4.1
1981	10	14	08	09	12.384	-87.643	52.5	SU	62.1	12.610	-87.120	SOIL	5.3
1983	10	19	09	33	12.607	-87.734	92.0	SU	182.8	12.110	-86.130	SOIL	5.3
1981	10	20	19	48	10.967	-85.294	2.5	SC	201.9	12.610	-87.120	SOIL	4.1
1981	10	14	08	09	12.384	-87.643	52.5	SU	55.0	12.330	-87.140	SOIL	5.3
1981	10	14	11	30	12.439	-87.869	51.6	SU	80.1	12.330	-87.140	SOIL	5.1
1986	10	10	17	49	13.673	-89.203	8.0	SC	5.7	13.714	-89.171	SOIL	5.7
1986	10	10	17	49	13.673	-89.203	8.0	SC	4.3	13.700	-89.175	SOIL	5.7
1986	10	10	17	49	13.673	-89.203	8.0	SC	5.3	13.721	-89.206	SOIL	5.7
1986	10	10	17	49	13.673	-89.203	8.0	SC	4.5	13.712	-89.215	SOIL	5.7
1986	10	10	17	49	13.673	-89.203	8.0	SC	3.8	13.683	-89.237	SOIL	5.7
1986	10	10	17	49	13.673	-89.203	8.0	SC	6.2	13.713	-89.243	SOIL	5.7
1991	3	13	01	09	12.733	-87.999	60.0	SU	65.6	13.307	-87.859	ROCK	5.3
1988	11	04	02	43	13.775	-90.916	86.0	SU	116.3	13.925	-89.850	SOIL	5.7
1992	7	02	12	34	14.050	-89.866	28.0	SC	14.6	13.978	-89.753	SOIL	3.3
1992	2	08	16	30	13.966	-89.733	20.0	SC	2.5	13.978	-89.753	SOIL	3.0
1987	11	17	03	40	12.280	-87.580	30.0	SU	234.6	13.712	-89.170	SOIL	6.5
1992	6	06	15	51	12.635	-88.536	80.0	SU	94.9	13.486	-88.471	SOIL	5.6
1992	1	21	12	54	14.140	-91.110	76.8	SU	129.8	13.901	-89.932	SOIL	4.5
1988	11	03	14	47	13.090	-90.440	69.0	SU	145.7	13.677	-89.236	SOIL	6.6
1976	2	04	09	02	15.279	-89.193	50.0	SC	175.6	13.700	-89.180	SOIL	7.5
1979	10	27	14	36	13.794	-90.891	50.0	SU	185.1	13.700	-89.180	SOIL	6.8
1988	11	03	14	47	13.090	-90.440	69.0	SU	112.6	13.925	-89.850	SOIL	6.6
1988	3	13	23	28	12.970	-89.470	17.0	SU	105.5	13.646	-88.786	SOIL	5.3
1988	03	13	23	29	12.970	-89.470	30.0	SU	160.2	13.721	-88.206	SOIL	5.3
1985	09	19	00	00	18.140	-102.710	16.0	SU	394.3	19.330	-99.183	ROCK	8.0
1985	09	19	00	00	18.140	-102.710	16.0	SU	396.5	19.358	-99.171	SOIL	8.0
1985	09	19	00	00	18.140	-102.710	16.0	SU	395.9	19.403	-99.194	SOIL	8.0
1985	09	19	00	00	18.140	-102.710	16.0	SU	484.6	19.043	-98.212	SOIL	8.0
1985	09	19	00	00	18.140	-102.710	16.0	SU	8.8	18.073	-102.755	ROCK	8.0
1985	09	19	00	00	18.140	-102.710	16.0	SU	56.6	18.047	-102.184	ROCK	8.0
1985	09	19	00	00	18.140	-102.710	16.0	SU	97.3	17.982	-101.805	ROCK	8.0
1985	09	19	00	00	18.140	-102.710	16.0	SU	145.6	17.603	-101.455	UNKN	8.0
1985	09	19	00	00	18.140	-102.710	16.0	SU	198.6	17.328	-101.040	ROCK	8.0
1985	09	19	00	00	18.140	-102.710	16.0	SU	241.5	17.226	-100.642	ROCK	8.0
1985	09	19	00	00	18.140	-102.710	16.0	SU	262.6	17.211	-100.431	ROCK	8.0
1985	09	19	00	00	18.140	-102.710	16.0	SU	286.2	17.045	-100.266	SOIL	8.0
1985	09	19	00	00	18.140	-102.710	16.0	SU	305.4	16.997	-100.090	ROCK	8.0
1985	09	19	00	00	18.140	-102.710	16.0	SU	335.8	16.913	-99.816	ROCK	8.0
1985	09	19	00	00	18.140	-102.710	16.0	SU	360.2	16.769	-99.633	ROCK	8.0
1985	09	19	00	00	18.140	-102.710	16.0	SU	367.1	17.007	-99.457	ROCK	8.0
1985	09	19	00	00	18.140	-102.710	16.0	SU	353.0	17.250	-99.511	ROCK	8.0
1985	09	19	00	00	18.140	-102.710	16.0	SU	347.8	18.617	-99.453	ROCK	8.0
1985	09	21	00	00	17.620	-101.820	20.0	SU	38.7	17.603	-101.455	UNKN	7.6
1985	09	21	00	00	17.620	-101.820	20.0	SU	88.9	17.328	-101.040	ROCK	7.6
1985	09	21	00	00	17.620	-101.820	20.0	SU	132.4	17.226	-100.642	ROCK	7.6

Table 2.2. Cont. ...

Year	M	D	H	m	Elat (deg)	Elon (deg)	Dt (km)	Ev	Edist (km)	Slat (deg)	Slon (deg)	Stype	M_w
1985	09	21	00	00	17.620	-101.820	20.0	SU	196.3	16.997	-100.090	ROCK	7.6
1985	09	21	00	00	17.620	-101.820	20.0	SU	250.8	16.769	-99.633	ROCK	7.6
1985	09	21	00	00	17.620	-101.820	20.0	SU	273.6	18.617	-99.453	ROCK	7.6
1985	09	19	00	00	18.14	-102.71	16.0	SU	262.4	17.211	-100.433	ROCK	8.0
1985	09	19	00	00	18.14	-102.71	16.0	SU	144.7	17.608	-101.462	ROCK	8.0
1985	09	19	00	00	18.14	-102.71	16.0	SU	9.0	18.071	-102.754	ROCK	8.0
1985	09	19	00	00	18.14	-102.71	16.0	SU	286.1	17.045	-100.267	SOIL	8.0
1985	09	19	00	00	18.14	-102.71	16.0	SU	302.6	16.995	-100.120	ROCK	8.0
1985	09	19	00	00	18.14	-102.71	16.0	SU	359.6	16.761	-99.644	ROCK	8.0
1985	09	19	00	00	18.14	-102.71	16.0	SU	198.8	17.325	-101.039	ROCK	8.0
1985	09	19	00	00	18.14	-102.71	16.0	SU	241.9	17.224	-100.639	ROCK	8.0
1985	09	19	00	00	18.14	-102.71	16.0	SU	96.8	17.980	-101.810	ROCK	8.0
1985	09	19	00	00	18.14	-102.71	16.0	SU	56.1	18.045	-102.189	ROCK	8.0
1985	09	19	00	00	18.14	-102.71	16.0	SU	335.5	16.913	-99.819	ROCK	8.0
1985	09	21	00	00	17.62	-101.82	20.0	SU	154.0	17.211	-100.433	ROCK	7.6
1985	09	21	00	00	17.62	-101.82	20.0	SU	38.0	17.608	-101.462	ROCK	7.6
1985	09	21	00	00	17.62	-101.82	20.0	SU	176.8	17.045	-100.267	SOIL	7.6
1985	09	21	00	00	17.62	-101.82	20.0	SU	193.4	16.995	-100.120	ROCK	7.6
1985	09	21	00	00	17.62	-101.82	20.0	SU	250.1	16.761	-99.644	ROCK	7.6
1985	09	21	00	00	17.62	-101.82	20.0	SU	89.1	17.325	-101.039	ROCK	7.6
1985	09	21	00	00	17.62	-101.82	20.0	SU	132.8	17.224	-100.639	ROCK	7.6
1985	09	21	00	00	17.62	-101.82	20.0	SU	40.0	17.980	-101.810	ROCK	7.6
1985	09	21	00	00	17.62	-101.82	20.0	SU	226.6	16.913	-99.819	ROCK	7.6
1989	04	25	00	00	16.58	-99.48	17.0	SU	123.3	17.211	-100.433	ROCK	6.9
1989	04	25	00	00	16.58	-99.48	17.0	SU	98.4	17.045	-100.267	SOIL	6.9
1989	04	25	00	00	16.58	-99.48	17.0	SU	203.9	18.122	-100.520	ROCK	6.9
1989	04	25	00	00	16.58	-99.48	17.0	SU	53.4	16.610	-98.980	ROCK	6.9
1989	04	25	00	00	16.58	-99.48	17.0	SU	82.3	16.995	-100.120	ROCK	6.9
1989	04	25	00	00	16.58	-99.48	17.0	SU	26.7	16.761	-99.644	ROCK	6.9
1989	04	25	00	00	16.58	-99.48	17.0	SU	125.0	17.650	-99.840	ROCK	6.9
1989	04	25	00	00	16.58	-99.48	17.0	SU	166.8	17.344	-100.830	ROCK	6.9
1989	04	25	00	00	16.58	-99.48	17.0	SU	148.6	17.387	-100.594	ROCK	6.9
1989	04	25	00	00	16.58	-99.48	17.0	SU	47.7	17.008	-99.457	ROCK	6.9
1989	04	25	00	00	16.58	-99.48	17.0	SU	66.2	17.036	-99.880	ROCK	6.9
1989	04	25	00	00	16.58	-99.48	17.0	SU	74.1	17.246	-99.507	ROCK	6.9
1989	04	25	00	00	16.58	-99.48	17.0	SU	116.1	17.343	-100.225	ROCK	6.9
1989	04	25	00	00	16.58	-99.48	17.0	SU	21.8	16.772	-99.439	ROCK	6.9
1989	04	25	00	00	16.58	-99.48	17.0	SU	226.2	18.614	-99.453	ROCK	6.9
1989	04	25	00	00	16.58	-99.48	17.0	SU	33.2	16.758	-99.230	ROCK	6.9
1989	04	25	00	00	16.58	-99.48	17.0	SU	51.7	16.913	-99.819	ROCK	6.9
1989	04	25	00	00	16.58	-99.48	17.0	SU	62.6	17.091	-99.726	ROCK	6.9

Table 2.2 Records used in the regression of response spectral ordinates. M=month, D=day, H=hour, m=minute, Elat=epicentral latitude, Elon=epicentral longitude, Dt=depth of focus, Ev=event class (SU=subduction event, SC= shallow crustal event), Edist=epicentral distance, Slat=station latitude, Slon=station longitude, Stype=recording site classification (rock, soil or unknown), M_w=moment magnitude.

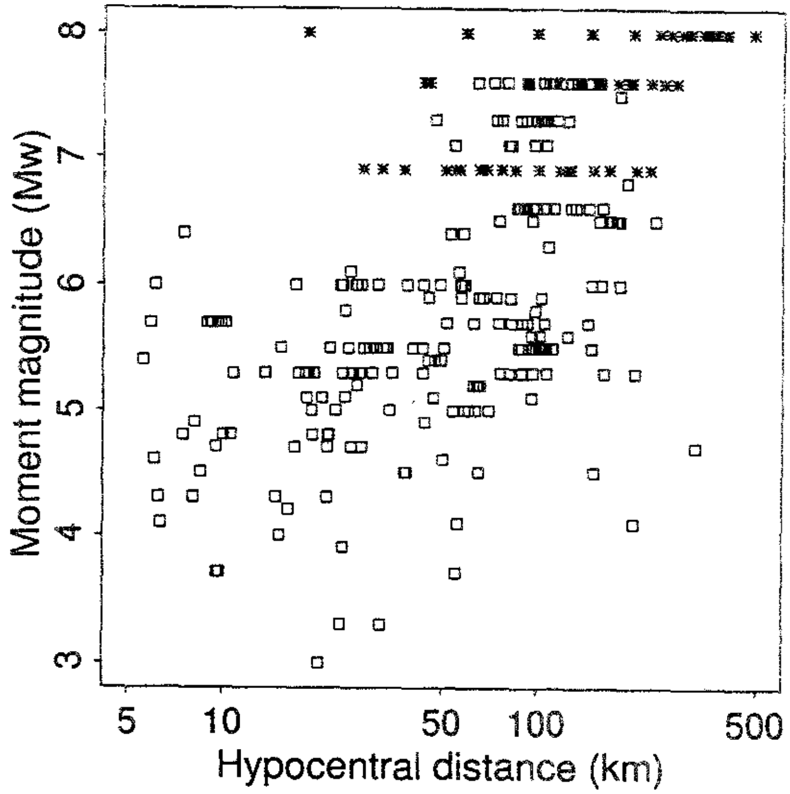


Figure 2.1 Magnitude and distance distribution of the strong motion data used in the regression of response spectral ordinates. The data points plotted correspond to Table 2.2. Open squares represent Central American data, while the asterisks correspond to the Guerrero, Mexico data.

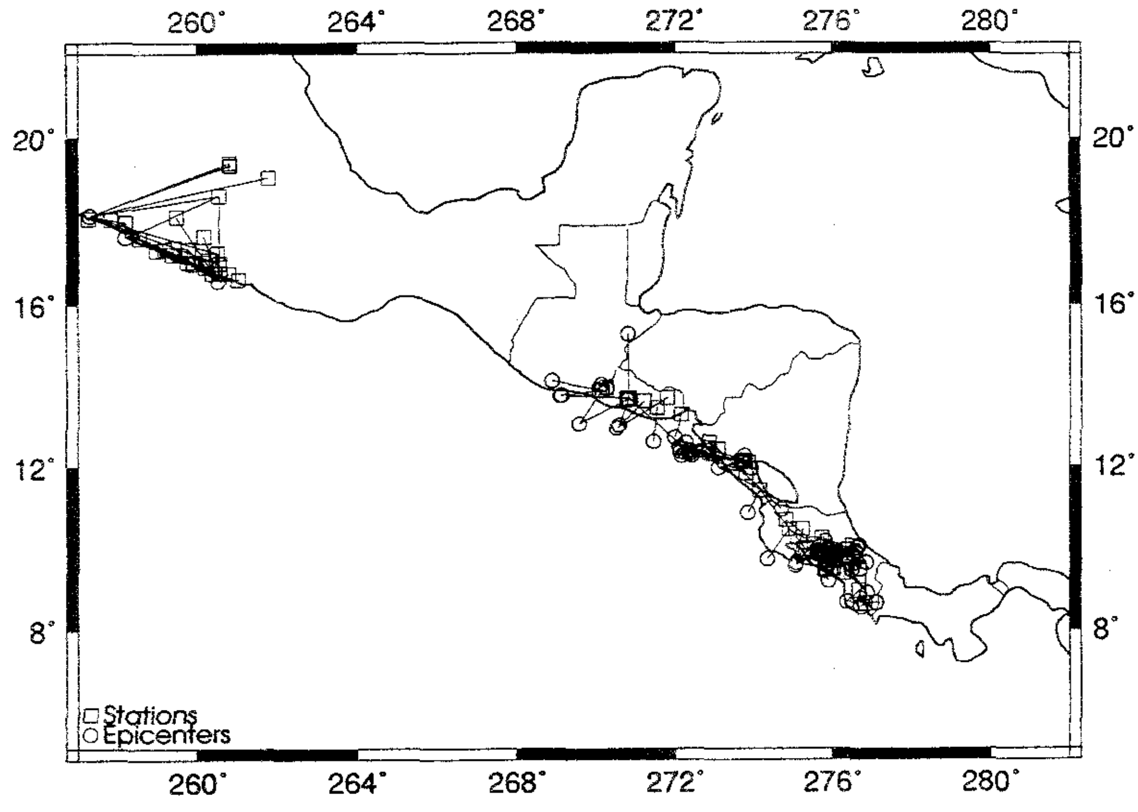


Figure 2.2. Epicenters and stations for the records in Table 2.2 used in the regression of response spectral ordinates.

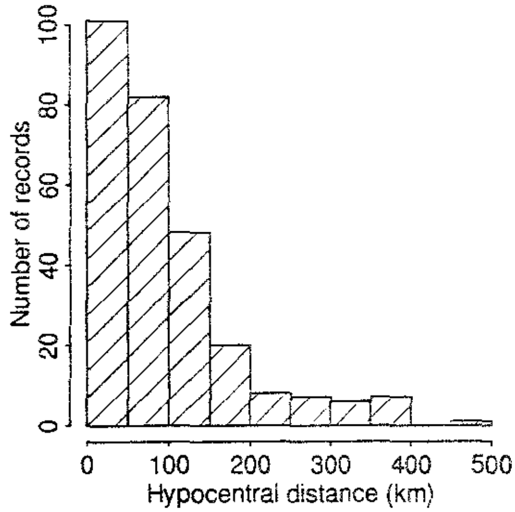


Figure 2.3. Distribution of hypocentral distances for the 280 strong motion records from Central America and Guerrero, Mexico.

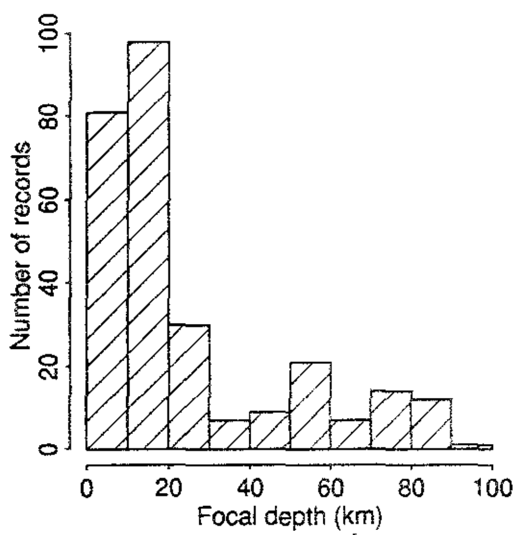


Figure 2.4. Distribution of focal depth for the 280 strong motion records from Central America and Guerrero, Mexico.

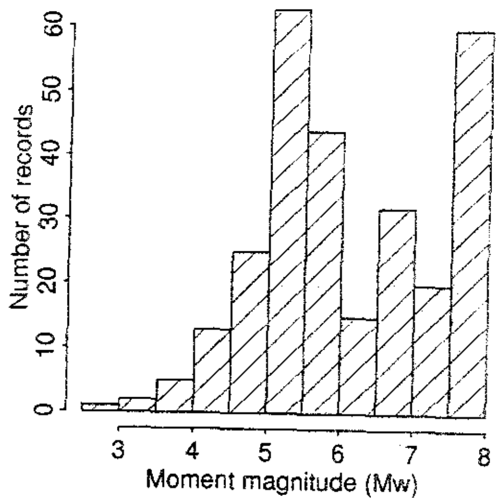


Figure 2.5. Distribution of moment magnitude for the 280 strong motion records from Central America and Guerrero, Mexico.

3 Data Analysis

The analysis of data is based on a simple one-step procedure incorporating a term that accounts for soil amplification. This procedure requires a classification of recording sites (rock or soil), which was performed as a part of the data base establishment (Taylor et. al., 1994).

3.1 Model formulation

The initial analytical approach taken to develop prediction equations for earthquake ground motion was based on the general linearized form of the ground motion amplitude formula:

$$\ln A = c_1 + c_2 M + G(r, r_0) + c_4 r + c_5 S + \ln \varepsilon \tag{2}$$

where M is moment magnitude, r is hypocentral distance, S is zero for rock sites and 1 for soil sites and $\ln \varepsilon$ is a normally distributed error term with zero mean and standard deviation σ i.e. $\ln \varepsilon = N(0, \sigma)$.

The term $G(r, r_0)$ describing the geometrical spreading is a conventional Herrmann and Kijko (1983) type of model which incorporates purely spherical spreading in the near field below a certain critical distance r_0 and somewhat weaker spreading corresponding to Airy phase (c_3=5/6) beyond this distance in the time domain (which is the case for response spectral estimates) and cylindrical spreading (c_3=1/2) in the frequency domain (Fourier spectral estimates). In the inversions the c_3-parameter can then either be fixed at these values or determined independently by the data:

$$G(r, r_0) = \ln \begin{bmatrix} r^{-1} & r \le r_0 \\ r_0^{-1} \left(\frac{r_0}{r}\right)^{c_3} & r > r_0 \end{bmatrix} \tag{3}$$

The distance r_0 was chosen here as 100 km, which is a commonly adopted value, and the spreading model is fixed to spherical spreading below this distance, i.e. the only coefficient to be estimated for geometrical spreading is c_3 applicable for distances above 100 km.

A simpler alternative to is a model with one common geometrical spreading parameter applicable for all distances:

$$\ln A = c_1 + c_2 M + c_3 \ln r + c_4 r + c_5 S + \ln \varepsilon \tag{4}$$

When performing the initial regressions using the Herrmann and Kijko type of model, we obtained a poorer fit in terms of standard errors, compared with that derived using equation (4).

Using equation (3) we also derived results that were physically less realistic, and equation

(4) was therefore eventually chosen as the preferred analytical model for the inversion. The comparison of Hermann and Kijko model regression results with those obtained using equation (4) is presented in more detail in Section 5.1.

3.2 Bayesian analysis

One of the basic problems in the estimation of prediction equations for earthquake ground motion by ordinary least squares procedures, is that the resulting coefficients may not conform to the physics of wave propagation. In particular, those physical effects which are dependent on distance (geometrical spreading, anelastic attenuation and dispersion) may be difficult to resolve in terms of physically meaningful, predictive coefficients (see Section 5).

The fact that seismological problems may be described by physical theory, presents some important a priori expectations of the coefficients that represent different physical properties of the wave-field. Also, earlier empirical and analytical results pertaining to the same problems, contribute directly to a better understanding of the distribution of the coefficient values in equations (3) and (4). Bayesian analysis (Broemling, 1985) combines information contained in the above mentioned background sources with the actual empirical data being analyzed, resulting in predictive equations that are more in accord with the a priori expectations, and avoid physically unrealistic coefficient values.

The bayesian approach to the determination of attenuation regression coefficients by equation (4) incorporates the prior information on the distribution of individual coefficients. Following the requirements of the procedure and computer program of Ordaz et al. (1994), we have assessed the 90% confidence interval for each of the parameters c_1-c_5 and determined the standard deviation SD corresponding to half of this range divided by 1.7 ($SD=RANGE_{90\%}/3.4$).

The coefficients c_2, c_4 and c_5 may be frequency dependent and therefore require a somewhat more comprehensive estimation of prior distributions than do c_1 and c_3. The prior values for each of the coefficients are discussed in the following.

Coefficient c_1

The coefficient c_1 relates to the earthquake source. In assessing the 90% confidence interval for this coefficient, we have adopted the wide range approach used by Ordaz et al. (1994) allowing for a variation in this parameter by 3 natural logarithmic units either way. However, since we have included the term c_5S to account for site effects in equation (2), we have narrowed this interval by 0.5 natural logarithmic units on either side of the a priori center value. This corresponds to the average soil amplification of PGA found by Boore et al. (1993) for Western North America. The center value was chosen as corresponding to the least squares solution of c_1 for the data set, but no frequency variation was accounted for as the5 unit range of variation in natural logarithm was considered wide enough to allow this coefficient to be determined by the empirical data. Prior values of c_1 for the bayesian regression of spectral ordinates are given in Table 3.1.

Freq. (Hz)	mean value	5% confidence	95% confidence	$\frac{1}{\sigma^2}$
all	-5.3	-2.8	-7.8	4.0

Table 3.1. Prior input values for c_1 applied in the bayesian regression of strong motion spectral ordinates.

Coefficient c_2

The magnitude scaling coefficient c_2 was considered theoretically using the simple Brune model for far-field displacement spectra (Fig. 3.1) and found to have a mean value around 1.2 for PGA (as derived from 40 Hz PSV), increasing rapidly towards lower frequencies and with a strong sensitivity to magnitude. This mean PGA value was also confirmed empirically by considering the average of 11 PGA relations published by Campbell (1985). It was not considered feasible at this stage to include a magnitude-dependent magnitude scaling as indicated from Fig. 3.1.

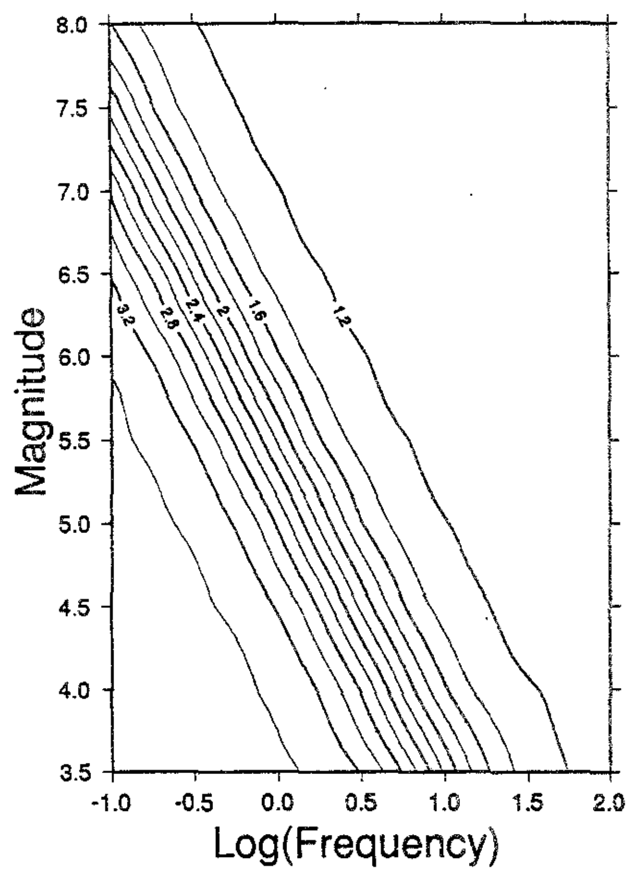


Figure 3.1. Theoretical mean values of c_2 as a function of frequency and magnitude.

The mean value of c_2 at 0.25 Hz was chosen to be 2.0 (corresponding to the theoretical value from Fig. 3.1 at a magnitude around 7), and for all frequencies 5% and 95% confidence values were selected as corresponding to the mean ±0.5 magnitude units respectively. For frequencies between 0.25 and 40 Hz, the prior values for the bayesian regression were determined by linear interpolation between the low- and high-frequency values as given in Table 3.2.

Freq. (Hz)	mean value	5% confidence	95% confidence	$\frac{1}{\sigma^2}$
0.25	2.00000	1.50000	2.50000	11.6
0.35	1.92857	1.42857	2.42857	11.6
0.50	1.85714	1.35714	2.35714	11.6
0.70	1.78571	1.28571	2.28571	11.6
1.00	1.71429	1.21429	2.21429	11.6
1.40	1.64286	1.14286	2.14286	11.6
2.0	1.57143	1.07143	2.07143	11.6
3.2	1.50000	1.00000	2.00000	11.6
5.0	1.42857	0.92857	1.92857	11.6
7.0	1.35714	0.85714	1.85714	11.6
10.0	1.28571	0.78571	1.78571	11.6
14.0	1.21429	0.71429	1.71429	11.6
20.0	1.14286	0.64286	1.64286	11.6
28.0	1.07143	0.57143	1.57143	11.6
40.0	1.00000	0.50000	1.50000	11.6

Table 3.2. Prior input values for c_2 applied in the bayesian regression of strong motion spectral ordinates.

Coefficient c_3

The c_3 coefficient relating to geometrical spreading is constrained by theory between -0.5, corresponding to non-dispersive propagation of cylindrical surface waves, to -1.0 corresponding to spherical spreading of body waves. In the time domain (which is the case for response spectral ordinates) the spreading should be close to Airy-phase spreading with a coefficient c_3 of about 0.8. This figure was chosen as the center value, but with a wider range for the 90% confidence interval (-0.3 to -1.3) than theory predicts, allowing for a wide empirical variation of this parameter. Prior values of c_3 input to the bayesian regression of spectral ordinates are given in Table 3.3.

Freq. (Hz)	mean value	5% confidence	95% confidence	$\frac{1}{\sigma^2}$
all	-0.8	-0.3	-1.3	11.0

Table 3.3. Prior input values for c_3 applied in the bayesian regression of strong motion spectral ordinates.

Coefficient c_4

Anelastic attenuation is determined by the coefficient c_4 through the formula:

$$c_4 = \frac{\pi f}{v Q} \tag{5}$$

where f is frequency, v is Lg wave velocity (around 3.5 km/s) and Q is the quality factor often expressed as:

$$Q = Q_0 f^{\eta} \tag{6}$$

where Q_0 is a constant, f is frequency and η is a positive constant less than unity.

In this analysis we adopted $\eta = 0.66$ as found for Mexico (Ordaz and Singh, 1992) while we determined Q_0 using equations (5) and (6) from the least squares solution of c_4 for the present response spectral data at 10 Hz (c_4=-0.00199), resulting in Q_0=986.

Mean values for prior estimates of c_4 at all frequencies have thus been determined by equations (5) and (6), using this value of Q_0 as determined by least the squares solution of c_4 at 10 Hz. The bayesian inversion has been constrained by a relatively narrow, 90% confidence interval for c_4 in order to maintain a physically realistic anelastic attenuation, i.e. a c_4 coefficient less than zero. The 5% and 95% confidence values for c_4 were chosen as the mean value $\mp$0.0052 for all frequencies. The value 0.00052 corresponds to 0.9c_4 at 0.25 Hz.

Table 3.4 shows the prior input values for c_4 entered in the bayesian regression for all frequencies analyzed.

Freq. (Hz)	mean value	5% confidence	95% confidence	$\frac{1}{\sigma^2}$
0.25	-0.00057	-0.00005	-0.00108	10842130.0
0.35	-0.00064	-0.00012	-0.00115	10842130.0
0.50	-0.00072	-0.00020	-0.00124	10842130.0
0.70	-0.00081	-0.00029	-0.00132	10842130.0
1.0	-0.00091	-0.00039	-0.00143	10842130.0
1.4	-0.00102	-0.00050	-0.00154	10842130.0
2.0	-0.00115	-0.00064	-0.00167	10842130.0
3.2	-0.00135	-0.00083	-0.00187	10842130.0
5.0	-0.00157	-0.00106	-0.00209	10842130.0
7.0	-0.00176	-0.00125	-0.00228	10842130.0
10.0	-0.00199	-0.00147	-0.00251	10842130.0
14.0	-0.00223	-0.00172	-0.00275	10842130.0
20.0	-0.00252	-0.00200	-0.00304	10842130.0
28.0	-0.00282	-0.00231	-0.00334	10842130.0
40.0	-0.00319	-0.00267	-0.00371	10842130.0

Table 3.4. Prior input values for c_4 applied in the bayesian regression of strong motion spectral ordinates.

Coefficient c_5

For c_5, which factors the site response for average soil vs. rock, an average amplification level has been selected from values obtained by Boore et al. (1993) for Western NA, which is about 0.2 $\log_{10}$ units (amplification of about 1.6). In terms of ln-units, this corresponds to about 0.5.

The soil amplification at low frequencies (0.25) is normally much higher than for PGA (where often none is found), and for the prior mean value at this frequency, we have selected 1.0 as the appropriate mean value, corresponding to an amplification of about 2.7.

The 90% confidence interval (mean value ± 0.6) has been set wide in order to accommodate de-amplification which may also be observed for high frequencies (PGA) at certain sites. The prior values between 0.25 and 40 Hz were determined as before by linear interpolation, and are shown in Table 3.5.

Freq. (Hz)	mean value	5% confidence	95% confidence	$\frac{1}{\sigma^2}$
0.25	1.00000	0.40000	1.60000	8.0
0.35	0.96429	0.36429	1.56429	8.0
0.50	0.92857	0.32857	1.52857	8.0
0.70	0.89286	0.29286	1.49286	8.0
1.0	0.85714	0.25714	1.45714	8.0
1.4	0.82143	0.22143	1.42143	8.0
2.0	0.78571	0.18571	1.38571	8.0
3.2	0.75000	0.15000	1.35000	8.0
5.0	0.71429	0.11429	1.31429	8.0
7.0	0.67857	0.07857	1.27857	8.0
10.0	0.64286	0.04286	1.24286	8.0
14.0	0.60714	0.00714	1.20714	8.0
20.0	0.57143	-0.02857	1.17143	8.0
28.0	0.53571	-0.06429	1.13571	8.0
40.0	0.50000	-0.10000	1.10000	8.0

Table 3.5. Prior input values for c_5 applied in the bayesian regression of strong motion spectral ordinates.

Scatter coefficient σ

In addition to c_1-c_5 there is also a need for assessing the 90% confidence interval for the sigma parameter in equation (4). Sigma values are normally found in the range 0.4-0.9 for most empirical regressions. Values outside the range 0.1-1.3 are unlikely, as noted also by Ordaz et al. (1994), and this wide range for sigma has therefore been used for determining r' and λ', the proportionality coefficients used to establish the covariance matrix for the bayesian estimation procedure (Ordaz et al., 1994). The 0.1-1.3 distribution of sigma corresponds to r'=2.05 and $\lambda' = 0.644$, values that were used in the bayesian regression.

4 Results

Regression coefficients and standard errors obtained by the bayesian least squares procedure using equation (4) are given in Table 4.1 for response spectral PSV in m/s, and in Table 4.2 for PGA in m/s^2.

The relations are shown for PSV at 0.25 Hz (extreme low frequency), 1.0 Hz (near top of spectrum) and for PGA (high frequency asymptote) in Figs. 4.1-4.3.

The relations are truncated for distances below 6 km in accordance with the limitation of the data set and the common assumption that the earthquake ground motion is constant in the near field.

Scatter plots for the regression of PGA are shown in Figs. 4.4 and 4.5 for observed/predicted PGA versus distance and magnitude, respectively. These scatter plots are produced by an ordinary least squares regression, which is equal to the bayesian procedure for demonstrating the uniform scatter in distance and magnitude for the observed versus predicted values, since the sigma value merely increases from 0.73 to 0.75 between the respective procedures.

f(Hz)	c_1	c_2	c_3	c_4	c_5	σ_{bay}	σ_{ls}
0.25	-7.441	1.007	-0.601	-0.00040	0.496	0.73	0.67
0.50	-7.348	1.128	-0.728	-0.00053	0.536	0.79	0.75
1.00	-6.744	1.081	-0.756	-0.00077	0.588	0.82	0.79
2.00	-5.862	0.917	-0.726	-0.00107	0.566	0.82	0.81
5.00	-4.876	0.642	-0.642	-0.00156	0.470	0.82	0.80
10.00	-4.726	0.483	-0.581	-0.00199	0.381	0.80	0.78
20.00	-5.487	0.447	-0.550	-0.00246	0.309	0.78	0.75
40.00	-7.214	0.553	-0.537	-0.00302	0.327	0.75	0.73

Table 4.1. Regression coefficients according to equation (4) for response spectral PSV in m/s for the largest horizontal component of ground motion at 5% damping. The sigma values are given for the bayesian regression (bay) and the least squares (ls) for comparison.

	c_1	c_2	c_3	c_4	c_5	σ_{bay}	σ_{ls}
PGA	-1.687	0.553	-0.537	-0.00302	0.327	0.75	0.73

Table 4.2. Regression coefficients according to equation (4) for response spectral PSV in m/s^2 for the largest horizontal component of ground motion at 5% damping. The sigma values are given for the bayesian regression (bay) and the least squares (ls) for comparison.

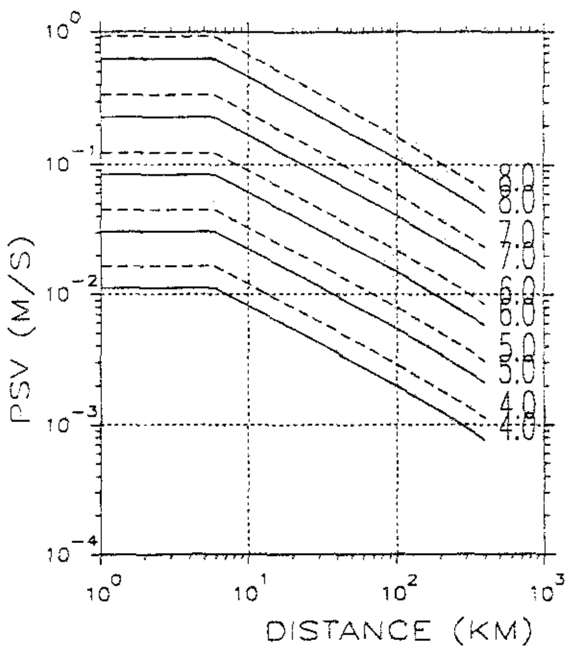


Figure 4.1. Attenuation relations for PSV at 0.25 Hz for the largest horizontal component of ground motion at 5% damping, for rock (solid line) and soil (dashed line).

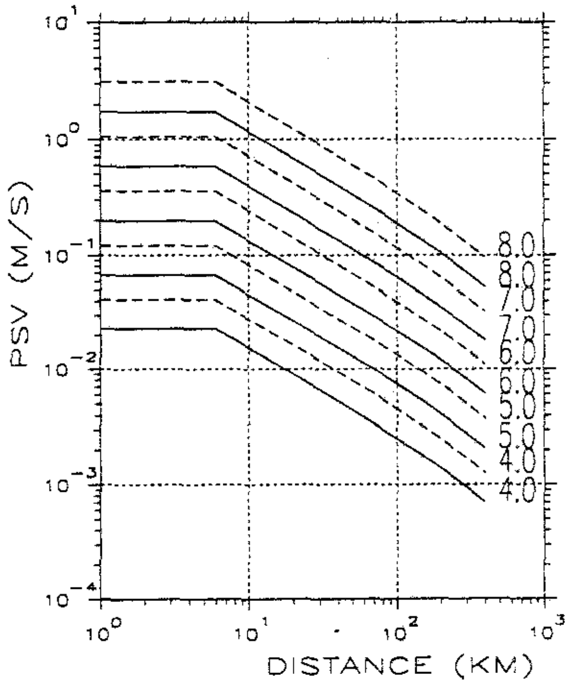


Figure 4.2. Attenuation relations for PSV at 1.0 Hz for the largest horizontal component of ground motion at 5% damping, for rock (solid line) and soil (dashed line).

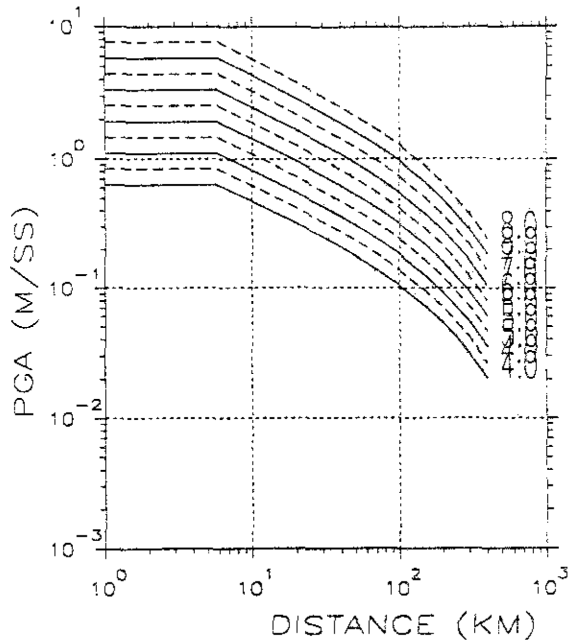


Figure 4.3. Attenuation relations for PGA (at 40.0 Hz) for the largest horizontal component of ground motion at 5% damping for rock (solid line) and soil (dashed line).

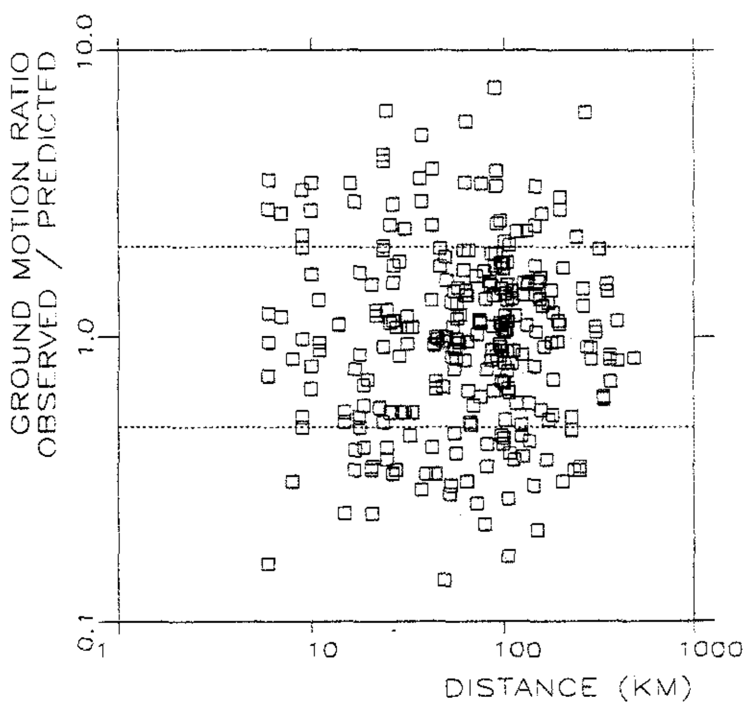


Figure 4.4. Ratio of observed to predicted PGA as function of distance in ordinary LS fit. The dotted lines correspond to the sigma value of 0.73 estimated for the inversion.

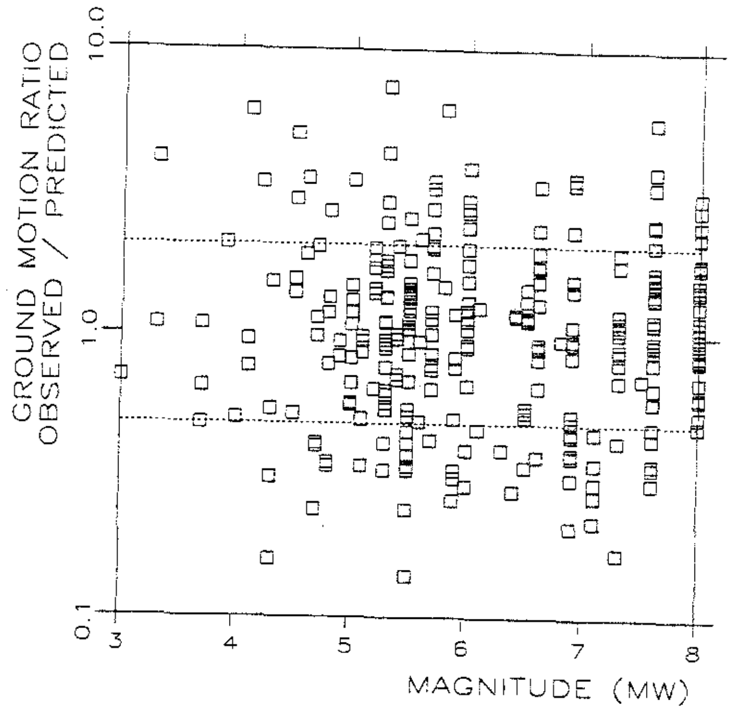


Figure 4.5. Ratio of observed to predicted PGA as function of moment magnitude in ordinary LS fit. The dotted lines correspond to the sigma value of 0.73 estimated for the inversion.

The coefficients in Table 4.1 (and 4.2) are smoothed values except for the 0.25 Hz and PGA (40Hz) values. The smoothing was done (as is evident from Section 3 describing the prior information for the bayesian regression) on the basis of nearly twice the number of points in frequency as those shown in Table 4.1, using a conventional third order polynomial fit.

The un-smoothed coefficient values together with the smoothed curve (values) are shown in Figs. 4.6 for c_1-c_4 and in Fig. 4.7 for c_5 and σ. Predicted spectra for various combinations of magnitude(s), distance (s) and site condition(s) are shown in Figs. 4.8-4.10.

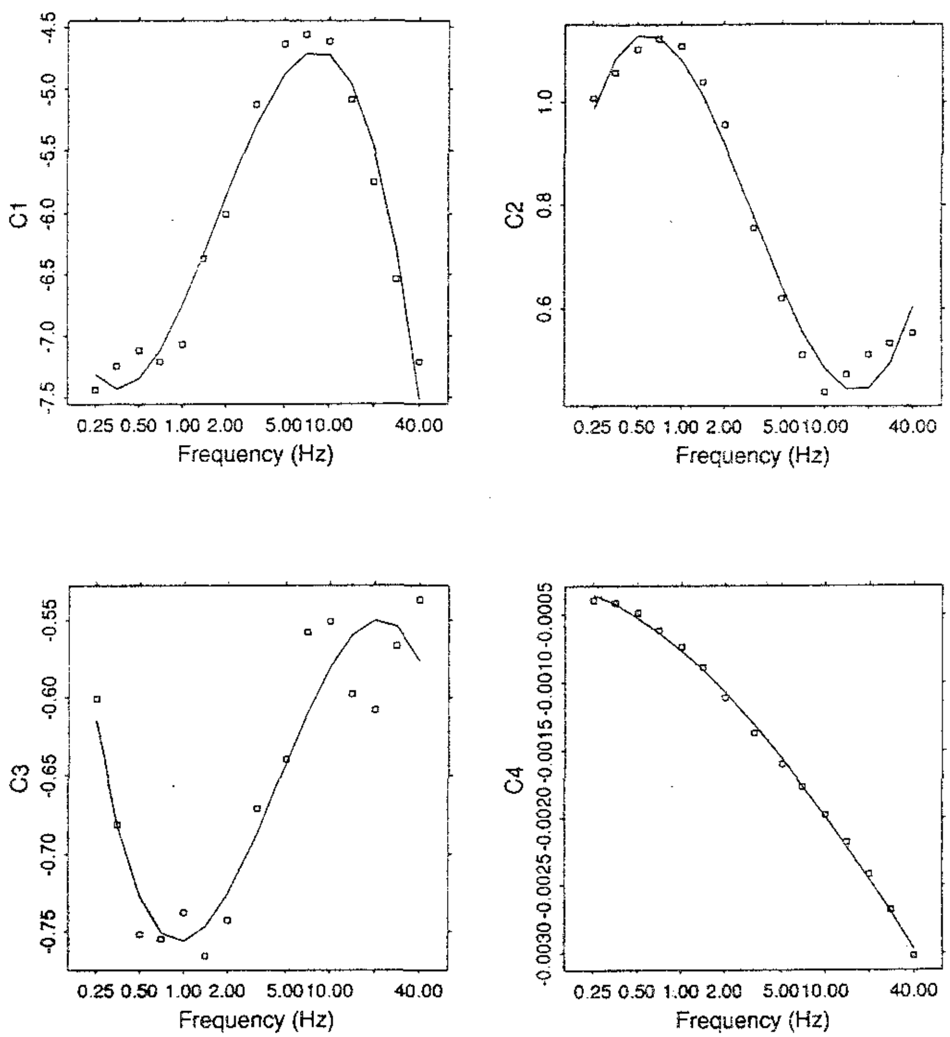


Figure 4.6. Un-smoothed coefficient values (open squares) and smoothed values (solid line) for coefficients c_1-c_4.

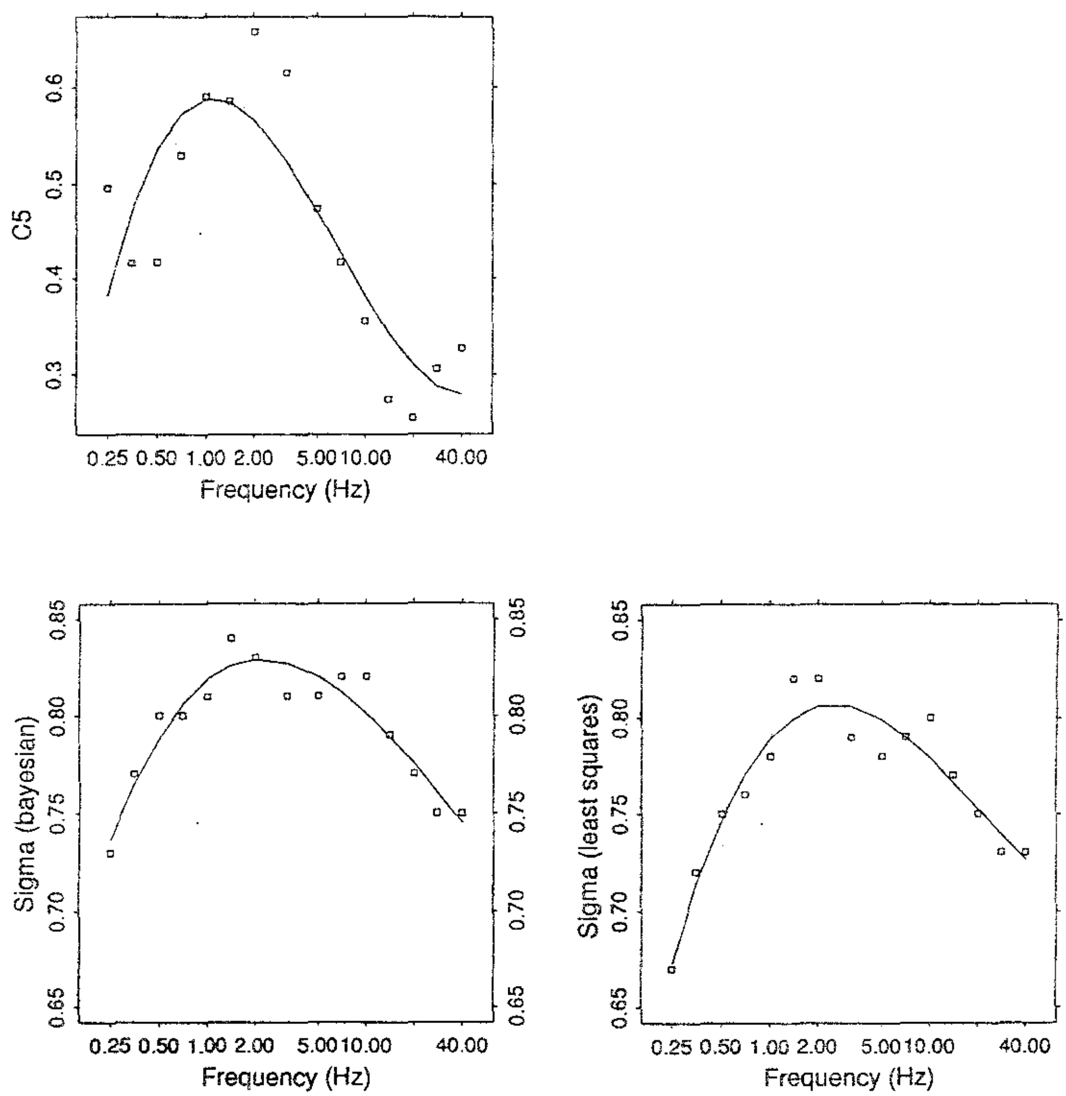


Figure 4.7. Un-smoothed coefficient values (open squares) and smoothed values (solid line) for coefficients c_5, bayesian sigma and least squares sigma.

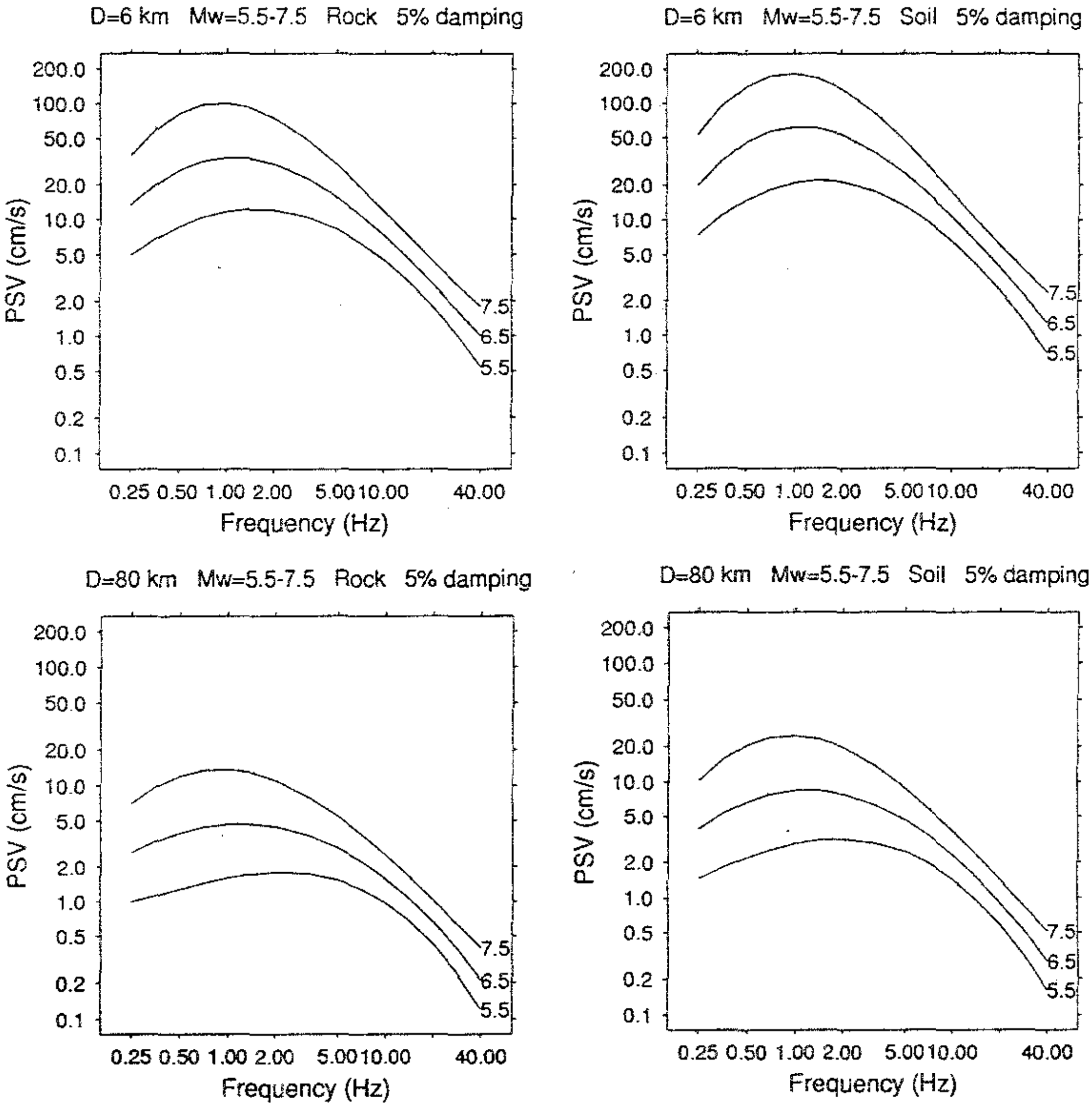


Figure 4.8. Predicted spectra for 6 km (upper) and 80 km (lower) distance shown for soil and rock site conditions.

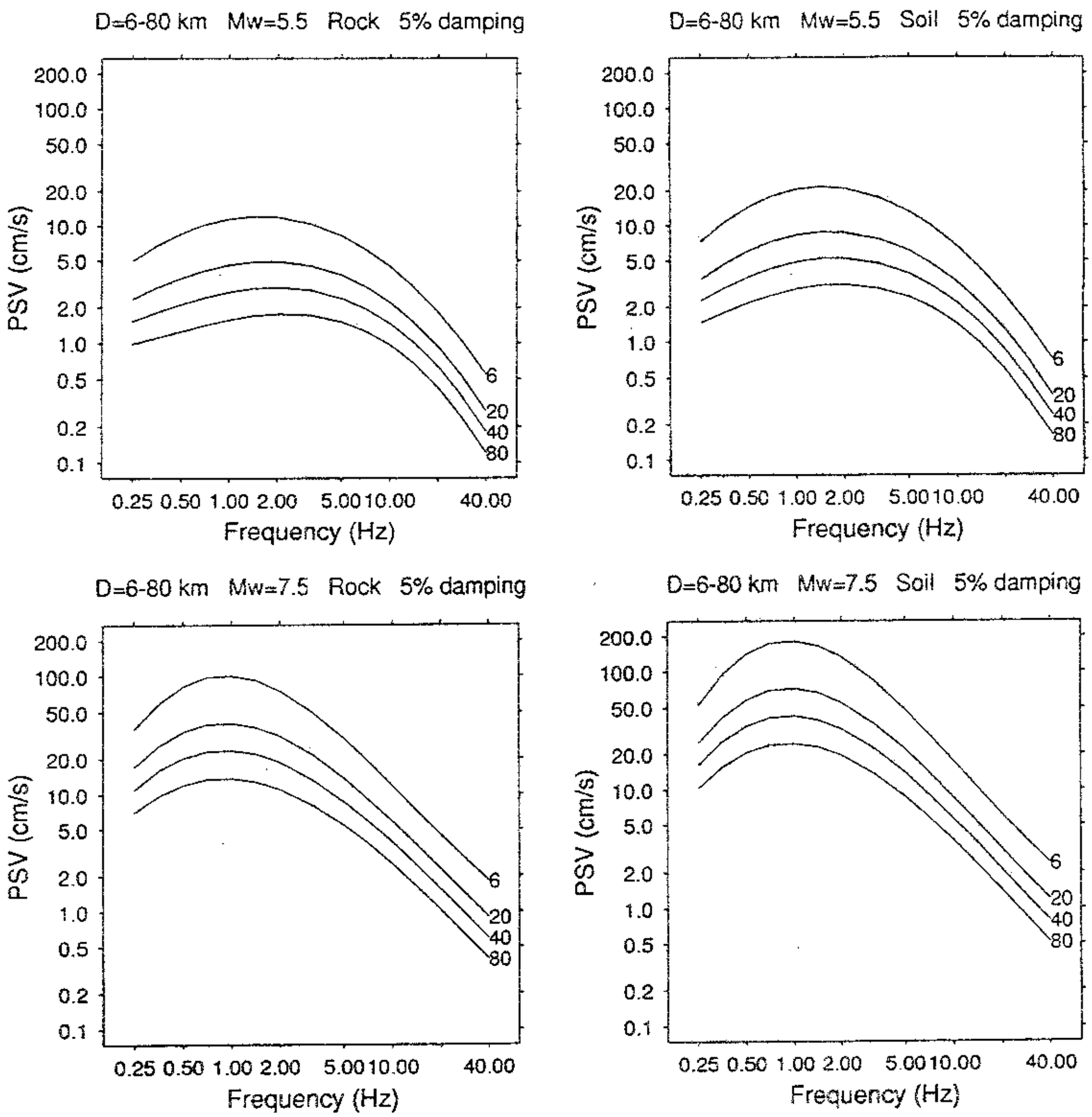


Figure 4.9. Predicted spectra for distances between 6-80 km shown for magnitude 5.5 and 7.5 for rock and site conditions.

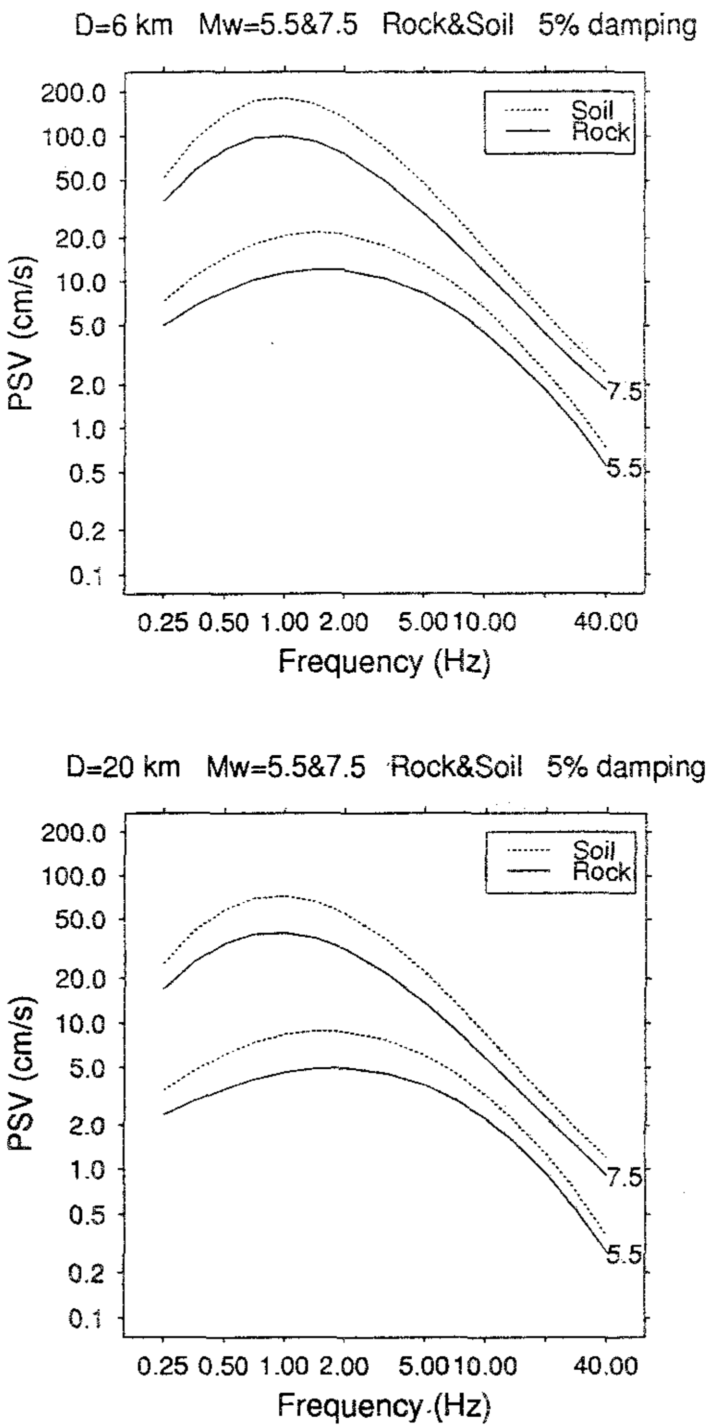


Figure 4.10. Predicted spectra for soil and rock site conditions at 6 and 20 km distance for magnitudes 5.5 and 7.5.

5 Discussion and Conclusions

5.1 Validation of analytical model

The initial regression analyses were performed with the Herrmann and Kijko type of model (equations (2) and (3)) for a critical distance r_0 of 100 km. This resulted in a PGA (in m/s^2) relation for the largest horizontal component of ground motion at 5 % damping with the following coefficient values conforming to equations (2) and (3) in a bayesian regression: c_1=-0.446, c_2=0.629, c_3=-0.394, c_4=-0.001, c_5=0.267 and sigma 0.84. This relation was used in a hazard study for Panama by Camacho et al. (1994a), which was later updated with the relations presented in Section 4 (Camacho et al., 1994b).

Ordinary least squares regressions were performed both with the Herrmann and Kijko model (equations (2) and (3) and for the simpler model (equation (4)). A comparison of regression coefficients is given in Table 5.1, showing that:

1) The Herrmann and Kijko model (equation (2) and (3)) produces a larger variance except for the very low frequency at 0.25 Hz.

2) The coefficients c_3 and c_4 are much closer to the physically acceptable values for the simple model represented by equation (4).

In fact the simple model presented bin equation (4) gives physically realistic values for geometrical spreading and anelastic attenuation for frequencies above 1 Hz, while the Herrmann and Kijko model fails to do so for all frequencies. As a consequence, the simple model (equation (4)) was preferred for the bayesian regression analysis.

It should be noted here that the Herrmann and Kijko model works well for Fourier spectra of the Guerrero, Mexico data (Ordaz and Singh, 1992).

5.2 The use of Guerrero data

One of the main concerns in merging Guerrero (Mexico) data with the Central American data to strengthen the coverage at high magnitudes is the possible misfit of the two data sets. This has been evaluated by plotting the observed PGA (derived from PSV at 40 Hz), corrected to the nearest magnitude using the c_2 coefficient of Table 4.1, simultaneously for both data sets, together with the mean curve for the ground motion relations.

Fig. 5.1 shows these comparative plots for soil site observations, while Fig. 5.2 shows the same plots for rock site observations. It may be concluded that no difference is clearly visible in the data, neither for rock conditions nor soil conditions.

The numerical effect on the ground motion relations by including the Mexican data has been studied by computing PGA and PSV (at 1 Hz) relations, with and without the Mexican data.

The prediction equation for PGA in m/s^2 for the largest horizontal component of ground motion at 5% damping using only Central American data was found to be:

$$\ln A = -1.348 + 0.492M - 0.564\ln r - 0.0031r + 0.439S$$

and correspondingly for 1 Hz PSV in m/s:

$$\ln A = -6.816 + 1.091M - 0.785\ln r - 0.0009r + 0.631S$$

The different curves are shown in Fig. 5.3 for rock site conditions (S=0). The effect of including the Guerrero, Mexico data is to increase slightly the predicted ground motion levels of PGA, most clearly expressed for large distances and high magnitudes. For PSV at 1 Hz, the differences are minor.

5.3 Shallow crustal vs. subduction events

The data base of strong motion data (Taylor et al., 1994) classifies strong motion records according to their inferred origin as shallow crustal or subduction zone events. In the regression analysis, observations were compared in order to reveal potential differences between subduction zone and shallow crustal events. Figs. 5.4 and 5.5 show subduction and shallow crustal event observations plotted against the regression results for PGA and 1 Hz PSV, respectively. The observations are corrected to the nearest integer magnitude using the magnitude scaling coefficient of Table 4.1.

As may be seen, no clear difference exists between the populations, and the distinction between shallow crustal and subduction zone events was therefore disregarded in the final analysis.

5.4 Comparison with other relations

Newly developed attenuation relations from the Western U.S. (Boore et al.,1993) and Japan (Fukushima and Tanaka, 1990) were chosen for comparison.

The comparison with Western U.S relations is shown in Fig. 5.6 for PGA and 1 Hz PSV for rock site conditions. As may be seen, the Western U.S. relations are generally lower, but the scaling with magnitude and the fall-off with distance are reasonably similar to the Central American-Mexican data model.

The Japanese relation is available only for PGA, and it should be noted that this was developed for M_S magnitude rather than M_w. The comparison is shown in Fig. 5.7 for rock site conditions. The relations are fairly close for ground motion at the intermediate range distances, but diverge significantly in the near and far fields.

The difference between rock and soil site ground motion attenuation relations, expressed by the coefficient c_5 (c.f. Table 4.1), represents the soil amplification between rock and an average soil site for the Central American and Guerrero (Mexico) data. The largest amplification is found at 1 Hz (a factor of 1.8) while the smallest is experienced at 20 Hz (a factor of 1.4). The 1 Hz amplification value is close to the 'old' difference between soil and rock found by Boore and Joyner (1992) and consistent with the persistence of this difference (although not as large as in their new analysis) to high frequencies.

5.5 Sensitivity to extreme data values

Another important issue is the sensitivity of the analysis to individual extreme data values. The Siquirres Dam site record of PGA from the April 22, 1991, Limon earthquake is one such example. This observation is shown in Fig. 5.8 in terms of PSV at 40 Hz, and is seen to be much higher than other observations for earthquakes of similar magnitude. This record was studied in detail by Laporte (1994), who found that a significant amount of this high peak acceleration value could be explained by soil amplification.

The effect on the estimated attenuation relations in removing the Siquirres Dam site observation has been tested for PGA and PSV at 1 Hz, and is shown in Fig. 5.9. The difference is insignificant, indicating that the sample size of 280 observations is large enough to present a robust estimate of the mean ground motion attenuation.

5.6 Conclusions

In conclusion, as a first approximation, the inversion by a simple one step Bayesian linear regression procedure of strong ground motion spectral ordinates for the data set consisting of 62 Guerrero, Mexico and 218 Central American largest horizontal component recordings present a relatively robust estimate of response spectral PSV and PGA for rock and soil conditions. The attenuation of response spectral ground motion in Central America seems to be characterized by geometrical spreading closer in form to cylindrical than spherical spreading.

The effect of merging records of high magnitude earthquakes at large distance (Guerrero, Mexico) into the inversion to strengthen the data coverage, results in an increase of the predicted ground motion levels, and represents a conservative prediction model at this stage.

In the future, and particularly when additional strong motion data from Central America may be available, the use of two-step regression procedures and the study of more local differences in attenuation may be addressed. A separation between shallow crustal and subduction zone events may also be interesting in this respect, as well as an evaluation of possible differences related to faulting mechanisms and to the fault dimensions and directivity effects for the larger earthquakes. When considering alternative parameterizations, one of the main questions will be related to the possible use of a magnitude dependent, magnitude scaling.

Model	Freq. (Hz)	c_1	c_2	c_3	c_4	c_5	σ
eq. (2)	0.25	-5.944	0.916	-2.40806	0.01045	0.38489	0.667
eq. (4)	0.25	-6.595	0.927	-0.74293	0.00248	0.42464	0.672
eq. (2)	0.50	-6.003	1.021	-1.29283	0.00483	0.34878	0.754
eq. (4)	0.50	-6.022	1.034	-1.00370	0.00366	0.36744	0.754
eq. (2)	1.00	-6.110	1.060	-1.36213	0.00449	0.56643	0.785
eq. (4)	1.00	-6.303	1.060	-0.92132	0.00234	0.57437	0.785
eq. (2)	2.00	-5.192	0.938	-1.53601	0.00380	0.63674	0.825
eq. (4)	2.00	-5.743	0.915	-0.75446	-0.00051	0.62501	0.819
eq. (2)	5.00	-3.455	0.584	-2.33455	0.00705	0.38048	0.803
eq. (4)	5.00	-4.507	0.555	-0.54430	-0.00232	0.37959	0.785
eq. (2)	10.00	-3.125	0.383	-2.77392	0.00958	0.24121	0.812
eq. (4)	10.00	-4.312	0.365	-0.49746	-0.00199	0.25879	0.797
eq. (2)	20.00	-4.439	0.459	-2.21952	0.00696	0.17863	0.760
eq. (4)	20.00	-5.192	0.452	-0.68528	-0.00073	0.19631	0.755
eq. (2)	40.00	-5.867	0.523	-2.17650	0.00715	0.31235	0.734
eq. (4)	40.00	-6.616	0.514	-0.68552	-0.00036	0.32744	0.728

Table 5.1. Regression coefficients obtained by ordinary least squares for the Herrmann and Kijko model (eq.(2) and (3)) and the simple model (eq.(4)).

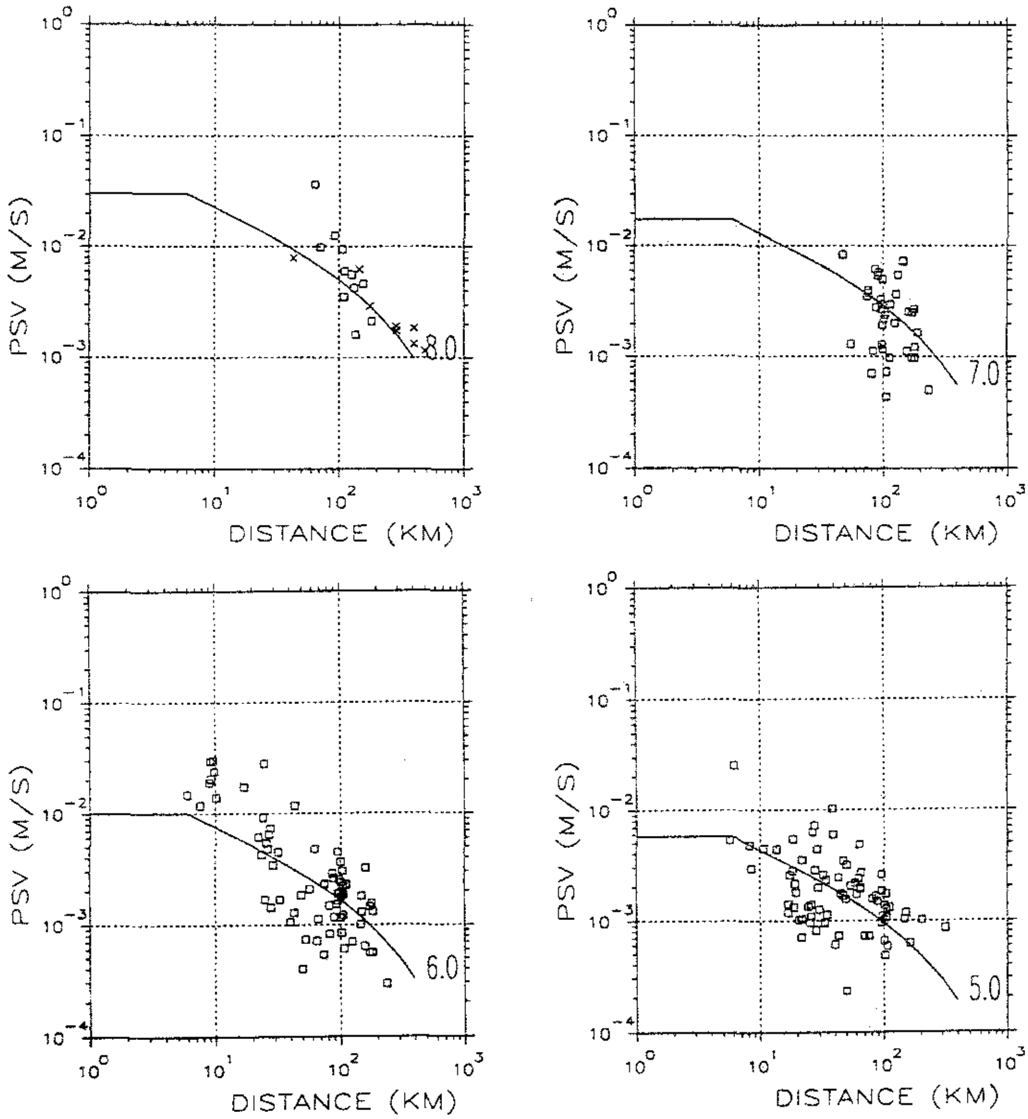


Figure 5.1. Soil site observations of PGA (PSV at 40 Hz) corrected to the nearest integer magnitude for magnitudes 5, 6, 7 and 8. Open squares represent Central American observations while crosses represent Mexican Data.

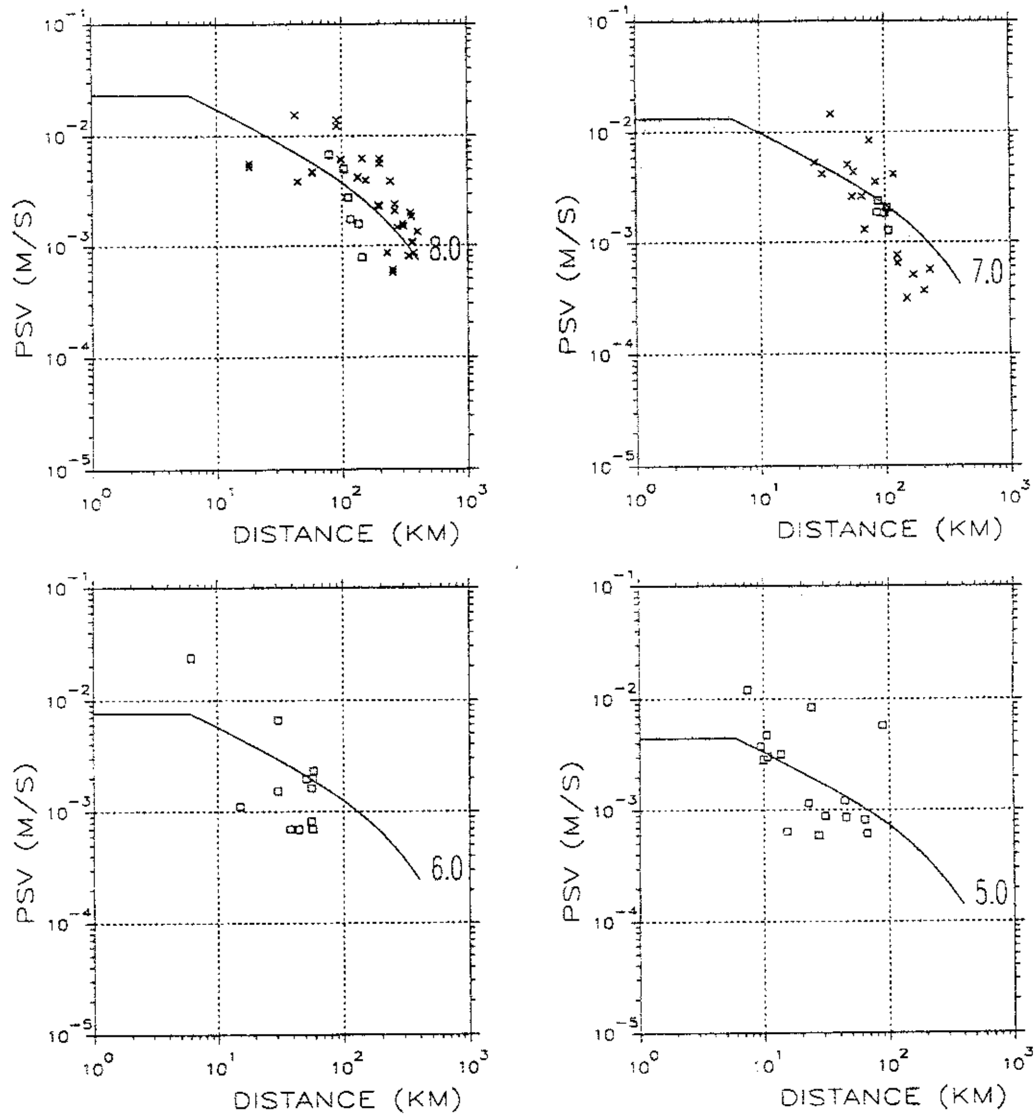
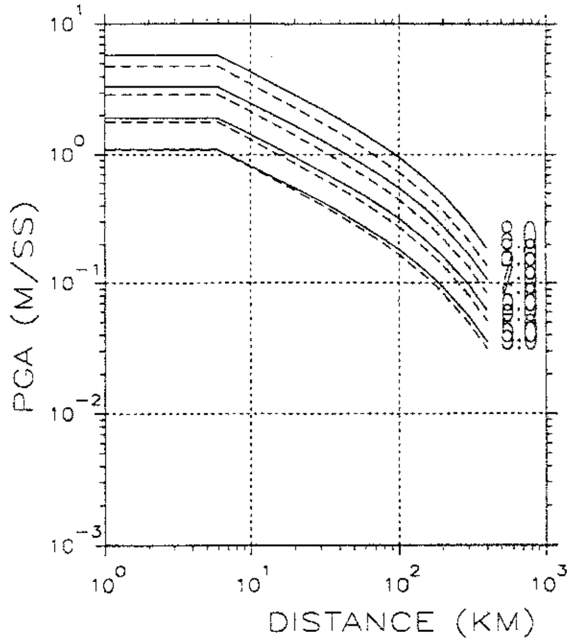


Figure 5.2. Rock site observations of PGA (PSV at 40 Hz) corrected to the nearest integer magnitude for magnitudes 5,6,7 and 8. Open squares represent Central American observations while crosses represent Mexican data.



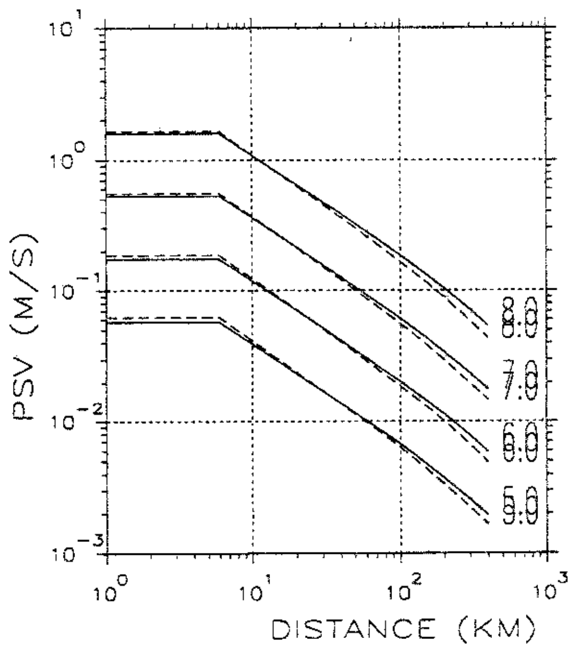


Figure 5.3. Ground motion attenuation curves for PGA (upper) and PSV at 1 Hz (lower) at rock sites for Central American data only (dashed) and the complete data set including Mexican Data (solid).

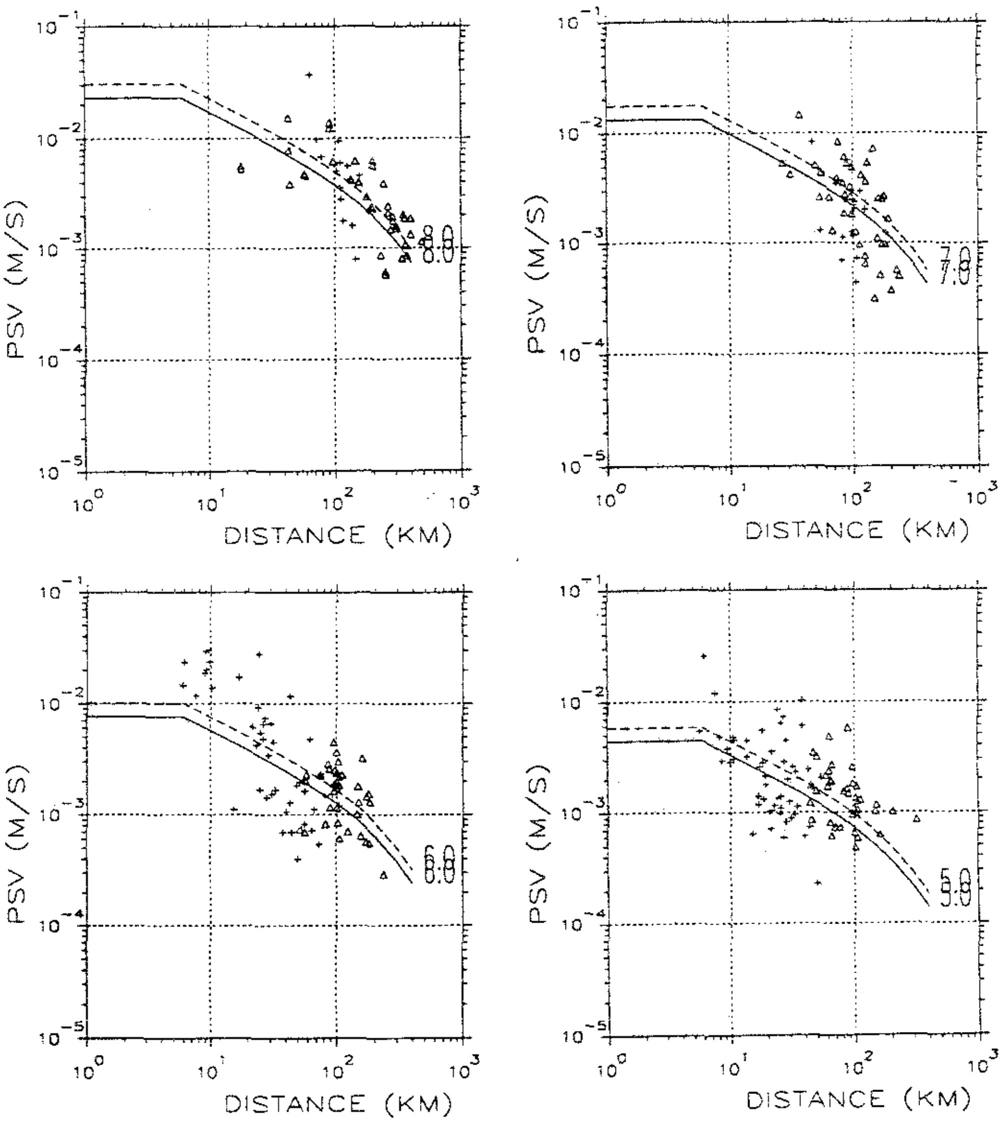


Figure 5.4. Observations of PSV at 40 Hz for Central American and Guerrero (Mexico) data for moment magnitudes 5,6,7 and 8. Subduction events (delta) and shallow crustal events (plus).

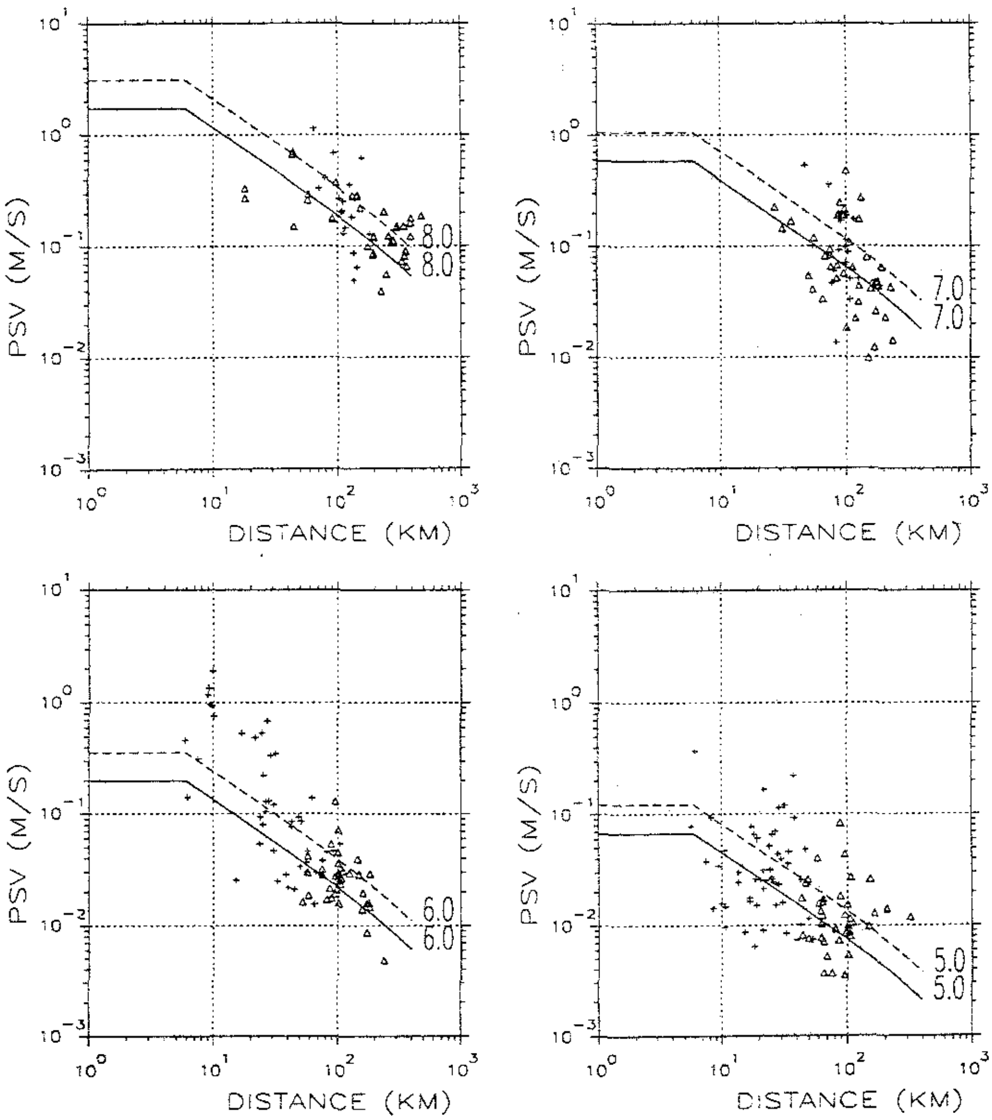


Figure 5.5. Observations of PSV at 1 Hz for Central American and Guerrero (Mexico) data for moment magnitudes 5,6,7 and 8. Subduction events (delta) and shallow crustal events (plus).

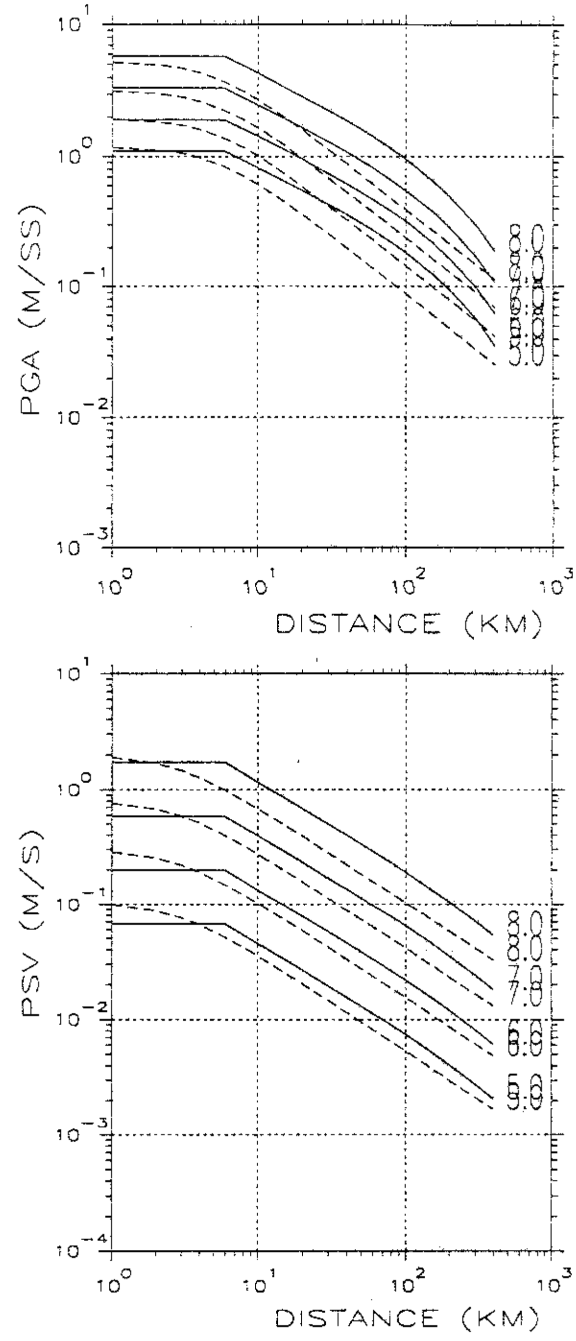


Figure 5.6. Comparison of attenuation relations developed in this project based on Central American and Guerrero (Mexico) data (solid curves), with relations developed by Boore et al. (1993) for Western U.S. (dashed curves). The curves represent the largest horizontal component of ground motion at 5 % damping for rock site conditions. PGA (upper) and 1 Hz PSV (lower). Curves for moment magnitudes 5, 6, 7 and 8 are shown.

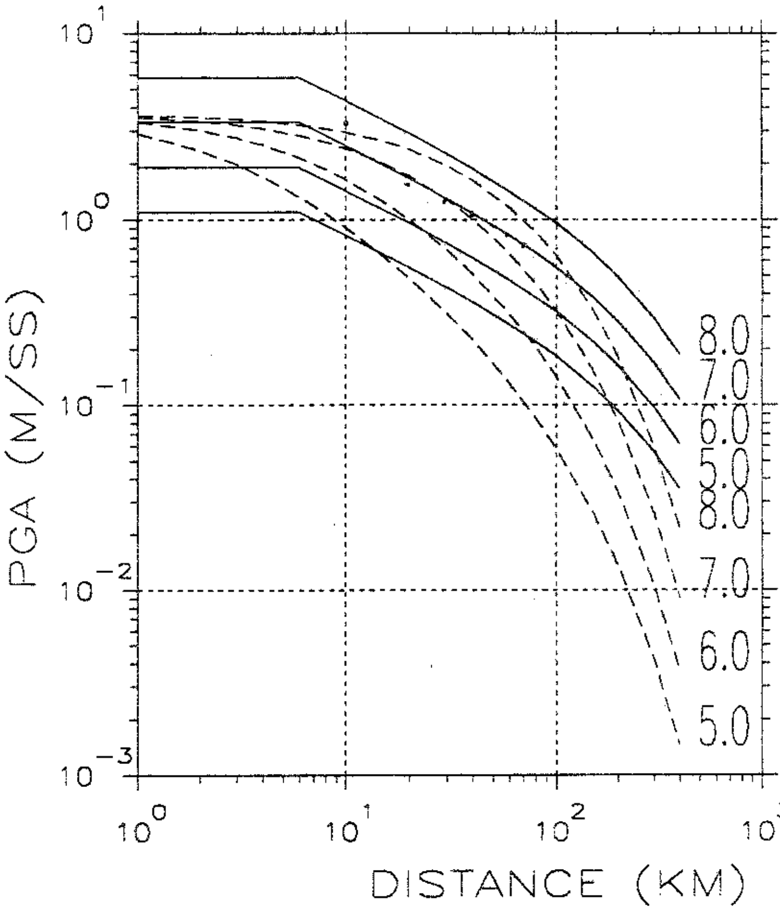


Figure 5.7. Comparison of PGA attenuation relation developed in this project based on Central American and Guerrero (Mexico) data (solid curves), with relations developed by Fukushima and Tanaka (1990) for Japan (dashed curves). The curves represent the largest horizontal component of ground motion at 5 % damping for rock site conditions, for magnitudes 5,6,7 and 8. The Japanese relations are developed for M_S magnitudes and no correction has been made for possible differences in type of magnitude.

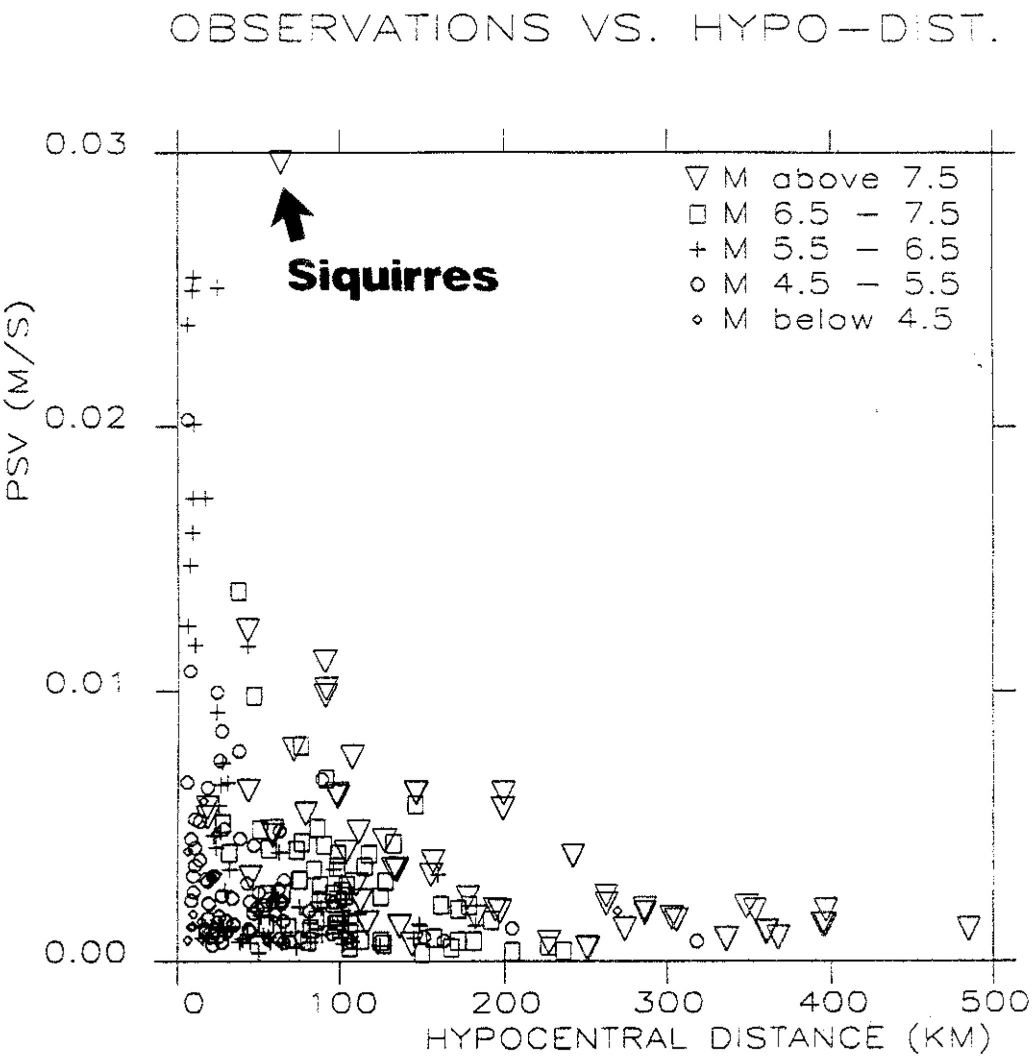


Figure 5.8. Observations of PSV at 40 Hz for Central American and Mexican Data used in the regression for obtaining ground motion relations. The Siquirres Dam site observation of the April 22, 1991, Limon earthquake is indicated by an arrow.

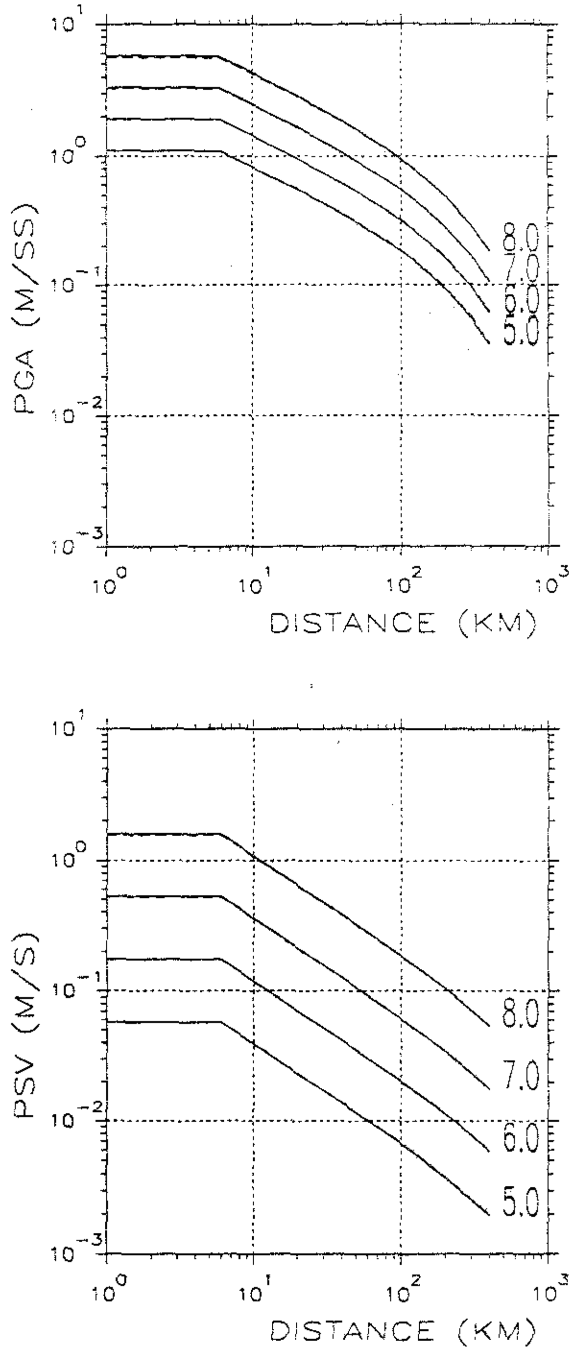


Figure 5.9. Effect on the ground motion relations of removing the Siquirres Dam site observation from the data set. Dashed line represent the relation estimated when the Siquirres Dam site observation of the April 22, 1991, Limon earthquake is removed. PGA (upper) and PSV at 1 Hz (lower) are shown.

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