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An empirical model for estimating horizontal acceleration Fourier spectra for the Imperial-Mexicali Valley region

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RESUMEN

Se propone un modelo empírico para estimar los espectros de aceleración horizontal con base en acelerogramas de estaciones localizadas en las regiones de Valle Imperial (California) y Valle de Mexicali (Baja California), empleando el formato de Joyner y Boore (1981) para las relaciones de atenuación. El modelo adoptado escala los espectros de aceleración con la magnitud y con la distancia horizontal más corta a la ruptura. Para tomar en cuenta el efecto de las condiciones locales de los sitios de registro se incorporó en el modelo una corrección dependiente de la frecuencia para cada estación. Los coeficientes del modelo se determinaron mediante una regresión en dos etapas. Se incluyeron datos de 44 sismos de magnitud entre 2.9 y 6.8 y distancias de 0.2 a 136 km. Se ensayaron dependencias lineares y cuadráticas en magnitud, encontrándose que la introducción de un término cuadrático mejora el modelo. Las correcciones de sitio fluctúan considerablemente en frecuencia y de un sitio a otro, lo que demuestra la importancia de usar correcciones de sitio para predecir los espectros de aceleración para movimientos fuertes.

PALABRAS CLAVE: Relaciones de atenuación, región Valle Imperial-Mexicali, correcciones de sitio.

ABSTRACT

An empirical model for estimating the horizontal acceleration spectra is obtained using strong motion records from stations located in the Imperial Valley, California and the Mexicali Valley, Baja California regions. The functional form of the model is based on the regression relation used by Joyner and Boore (1981) to derive attenuation relations for peak horizontal velocity and acceleration. The model adopted scales the acceleration spectra in terms of the magnitude, and the closest distance to the surface projection of the fault that generated the earthquake. To account for the effect of the local site conditions, a frequency-dependent correction term for each station is also incorporated in the model. The coefficients of the model were determined using a two-stage regression procedure. The data set used consists of 44 events, in the magnitude range between 2.9 and 6.8, and distances between 0.2 and 136 km. The dependence of the spectral amplitudes on magnitude was tested using linear and squared dependence. The use of a squared term to scale the amplitudes improved the accuracy of the model. In addition, the site corrections show a considerable variation with frequency and between sites. This observation emphasizes the importance of using site specific corrections for predicting ground motion spectra if they are available.

KEY WORDS: Attenuation relations, Imperial-Mexicali Valley region, site specific corrections.

INTRODUCTION

Because the evaluation of the frequency content of ground shaking induced by earthquakes is particularly important in many earthquake engineering applications, a considerable effort has been devoted to study the dependence of spectral amplitudes with the earthquake source parameters and source-to-site propagation effects. Although reliable source models (Haskell, 1964; Aki, 1967; Brune, 1970; among others) can be used to evaluate the energy radiated by an earthquake, the implementation of these models requires the knowledge of specific source parameters which are not generally reported in seismic catalogs. For this reason, the use of simple empirical models, based on basic source parameters such as magnitude and distance, continues to be a convenient procedure for estimating ground motion spectra generated by an earthquake. Although some of the empirical models obtained before (e.g. Seed *et al.*, 1976; Trifunac, 1976; McGuire, 1978) follow the general trends of spectral records of California reasonably well, their applicability may be limited by the characteristics of the earthquakes used to derive them, and the seismic attenuation of the regions for which they were obtained. An additional limitation of some of the first models proposed is the broad classification of the recording sites into rock or soil. The effectiveness of this site classification has been examined by Aki (1988). To improve this limitation, models that include the thickness of sediments below the recording station have also been proposed (Trifunac, 1989).

The purpose of this paper is to find an empirical model to estimate the Fourier acceleration spectra specific for the regions of Imperial Valley, Southern California and Mexicali Valley, Baja California, based on typical magnitudes, and distances of the earthquakes observed in these regions. The effect of the geologic conditions of the sites is accounted by including a station correction function that may vary with frequency. By including in the analyses only events located in the neighborhood of the Imperial-Mexicali Valleys, the seismotectonics of the region is implicitly included in the model.

MODEL

In this paper, the model proposed by Joyner and Boore

(1981) is modified to estimate the acceleration spectra of events in the Imperial-Mexicali Valley region. Instead of using a broad classification of the geological site conditions, the model includes a site-specific amplification factor. This approach has been used before by Kamiyama and Yanagisawa (1986) to estimate response spectra in Japan. The model selected estimates the acceleration spectra $U_{ij}(f)$ expected from an earthquake i recorded at station j in terms of the magnitude M_i, and the closest distance to the surface projection of the fault where the event was originated Δ_{ij}. The acceleration spectra is scaled according to the following relation

$$\mathrm{Log} U_{ij}(f) = S_i(f) - \mathrm{Log} r_{ij} + b(f) r_{ij} + z_j(f) \qquad (1)$$

where

$$S_i(f) = a_1(f) + a_2(f) M_i + a_3(f) M_i^2 \qquad (2)$$

$z_i(f)$ is the site correction function that accounts for the effect of the geological site conditions and any other station related effect, $r_{ij} = (\Delta_{ij}^2 + \overline{H}^2)^{1/2}$ and $\overline{H} = 12$ is the average depth of the earthquakes of the sample (see Table 1). The introduction of H in the definition of the distance is similar to that used by Joyner and Boore (1981) to account for the fact that the origin of the peak motion may not be the closest point on the rupture.

Because there is a linear dependence between $S_i(f)$ and $z_j(f)$ in equation (1), it is necessary to constrain the possible solutions by using a station with known site response as a reference site or by using an average site response as reference. Since the station at Cerro Prieto (CPRI) is on a small basalt volcano, this site was chosen as a reference site to solve equation (1). Thus, values of $S_i(f)$, b(f) and $z_j(f)$ were estimated by a least-squares inversion using a singular value decomposition (Press *et al.*, 1986). Once the values of $S_i(f)$ and the standard errors were obtained, equation (2) was solved using a weighted linear least-squares procedure by minimizing chi-square.

DATA

The data set used consists of 44 events with magnitudes ranging between 2.9 and 6.8 and distances between 0.2 and 136 km (see Table 1). A total of 180 strong-motion records from 38 stations were selected from the *Digitized Strong-Motion Accelerograms from North & Central American Catalog* (Seekins *et al.*, 1992). We used all the accelerograms available at recording sites inside the Imperial-Mexicali Valleys reported in the catalog. These include the 1940 El Centro record (event 5 in Table 1) and the records from the 1979 (M=6.6) Imperial Valley earthquake. Figure 1 shows the distribution of the stations used and the epicenters of the events listed in Table 1. To simplify the map, the stations were numbered instead of using the standard station code. Table 2 lists the coordinates of the stations. The site condition of all stations is soil except for CPRI and SUPO which are on rock.

The records were instrument corrected to remove the effects of the frequency-dependent instrument response and band-pass filtered to remove high-frequency noise amplified by the instrument correction. These corrections were made using the *Basic Accelerogram Processing* software package (BAP) of Converse (1992). The time series were also base-line corrected and Fourier transformed. To calculate the acceleration spectra, time windows were selected starting with the S wave arrival and ending them when 90% of the energy in the record was reached. Although it is a common procedure to use the whole record to calculate the spectral amplitudes, since most of the stations did not trigger with the P waves, for consistency only the S wave package of the record was used in the analyses. The resulting acceleration spectra was smoothed around 14 preselected frequencies between 1 and 20 Hz. The spectra were smoothed using a variable frequency band of ± 25 per cent of the central frequency. Then the spectral amplitudes calculated, together with the magnitudes and distances of the events listed in Table 1 were used to solve equations (1) and (2).

RESULTS

The site response of the reference site (CPRI) was estimated using horizontal to vertical component (H/V) spectral ratios (e.g. Lermo and Chávez-García, 1993). Figure 2 shows the average H/V ratio obtained using events 35, 36, 41, 43 and 44. Although this station is on a hard-rock site, it shows moderate amplification between 1 and 5 Hz. However, as mentioned before, the specification of the site response of a reference site permit us to separate the effects of $S_i(f)$ and $z_j(f)$ from the observed amplitudes, and thus we were able to solve equations (1) and (2).

Figure 3 shows the values of $a_1(f)$, $a_2(f)$, $a_3(f)$ and b(f) obtained for each of the frequencies analyzed and the standard deviation resulting from the regression analyses (see also Table 3). These terms can be used to estimate the input bed-rock spectra by making $z_j(f)$=0 and substituting equation (2) in (1):

$$\mathrm{Log}\ U_{ij}(f) = a_1(f) + a_2(f) M_i + a_3(f) M_2^i - \mathrm{Log}\ r_{ij} + b(f) r_{ij} \qquad (3)$$

Equation (3) can also be used to estimate the acceleration spectra at sites not included in the analyses but located inside the Valley and for which the site effects have been determined by other means.

To analyze further the dependence of the spectral amplitudes with magnitude, equation (3) was used to estimate spectral amplitudes for various magnitudes and a fixed value of Δ (see Figure 4). Since the spectra shown in Figure 4 do not include the site term z_j, the amplitudes displayed represent the input bed rock spectra. Figure 4 also shows, as a reference (dashed lines), the spectral amplitudes calculated using the ω^2 model for a stress drop of 100 bars and the seismic moment corresponding to M=6.8

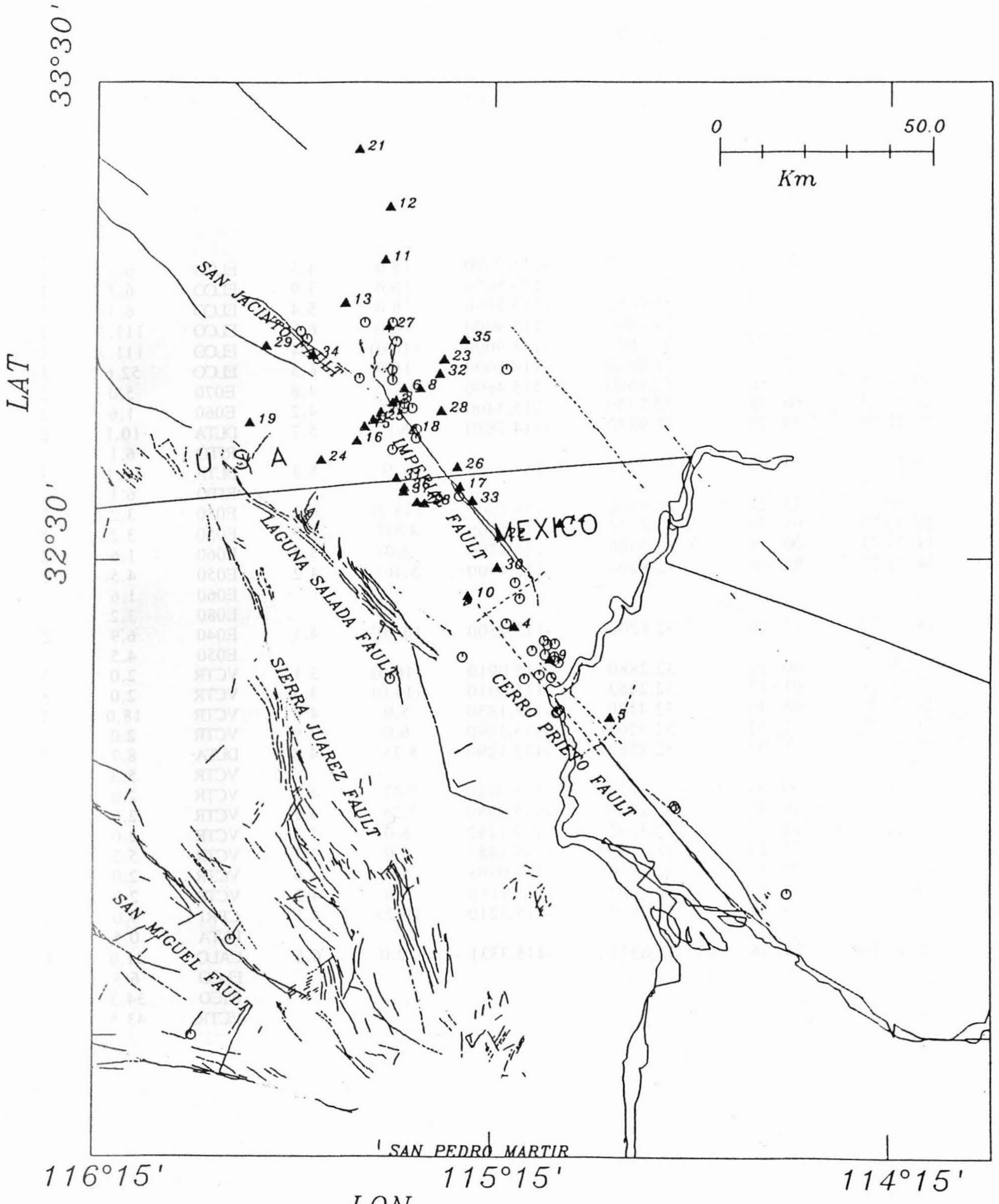

Fig. 1. Location of events (circles) and stations (triangles) used, the coordinates are also listed in Tables 1 and 2 respectively.

Table 1

Event Coordinates. Last column indicates the reference: 1 Trifunac (1989), 2 Seekins *et al.* (1992), 3 Caltech Catalog

NO.	DATE dy-mt-yr	ORIGIN	LAT N	LON W	H KM	M	STA	Δ	Ref
1	29 12 34	05 52	32.2500	-115.5000	16.0	6.5	ELCO	30.4	1
2	12 04 38	08 25	32.8833	-115.5833	16.0	3.0	ELCO	6.3	1
3	05 06 38	04 37	32.2500	-115.1667	16.0	4.0	ELCO	52.6	1
4	05 06 38	18 42	32.9000	-115.2167	16.0	5.0	ELCO	40.0	1
5	18 05 40	20 37	32.7333	-115.5000	16.0	6.7	ELCO	6.3	1
6	23 01 51	23 17	32.9833	-115.7333	16.0	5.6	ELCO	6.3	1
7	13 06 53	20 17	32.9500	-115.7167	16.0	5.5	ELCO	6.3	1
8	11 11 54	04 27	31.5000	-116.0000	16.0	6.3	ELCO	135.6	1
9	16 12 55	21 17	33.0000	-115.5000	16.0	4.3	ELCO	6.3	1
10	16 12 55	21 41	33.0000	-115.5000	16.0	3.9	ELCO	6.3	1
11	16 12 55	22 07	33.0000	-115.5000	16.0	5.4	ELCO	6.3	1
12	09 02 56	06 33	31.7000	-115.9000	16.0	6.8	ELCO	111.3	1
13	09 02 56	07 25	31.7000	-115.9000	(16.0)	6.4	ELCO	111.3	1
14	06 08 66	09 36	31.8000	-114.5000	16.0	6.3	ELCO	52.6	1
15	23 01 75	17 02	32.9600	-115.4900	4.29[3]	4.8	E070	5.0	2
16	20 06 75	05 48	32.7770	-115.4400	10.8	4.2	E060	1.6	2
17	07 12 76	12 59	31.9830	-114.7830	8.0	5.7	DLTA	10.1	2
							RITO	6.1	
18	07 12 76	13 00	31.9772	-114.7788	8.0	5.3	DLTA	10.1	3
							RITO	6.1	
19	06 09 77	13 24	32.9000	-115.5000	(15.2)	4.2	E050	3.2	2
20	30 10 77	05 30	32.8800	-115.5000	4.51[2]	4.0	E050	3.2	2
21	14 11 77	00 11	32.8300	-115.4700	(6.0)	3.9	E060	1.6	2
22	14 11 77	02 05	32.8200	-115.4700	5.46[3]	4.2	E050	4.5	2
							E060	1.6	
							E080	3.2	
23	14 11 77	12 20	32.8200	-115.4500	10.10[3]	4.3	E040	6.9	2
							E050	4.5	
24	11 03 78	00 22	32.2880	-115.0910	(16.0)	3.1	VCTR	2.0	3
25	11 03 78	05 17	32.2953	-115.0910	(16.0)	3.3	VCTR	2.0	3
26	11 03 78	05 40	32.4170	-115.1830	5.0	4.4	VCTR	18.0	2
27	11 03 78	21 52	32.3205	-115.1090	6.0	2.9	VCTR	2.0	3
28	11 03 78	23 57	32.2580	-115.1290	8.73[3]	4.8	DLTA	8.7	2
							VCTR	5.3	
29	12 03 78	00 30	32.3220	-115.0910	7.42[3]	4.5	VCTR	2.0	2
30	12 03 78	18 42	32.2520	-115.0980	7.26[3]	4.1	VCTR	2.0	2
31	12 03 78	22 01	32.3295	-115.1192	6.0	3.2	VCTR	2.0	3
32	12 03 78	23 10	32.3088	-115.1483	6.0	3.7	VCTR	5.2	3
33	13 03 78	09 11	32.2838	-115.0808	6.0	3.6	VCTR	2.0	3
34	16 03 78	01 51	32.3000	-115.1160	5.0	4.2	VCTR	2.0	2
35	10 10 79	19 48	32.2960	-115.3210	19.23	4.1	CPRI	9.0	2
							DLTA	0.5	
36	15 10 79	23 16	32.6331	-115.3331	12.0	6.6	CALO	21.0	1
							ELCO	6.3	
							NICO	34.3	
							VCTR	43.5	
							WSMO	15.0	
							CMPT	23.2	
							DLTA	32.7	
							E040	7.0	
							E050	4.7	
							E100	9.0	
							E110	12.7	
							CPRI	23.5	
							6616	1.4	
							EM00	0.5	
							PLSO	14.3	
							XMCF	9.7	
							CC40	47.6	

Table 1 (Cont.)

							CUCA	12.9	
							E020	16.3	
							E060	1.3	
							E070	0.2	
							E130	22.4	
							EDAO	5.3	
							BCRO	3.0	
							BRAO	6.3	
							HVPO	8.0	
							SUPO	26.7	
							CHIH	17.7	
							CX00	10.0	
							E030	13.0	
							E080	3.3	
							6618	0.5	
							EM00	0.2	
							PTSO	14.3	
							E010	23.0	
37	15 10 79	23 19	32.757	-115.441	26.45[3]	5.2[3]	DLTA	32.7	2
38	16 10 79	06 58	33.000	-115.570	33.	5.5	WSMO	15.0	2
39	16 10 79	06 58	33.0000	-115.5700	10.0	5.5	WSMO	6.3	2
40	21 12 79	20 40	32.450	-115.195	22.52[2]	4.8	CHIH	5.0	2
							CMPT	12.6	2
41	09 06 80	03 28	32.185	-115.076	5.0	6.4	CHIH	9.0	2
							CPRI	2.9	
							CUCA	15.8	
							VCTR	5.2	
							MHOS	31.9	
							XMVH	31.1	
							MXCS	26.3	
42	09 06 80	03 30	32.1833	-115.0833	5.0	4.5[4]	VCTR	5.2	3
43	09 06 80	10 00	32.1800	-115.0800	8.01[3]	4.5[3]	CPRI	2.9	2
44	09 06 80	23 33	32.3650	-115.2150	12.9[3]	4.3	CPRI	2.9	2

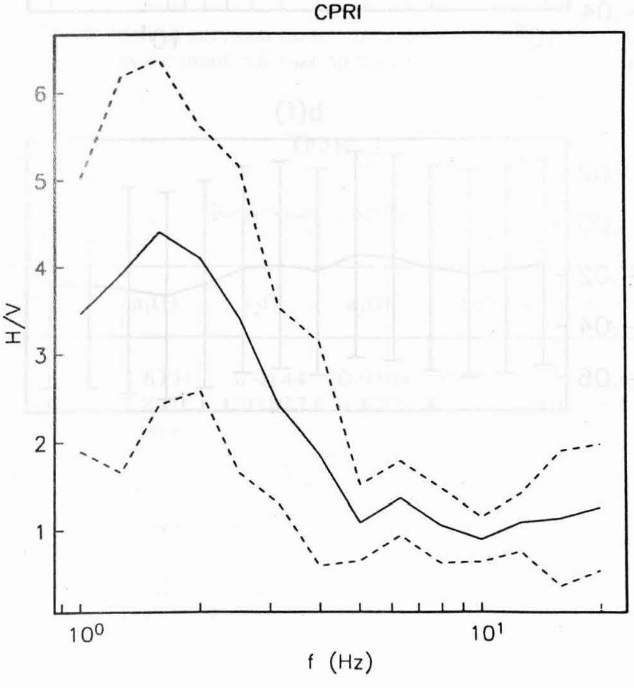

Fig. 2. Average site response of station Cerro Prieto (CPRI) obtained using H/V spectral ratios. The dashed lines are the 84% confidence levels.

(M_0=2.0$x10^{26}$) and M=4 (M_0=1.26$x10^{22}$). It can be noticed on that figure that at high frequencies, the rate of increase of the spectral amplitudes with magnitude, for a fixed distance, is less than at low frequencies. For instance, at 12.6 Hz the amplitude increases by a factor of 2.3 when the magnitude increases from 4 to 5, while at 1.3 Hz the amplitude increases by a factor of 4.5. On the other hand, high-frequency amplitudes decay faster with distance than low-frequency amplitudes (see bottom left frame of Figure 5). In Figure 5 we compare the decay of the spectral amplitudes with distance for different frequencies, as predicted by equation (3). For comparison, we also plotted in that figure the pseudoacceleration response spectra as function of distance predicted by a model recently obtained by Boore *et al.* (1997) using western North American earthquakes (bottom right frame of Figure 5). It is interesting to note that for distances greater than about 20 km the rate of amplitude decay of the response spectra, predicted by an attenuation model representative of a larger region, is approximately the same between 1 and 10 Hz. In contrast, the model obtained for a more specific region (equation (3)) shows more variability with frequency. This variability is also shown by the coefficient b(f) (see top frames in Figure 5).

The linear dependence of equation (2) with magnitude was also tested making $a_3(f)$=0 and fitting the estimates of

Table 2

Station coordinates

No.	Code	Name	Lat	Lon
1	ELCO	El Centro	32.794	-115.549
2	E070	Imperial V. College	32.830	-115.500
3	E060	El Centro Huston Rd	32.840	-115.490
4	DLTA	Delta	32.356	-115.195
5	RITO	Riito	32.166	-114.950
6	E050	El Centro James Rd	32.860	-115.470
7	E080	El Centro Cruikshank	32.810	-115.530
8	E040	El Centro Anderson	32.860	-115.430
9	VCTR	Victoria	32.289	-115.103
10	CPRI	Cerro Prieto	32.421	-115.311
11	CALO	Calipatria, Fire Station	33.130	-115.520
12	NILO	Niland, Fire Station	33.240	-115.510
13	WSMO	Westmoreland, FS	33.040	-115.620
14	CMPT	Compuertas	33.572	-115.083
15	E100	El Centro Array 10	32.780	-115.570
16	E110	El Centro Array 11	32.750	-115.590
17	6616	Aeropuerto Mexicali	32.651	-115.332
18	EM00	Meloland overpass	32.773	-115.448
19	PLSO	Plaster City	32.790	-115.860
20	XMCF	Casa Flores, Mex	32.618	-115.438
21	CC40	Coachella	33.360	-115.590
22	CUCA	Cucapah	32.545	-115.235
23	E020	El Centro Array 2	32.920	-115.370
24	E130	El Centro Array 13	32.710	-115.680
25	EDAO	El Centro Diff. Array	32.796	-115.535
26	BCRO	Bonds Corner	32.693	-115.338
27	BRAO	Browley Airport	32.990	-115.510
28	HVPO	Holfville Post Office	32.812	-115.377
29	SUPO	Superstation Mntn.	32.950	-115.820
30	CHIH	Chihuahua	32.480	-115.240
31	CX00	Calexico, Fire Station	32.670	-115.490
32	E030	El Centro Array 3	32.890	-115.380
33	6618	Agrarias	32.621	-115.301
34	PT50	Parachute Test	32.930	-115.700
35	5010	El Centro Array 1	32.960	-115.320
36	MH05	Mexicali Hosp. Sot.	32.650	-115.470
37	XMVH	Victoria Hosp. Sot.	32.641	-115.471
38	MXCS	Mexicali Sahop	32.616	-115.420

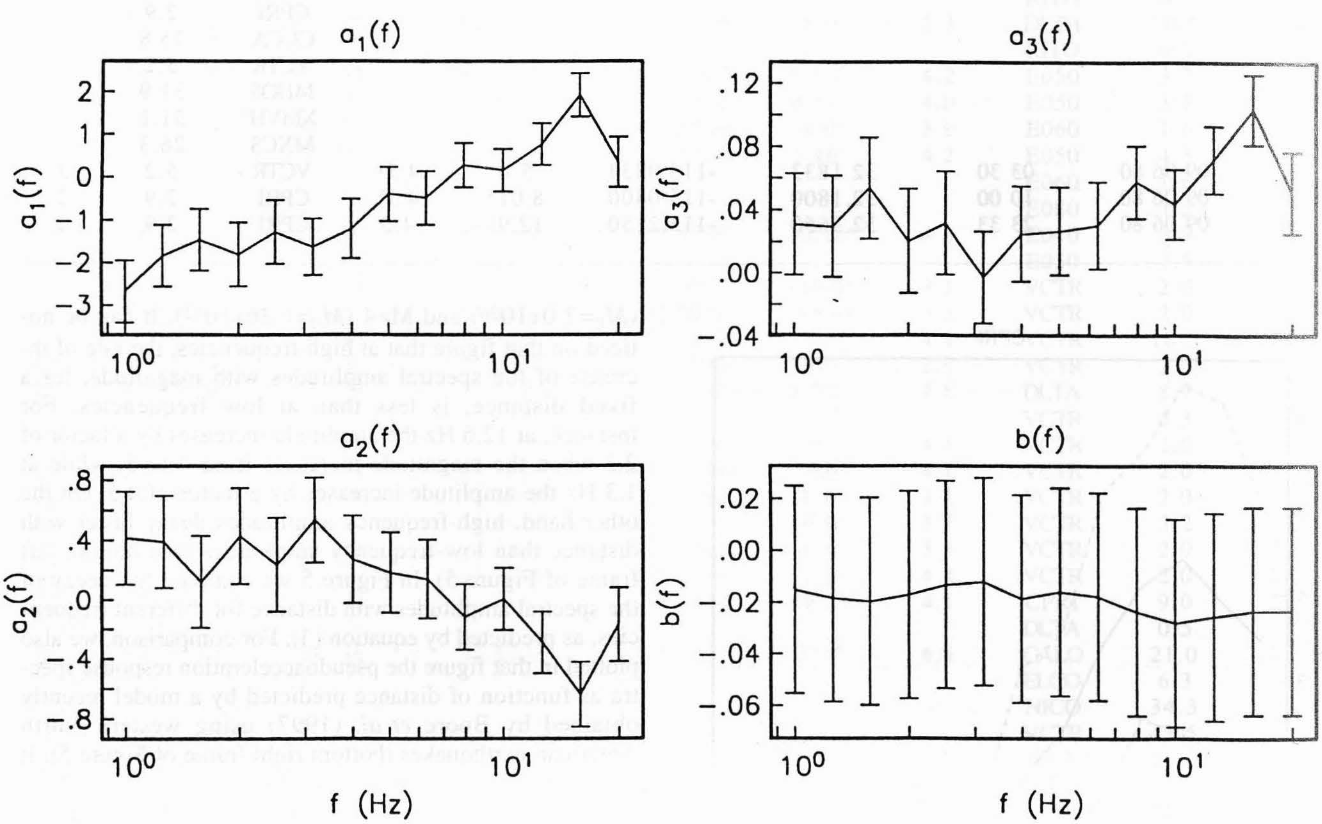

Fig. 3. Values obtained for the coefficients of the model (equations 1 and 2). The bars indicate the standard error of the estimates.

$S_i(f)$ with only the first two terms of equation (2). Figure 6 compares the standard deviation of the residuals obtained when using a linear relation for M (black dots) and when using a squared term (equation (2)). Although at 3.1 Hz the standard error is the same for both models, for the rest of the frequencies the use of a squared M term tends to decrease the fitting error. Because the wide magnitude range of magnitudes used (2.9< M < 6.8) a quadratic term to studies (Trifunac, 1976; Joyner and Boore, 1981; Boore *et al.*, 1997).

The site correction terms $z_j(f)$ show great variability with frequency and among the recording stations. Figure 7 shows a sample of 7 of these functions and their standard

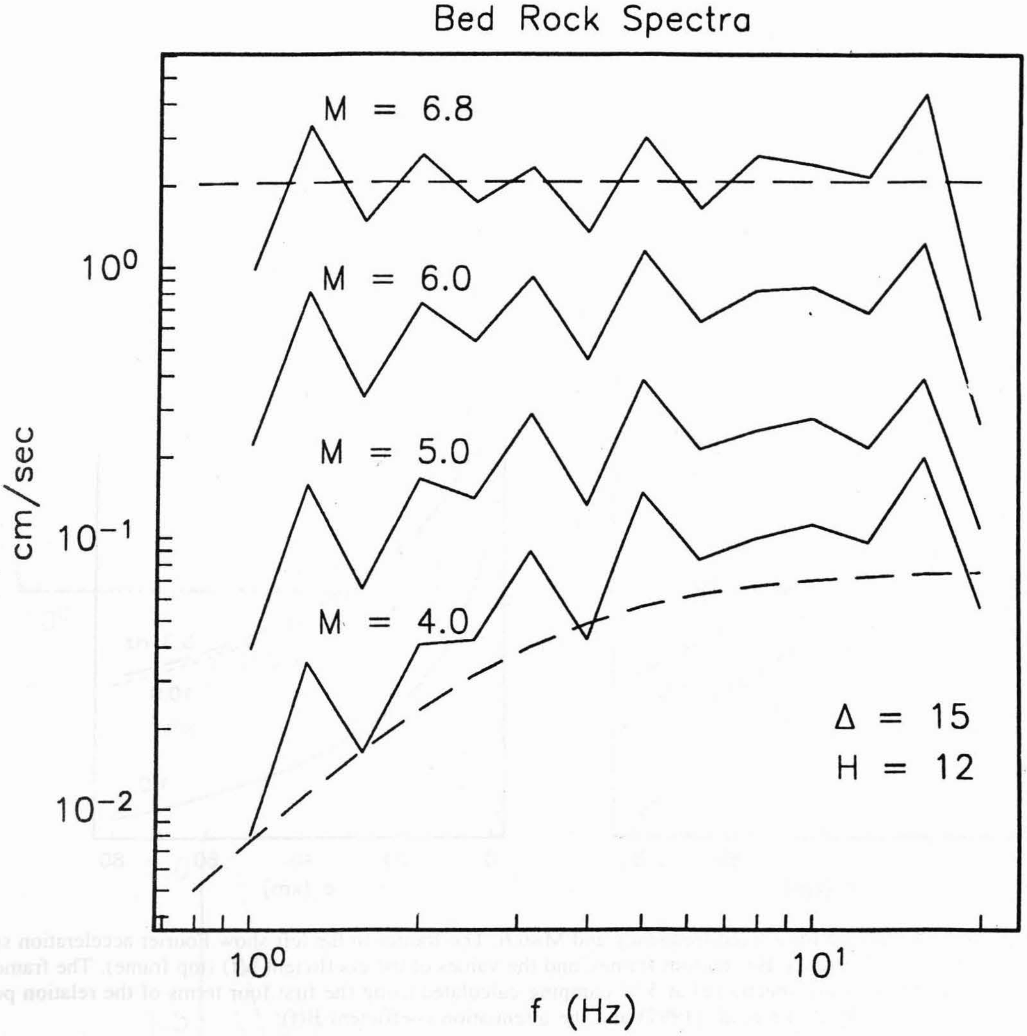

Fig. 4. Median acceleration spectra calculated for a distance of 15 km and four different magnitudes. These amplitudes can be considered as the input bed-rock spectra since $z_i(f)=0$ in equation (1). The dashed lines are spectral amplitudes calculated using the ω^2 model for a stress drop of 100 bars.

Table 3

Regression Coefficients

f(Hz)	$a_1(f)$	$a_2f)$	$a_3(f)$	b(f)	σ_t
1.00	-2.6731	0.4144	0.0308	-0.01518	0.7031
1.26	-1.8417	0.3877	0.0295	-0.01834	0.7587
1.58	-1.4668	0.1195	0.0538	-0.01969	0.8085
2.00	-1.8075	0.4270	0.0202	-0.01718	0.7273
2.51	-1.2818	0.2339	0.0318	-0.01319	0.7013
3.16	-1.6279	0.5319	-0.0023	-0.01199	0.6184
3.98	-1.2072	0.2684	0.0250	-0.01857	0.7958
5.01	-0.3960	0.1797	0.0269	-0.01592	0.7121
6.31	-0.4877	0.1357	0.0305	-0.01776	0.7378
7.94	0.2789	-0.1185	0.0579	-0.02363	.8601
10.00	0.1567	0.0020	0.0439	-0.02799	0.9999
12.59	0.7692	-0.2911	0.0718	-0.02557	0.9257
15.85	1.9261	-0.6394	0.1037	-0.02340	0.8555
19.95	0.3420	-0.1707	0.0511	-0.02345	0.7618

error. In spite of this variability, the trends of the site terms with frequency are similar, reflecting the fact that most of them are located in the same sedimentary valley. The variability of the amplitude of the site terms are probably related with the spatial change of thickness of the sediments inside the valley. In general, the standard error of the site terms is a factor of about 1.5 greater than the standard error of the regression. Figure 7 also illustrates the importance of using a frequency-dependent site term to account for specific soil conditions. For station El Centro (ELCO), located in the Terminal Substation Building (TSB), Brune and Anooshehpoor (1988) determined the response of the structure using a 3-D foam robber model. In figure 8 we compare the response of the TSB obtained by them with the site term z(f) estimated for ELCO (solid line) by solving equation (1). Although z(f) contains the effects of both the massive foundation and the soil deposits, the trend of this function is similar to the response of the building obtained by Brune and Anooshehpoor (1988) (dashed line). Figure 8 suggests that for f > 2 Hz the shape of the site term of ELCO is mainly controlled by the response of the structure.

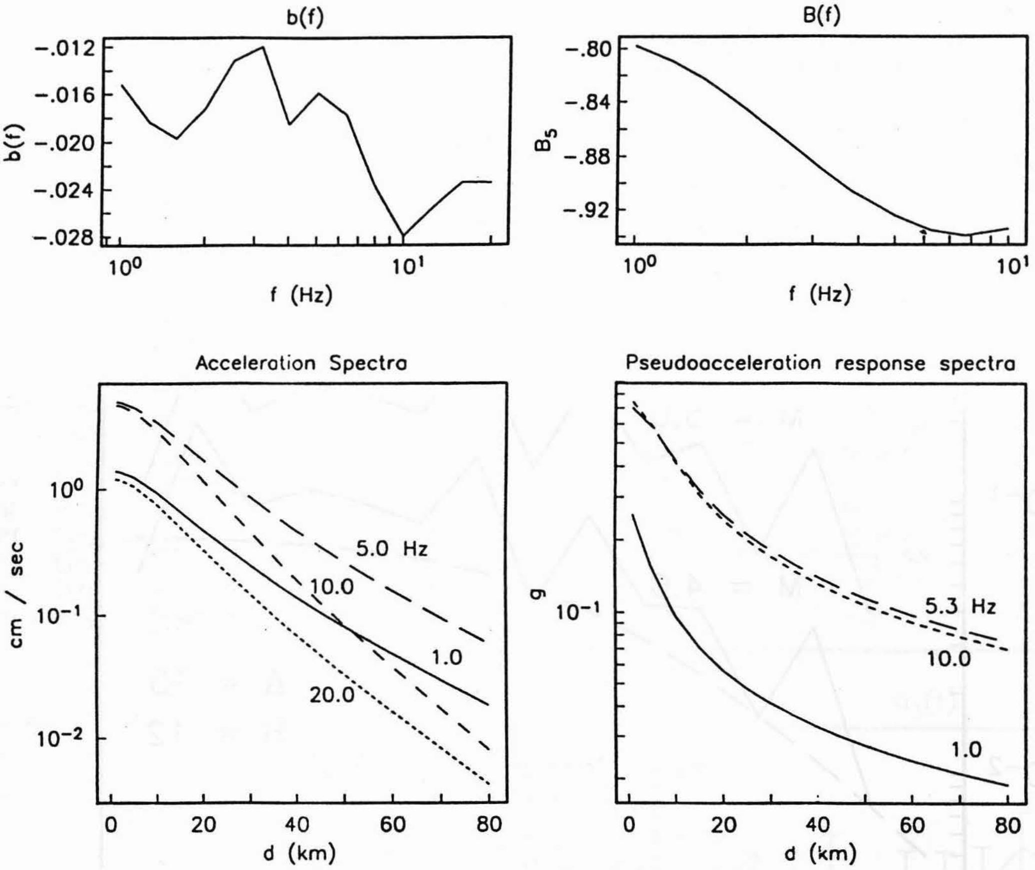

Fig. 5. Amplitude decay with distance for a fixed frequency and M=6.6. The frames to the left show Fourier acceleration spectra predicted by equation (3) for 1, 5, 10 and 20 Hz (bottom frame), and the values of the coefficient b(f) (top frame). The frames to the right display pseudoacceleration response spectra (g) at 5 % damping calculated using the first four terms of the relation proposed by Boore *et al.* (1997) and the attenuation coefficient B(f).

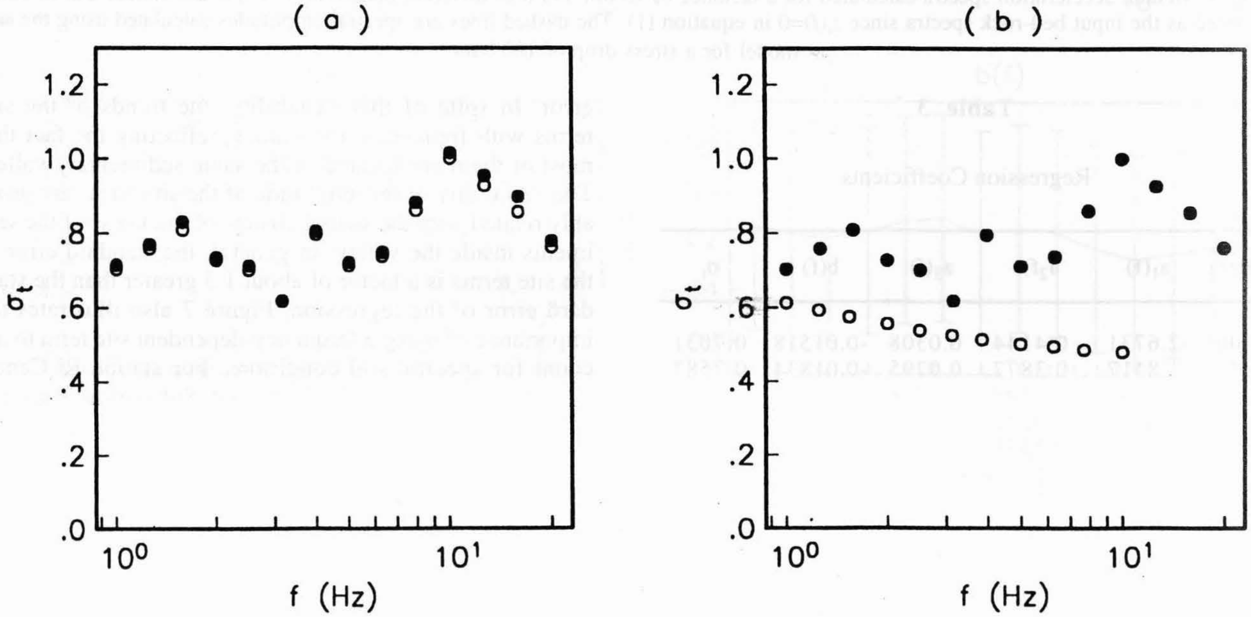

Fig. 6. (a) Comparison between the standard error (σ_t) obtained using a quadratic term in equation (2) for the magnitude dependence (open circles) and the error obtained when using only the first two terms of equation (2) (black dots). (b) Comparison between the standard error estimated in this study (black dots) and the error estimated by Boore *et al.* (1997) using western North American earthquakes (open circles).

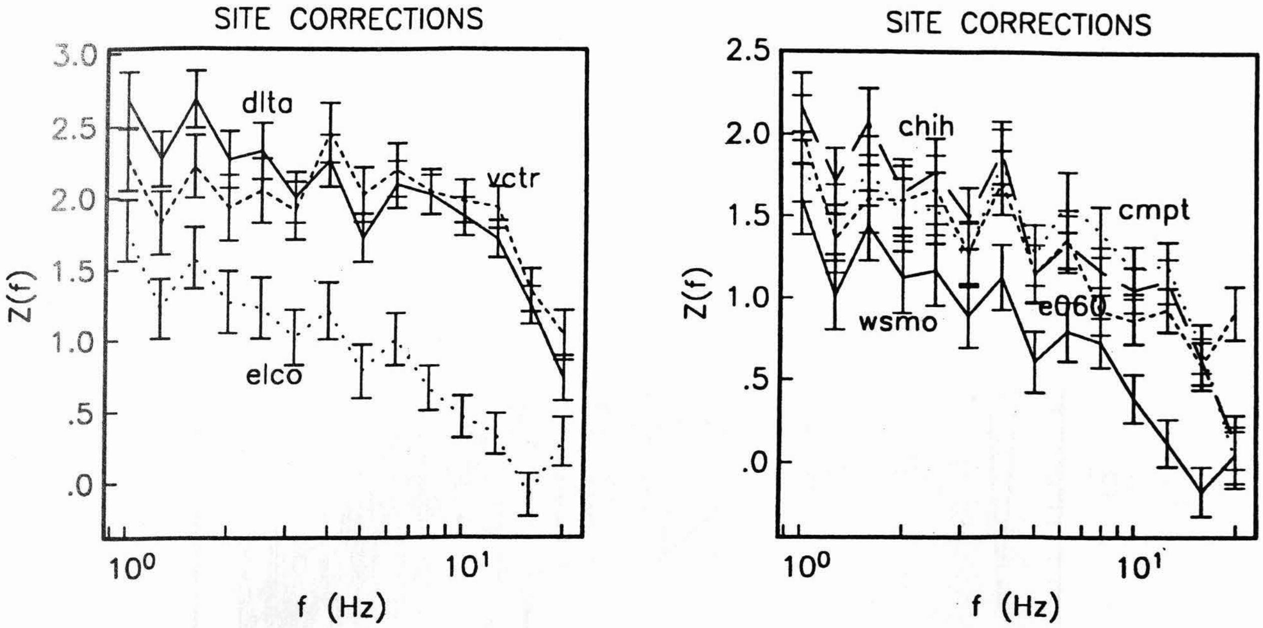

Fig. 7. Station site corrections obtained for seven of the sites listed in Table 2.

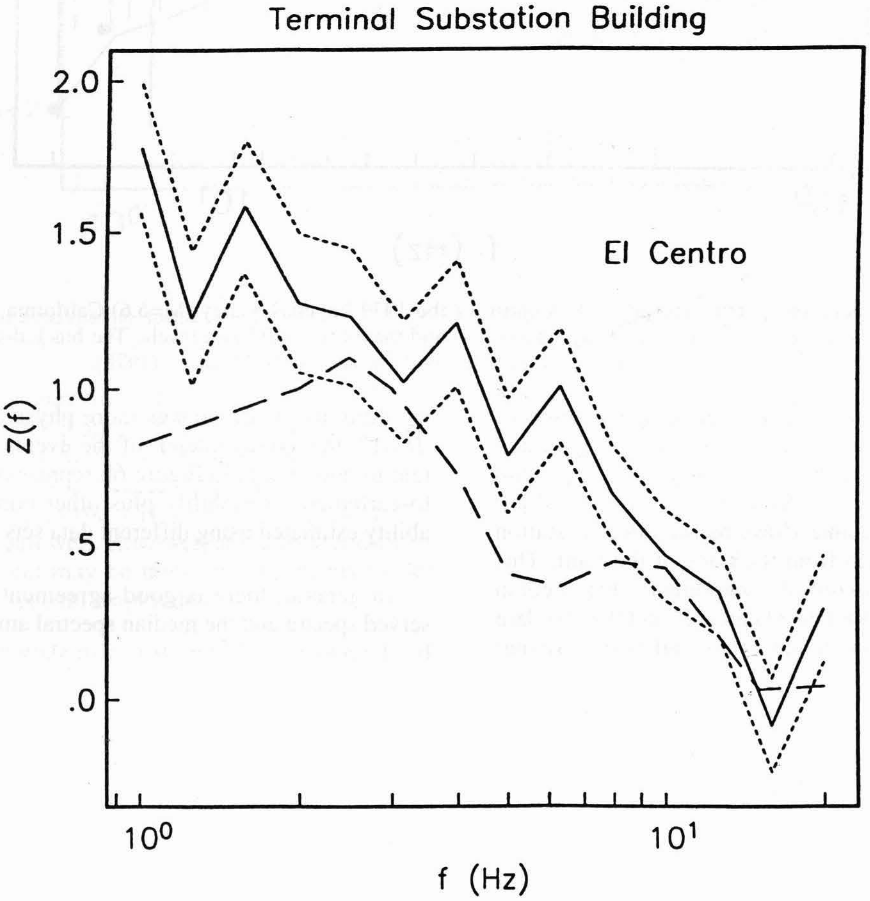

Fig. 8. Comparison between the site function obtained for ELCO using strong motion data (solid line) and the standard error of the estimate (dotted lines) and the response of the structure (dashed line) obtained by Brune and Anooshehpoor (1988) using a foam rubber model.

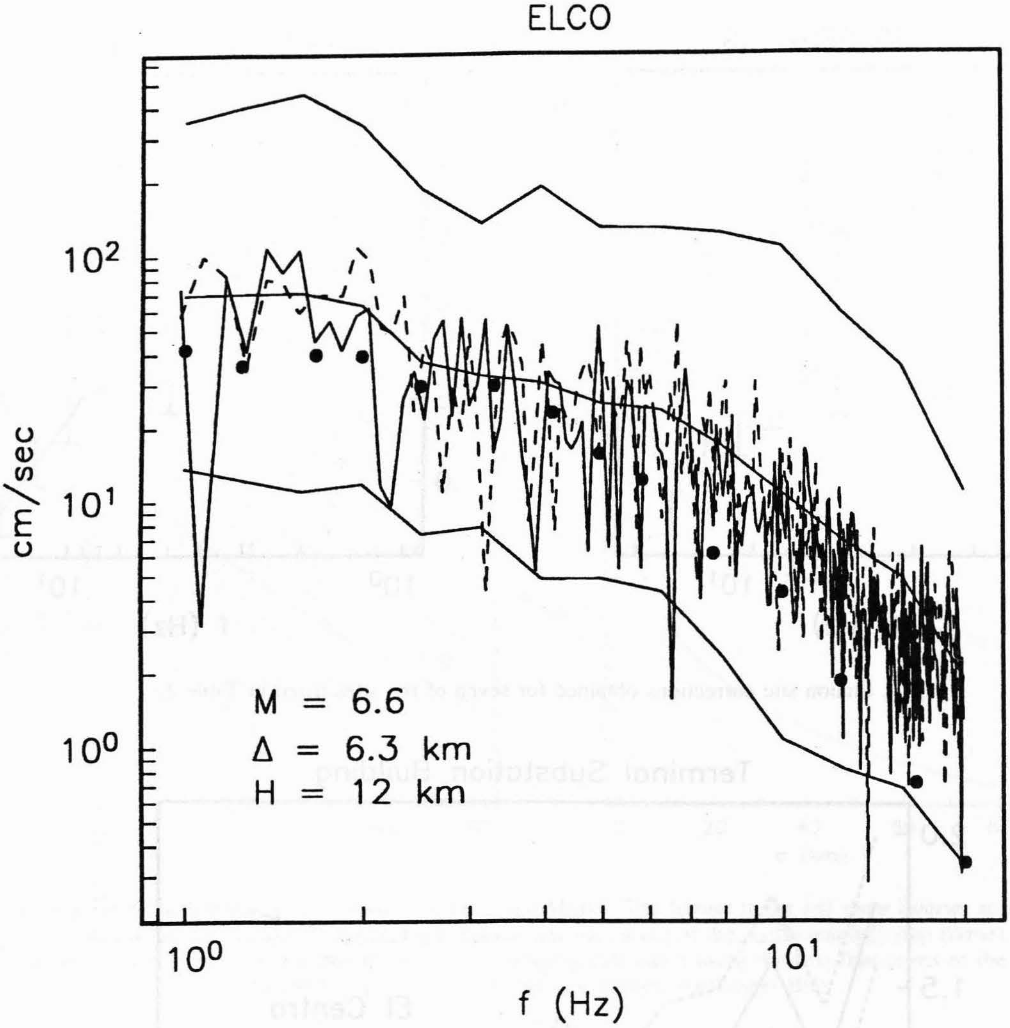

Fig. 9. Horizontal acceleration spectra recorded at El Centro for the 1979 Imperial Valley (M=6.6) California earthquake. The smooth lines are the median amplitudes predicted by equation (1) and the 84 % confidence levels. The black dots are the median spectral amplitudes calculated with the model proposed by McGuire (1978).

A consistency test can be made comparing the observed acceleration spectra of a record included in the regression analyzes with the spectra predicted by equations (1) and (2). Figure 9 shows the acceleration spectra of the 1979 Imperial Valley earthquake (M=6.6) recorded at station ELCO located at 6.3 km from the trace of the fault. This figure shows both horizontal components, the median spectra predicted by equations (1) and (2) and the standard error of the estimate, which was calculated as (e.g. Joyner and Boore, 1981):

$$\sigma_t = \left(\sigma_1^2 + \sigma_2^2\right)^{1/2} \tag{4}$$

where σ_1 and σ_2 are the standard deviation of the residuals resulting from equations (1) and (2) respectively. The last column of Table 3 list the total standard error estimated for each frequency. These values are larger than those reported by Boore *et al.* (1997) for a regression model similar to equation (1) (see Figure 6b). In order to decrease σ_t it is possible to search for a value of $\overline{H}$, in equation (1), that minimized σ_t instead of using the average depth. However, we think the model makes more physical sense by fixing $\overline{H}$=12, the average depth of the events. It is also important to note that σ_t in Figure 6b represents the earthquake-to-earthquake variability plus other components of variability estimated using different data sets.

In general, there is good agreement between the observed spectra and the median spectral amplitudes predicted by the model. In Figure 9 is also shown, for comparison, the spectral amplitudes predicted by the model proposed by McGuire (1978) (black dots). His model predicts median spectral amplitudes based on magnitude M, hypocentral distance R and a binary variable Y_s that takes a value of one for soil sites and zero for rock sites. This model has the following form:

$$\ln\ U(f) = b_1(f) + b_2(f)M + b_3(f)\ln\ R + b_4(f)Y_s\ . \tag{5}$$

McGuire (1978) obtained the coefficients b_i using strong-motion records from different regions of California.

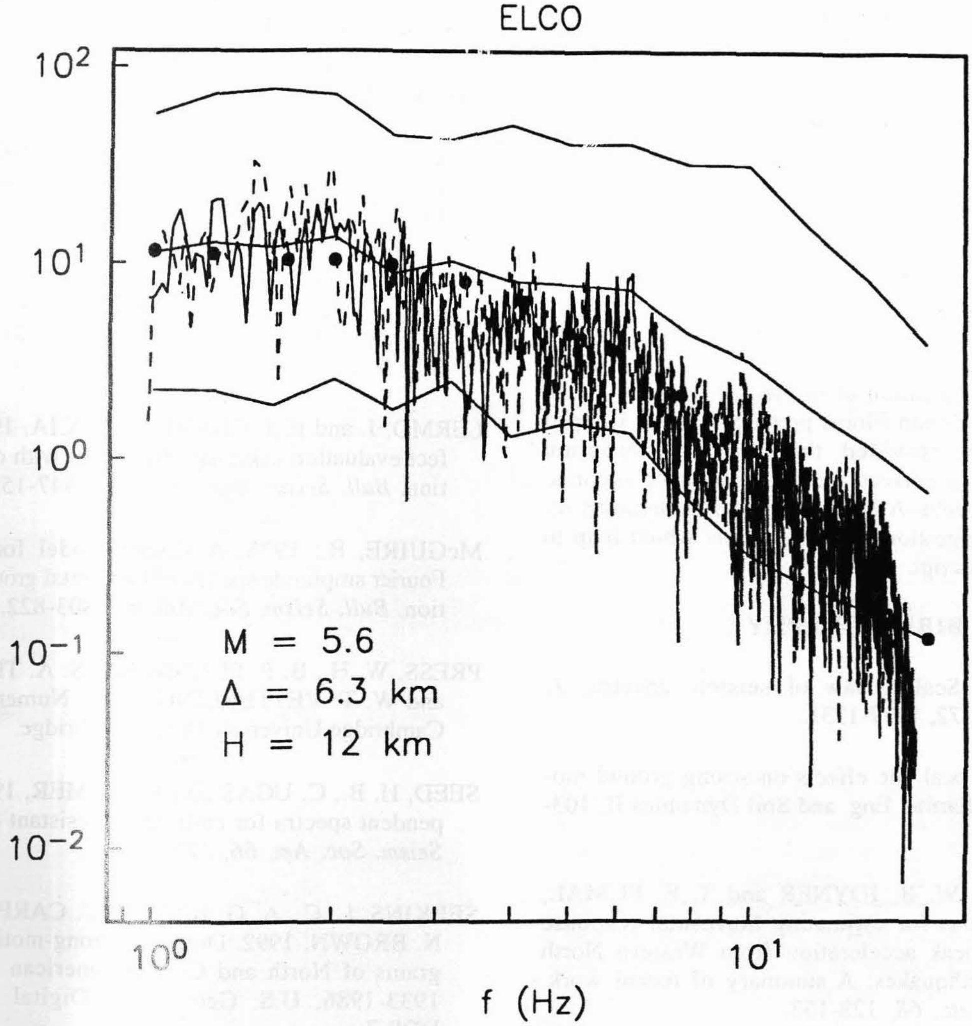

Fig. 10. Horizontal acceleration spectra of the January 23, 1951 earthquake (M=5.6) recorded at El Centro. The black dots are the median spectral amplitudes predicted by McGuire's (1978) model and the smooth lines by the model obtained in this study.

The black dots in Figure 9 are the median spectral amplitudes estimated with equation (5) using the regression coefficients obtained by McGuire (1978). Although the observed spectral record was not included in McGuire's analysis, at low frequencies (f< 6 Hz) his model predicts the mean amplitudes quit well. However, at higher frequencies where the site effect may be more important, his model underestimate the spectral amplitudes.

To test the validity of the spectral amplitudes predicted by equations (1) and (2), the spectral records from an earthquake excluded from the data set is compared in Figure 10. The event selected has a magnitude M=5.6, a depth of 16 km and was recorded by the station ELCO. This figure also shows for comparison the median spectral amplitudes predicted by equation (5). At low frequencies (f < 5 Hz), the spectral amplitudes estimated with equation (1) agree reasonably well with the mean spectrum recorded at ELCO, however, at higher frequencies the model tends to overestimate the mean spectral level. Since the record shown in Figure 10 was included in the data set used by McGuire (1978), equation (5) is able to obtain a good estimate of the median spectral level in the whole frequency range analyzed.

CONCLUSIONS

An empirical model to predict Fourier acceleration spectra in terms of simple source parameters and a site correction term was determined for the Imperial-Mexicali Valley region. The spectral amplitudes predicted by the model decay faster with distance at high frequencies (f > 5 Hz) than the low-frequency amplitudes. We also observed that while attenuation relations obtained for a larger region (Boore *et al.*, 1997) tend to predict the same rate of amplitude decay between 1 and 10 Hz, the model obtained in this paper shows more variability of the rate of amplitude decay between frequencies (see Figure 5). In addition, since the magnitudes of the events used vary from small (M 2.9) to large (M 6.8), the introduction of a quadratic term for M in the model results adequate for scaling the spectral amplitudes. Finally, the frequency variation of the site corrections observed (Figure 7) can be due to the combination of local variations of the thickness of the sediments, the topography around the recording stations and other site related effects. The strong frequency dependence of the site terms found reassure the importance of considering proper site-specific corrections when predicting ground motion spectra.

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