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EMPIRICAL GROUND-MOTION ESTIMATION EQUATIONS IN COLIMA FROM WEAK MOTION RECORDS

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ABSTRACT

We develop ground-motion estimation equations using data from small earthquakes recorded in the northern region of the subduction zone in the Pacific coast of Mexico. The equations predict peak ground acceleration and (5%-damping) pseudo-acceleration response spectra for ten period values. Magnitude dependence is modulated by the effect of focal depth. The dataset consists of 162 three-component acceleration records from 26 earthquakes (with $3.3 < M < 5.2$ and $5 <$ depth < 76 km). These data were recorded at local and regional distances (i.e., $R < 175$ km) with a temporal array of 12 autonomous digital accelerographs that operated during eight months (from January to August, 2006). In addition to those, we use the data recorded during the same period by five permanent strong motion stations installed recently. A two-step stratified regression model is used to decouple the evaluation of the distance dependence from magnitude and focal depth dependences. We compare our results with previous empirical attenuation models for subduction zones in Mexico and elsewhere. Our results predict larger intensity values for distances larger than 100 km in the magnitude range where they are most reliable.

KEYWORDS: Ground Motion, Estimation Equations, Response Spectra, Empirical Attenuation

INTRODUCTION

Current approaches to seismic risk studies require ground-motion models to predict expected ground motions. In many parts of the world reliable networks, including many permanent strong motion stations, have provided useful data for this aim. However, this is not the case in other seismic regions, especially in developing countries, where good quality data is scarce, and where only sparse strong motion networks exist or are just now being installed.

A large part of Mexico is subjected to seismic risk, especially on its west coast, along the Pacific Ocean, where ongoing subduction is at the origin of many large earthquakes. During the 20th century, Mexican Seismological Survey[1] reported 13 earthquakes with magnitudes larger than 7. The large seismic risk associated with this subduction zone has prompted many studies. In particular, ground-motion estimation equations have been developed by several authors. However, those efforts have not been equally distributed along the subduction zone. Most studies have concentrated on the Guerrero region, in the southern part of the country. There are several reasons for this. The first reason is the larger seismicity rate that allows obtaining useful data in a short time. Second, this section of the subduction zone is very active and it is there that most of the large destructive earthquakes have occurred. A foremost example is the 1985 earthquake ($M_w = 8.1$). The third reason is that, in 1985, most casualties and damage occurred in Mexico City, where the exposed infrastructure and population are the largest in the country. It is the Guerrero section of the subduction zone that is closest to Mexico City posing the largest threat to this city. At the same time, this city has been much less affected by large events occurring elsewhere in the subduction zone. The fourth reason is that a joint project between UNAM, Mexico and UC San Diego, USA allowed the installation of an extensive strong-motion network in the Guerrero coast (Anderson et al., 1987a, 1987b). At that time it was a momentous advance in strong-motion instrumentation in Mexico. This array has produced large amounts of high quality data that have been freely available spurring many studies.

Important as it is, however, Mexico City is not the only large city in the country. Urbanisation of the country is proceeding and medium-sized cities are fast becoming large. Many of them are close to the

[1] Website of Mexican Seismological Survey, http://www.ssn.unam.mx

Pacific coast and are, therefore, subjected to large seismic risk. This situation imposes the need to study attenuation of seismic energy better in those regions of the country that have received less attention in the past.

In Mexico, the first effort to develop ground-motion estimation equations was carried out by Esteva and Villaverde (1973), although they used mostly strong motion records from California and only about 30% of their data came from Mexico and Central America. Later, ground motion models using only Mexican data were developed by Bufaliza (1984), Ordaz et al. (1989), and García et al. (2005). All of these studies considered all the data available at the time of their analyses. Given the instrumentation history in Mexico, this means that the data used was essentially strong motion data from the southern part of the country. None of these studies included data from western Mexico, along the northern section of the subduction zone. Seismicity in this northern region is less than that in Guerrero. However, the two largest earthquakes that have struck the country in recent years occurred there: an M_w = 8 event in 1995 (Pacheco et al., 1997), and an M_w = 7.6 event in 2003 (Yagi et al., 2004; Nuñez-Cornú et al., 2004).

The federal state of Colima is located in Western Mexico, on the Pacific coast (see Figure 1). The tectonic environment is complex, as in this region we have the interplay of three different plates: Rivera, Cocos, and Pacific. In addition, the existence of a microplate has also been proposed (DeMets and Stein, 1990; Bandy et al., 1995). There are significant changes in the parameters of the subduction along the subduction zone on the Pacific coast of Mexico, which has been divided in four sections by Pardo and Suarez (1995). Although the dip of the interplate contact geometry is constant to a depth of 30 km, lateral changes in the dip of the subducted plate are observed once it is decoupled from the overriding plate. In front of the Jalisco block (see Figure 1), Rivera plate has a dip of 45º and a velocity of 2.4 cm/year. Cocos plate below Colima shows a similar dip to that of Rivera but has a larger velocity (i.e., 4.6 cm/year). To the south, the dip of Cocos plate decreases gradually and is almost sub-horizontal at Guerrero (where it subduces with a velocity of 6.7 cm/year), before increasing again further south to the large values observed in Central America. Pardo and Suarez (1995) explained the observed non-parallelism between the volcanic belt and the subduction zone by these large lateral variations. It is uncertain that ground-motion prediction equations developed for Guerrero, in a very different tectonic setting, can be applied straightforward to Colima. For this reason, we conducted an experiment specifically oriented to investigate this problem. In this paper, we present the results obtained from the analysis of the data recorded by a temporal strong motion network. We have also added the records obtained by the five accelerographs of the national permanent seismic network installed recently. The temporary array, consisting of 12 autonomous accelerographs, was installed in January 2006 along a line, perpendicular to the coast and extending to the capital of the state. This network operated for eight months and recorded a total of 29 events. The magnitude of the largest event was 5.2. We present the analysis of these data and the equations that were obtained. We derive ground-motion estimation equations for both PGA and (5%-damping) pseudo-acceleration response spectra at 10 period values. We compare our results with the previous ground motion estimation equations developed for Mexico and elsewhere. We are able to show that attenuation in Colima is different from that in Guerrero. This suggests that, even along the same subduction zone, different tectonics and regional geology may significantly change the attenuation of ground motion with distance, thus invalidating the extrapolation of attenuation relations to other sites. Our results provide the first constraint for attenuation in Colima, albeit only with small magnitude data.

DATA

Colima, one of the smallest federal states in Mexico, is located on the Pacific coast, close to the northern end of the subduction zone (see Figure 1). In this region a temporary accelerograph network was operated for eight months. Twelve digital accelerographs were installed along a line, perpendicular to the coast and extending to the capital city of the state (see Figure 2). The instruments used were five Etna recorders by Kinemetrics with Episensor FBA sensors, and seven GSR-18 by Geosig with AC-63 FBA accelerometers. Each instrument had its own GPS receiver for precise timekeeping. Most stations were installed on rock or firm ground, and only four instruments (i.e., those close to the coast) were installed on sandy or silt sandy soils. Unfortunately, data on the subsoil structure at each site is not available beyond the surface soil condition. Because of this, we have not corrected the data from those four stations for site effects. We do not have enough information of the subsoil structure to compute a reliable transfer function. However, we have two independent indications that site effects are not large at those four sites. First, we computed H/V spectral ratios (Lermo and Chávez-García, 1993) using all the recorded data. The results suggested no significant local amplification at any of our stations in the frequency band where our data is useful. Second, even if our data is not enough to process independently soil and firm ground sites, we checked whether the residuals for those four stations showed a systematic bias that could be ascribed to the site effects, and we found none. To the data recorded by the temporal array, we added the data recorded by the five permanent digital accelerographs of the national seismic network installed in Colima, all of which are on rock. They also are Etna recorders with FBA sensors. All the instruments used are recent models and therefore the quality of the data produced by all 17 digital stations is high, requiring only a baseline correction to the raw data.

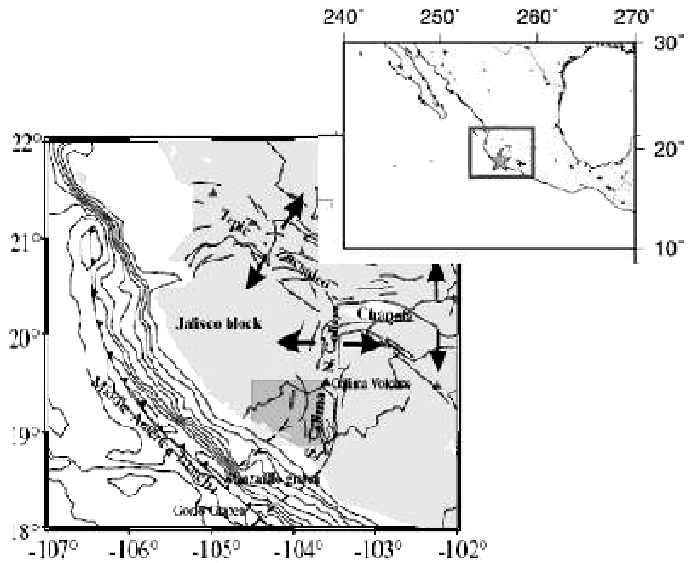

Fig. 1 Location of the federal state of Colima in Mexico and its tectonic environment (the solid star indicates the location of the studied area; the solid arrows show the directions of principal regional stresses; the inland solid lines show the main faults in the region and the limits between different states of the Mexican republic; the dashed line shows the limits of the Colima graben; the solid lines in the offshore indicate the bathymetric contours at 100 m interval; the solid line with triangles shows the subduction zone)

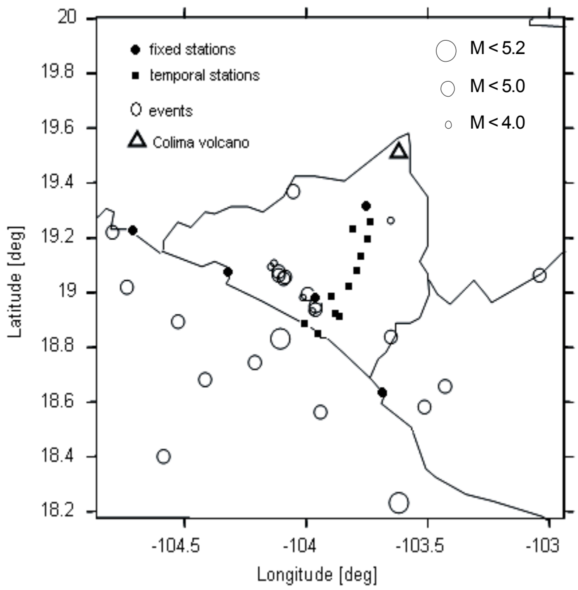

Fig. 2 Station distribution used in this study (the solid lines indicate either the coastline or the limit between the federal states in Mexico; open circles indicate the epicenters of the retained events, computed from the arrival times in the strong motion stations shown with solid symbols; the size of the open circles scales with the earthquake magnitude)

During the eight months when the temporal array operated, a total of 29 events were recorded. From these, only 26 were retained for the analysis; the other three were recorded at fewer than three stations. Those events gave a total of 162 three-component records. We used P and S arrival times read from all 17 stations to locate the events. Local magnitudes were determined from the accelerograms by using the standard procedure of simulating a Wood-Anderson record and by computing magnitude from the largest amplitude (Kanamori and Jennings, 1978). The Mexican Seismological Service (SSN) reported locations for 15 of the 26 events. We did not use the locations of SSN because their stations are very sparse in the Colima region, resulting in large epicentral distances and poor angle coverage. The data from our local array, which allowed the use of both P and S arrival times, led to better-constrained hypocentral determinations that show small root-mean-square (RMS) error. Our magnitudes differed from those of SSN by 0.2 at the most. The determined magnitudes span the range from 3.3 to 5.2. In this range, there are no significant differences between the local and moment magnitudes (Hanks and Boore, 1984; Heaton et al., 1986; Reiter, 1991). Figure 3 shows the magnitude-distance distribution of the data events for the analysis, while Figure 4 shows the relation between epicentral distance and depth for our data. Relevant data of the earthquakes is given in Table 1.

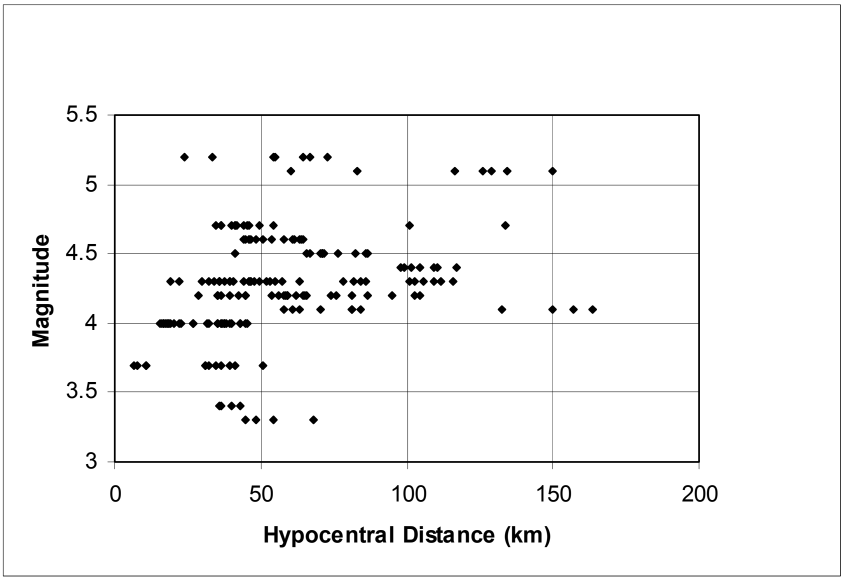

Fig. 3 Distribution of our data as a function of magnitude and hypocentral distance (our results will be best-constrained for distances shorter than 125 km and magnitudes smaller than 5)

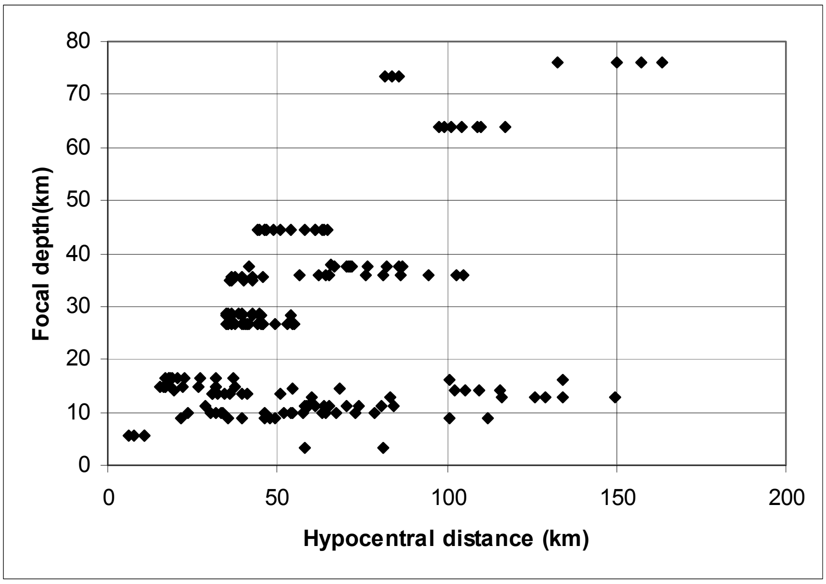

Fig. 4 Distribution of our data as a function of hypocentral distance and depth

Table 1: Relevant Data of the Events Retained for the Analysis

Event	Date	Origin Time	Latitude (°N)	Longitude (°E)	Depth (km)	Local Magnitude
1	17/03/2006	13:08	20.225	–103.851	76.0	4.1
2	20/03/2006	23:37	19.064	–103.038	64.0	4.4
3	22/03/2006	22:42	18.950	–103.961	16.3	4.0
4	23/03/2006	00:35	18.938	–103.963	14.9	4.0
5	25/03/2006	05:29	19.074	–104.116	26.8	4.7
6	25/03/2006	05:36	18.996	–103.993	35.7	4.0
7	25/03/2006	11:59	18.980	–104.014	34.9	3.4
8	26/03/2006	09:28	19.049	–104.092	28.5	4.0
9	29/03/2006	17:52	18.679	–104.418	35.8	4.2
10	30/03/2006	08:53	19.062	–104.116	26.6	4.3
11	03/04/2006	21:34	18.579	–103.514	37.8	4.5
12	07/04/2006	07:28	19.054	–104.089	28.3	4.2
13	09/04/2006	16:07	19.093	–104.145	13.6	3.7
14	23/04/2006	10:39	19.219	–104.802	14.3	4.3
15	01/05/2006	22:40	18.897	–104.529	11.2	4.1
16	03/05/2006	16:18	18.562	–103.941	3.4	4.1
17	06/05/2006	05:25	18.743	–104.212	10.0	4.3
18	13/05/2006	11:31	18.655	–103.425	11.1	4.2
19	18/05/2006	23:51	18.837	–103.654	44.3	4.6
20	19/05/2006	06:59	18.931	–103.974	5.5	3.7
21	20/05/2006	00:42	19.260	–103.650	39.9	3.3
22	27/05/2006	23:09	19.368	–104.055	73.3	4.3
23	02/06/2006	01:21	19.020	–104.740	9.0	4.3
24	31/07/2006	18:25	18.830	–104.110	10.0	5.2
25	03/08/2006	01.04	18.400	–104.590	16.0	4.7
26	13/08/2006	15:14	18.230	–103.620	13.0	5.1

ANALYSIS

Our analysis followed standard procedures (e.g., Joyner and Boore, 1981, 1993, 1994). We express a seismic intensity value A as a function of magnitude and distance using

$$\ln A = c_1 + c_2 M - c_3 \ln h - c_4 \ln R \tag{1}$$

where ln stands for the natural logarithm operator; A can be either peak ground acceleration (PGA) or a response spectral ordinate (say, PSA) at a given period value for 5% damping; M is the local magnitude; R and h respectively are the hypocentral distance between the event and the station and the focal depth (in km); and c_1, c_2, c_3 and c_4 are the coefficients to be computed from the regression procedure. The dependence coefficient c_4 is obtained from Equation (1), rewritten as

$$\ln A = -c_4 \ln R + \sum_{i=1}^{n} d_i l_i \tag{2}$$

where c_4 is assumed to be same for all earthquakes, and the constant term "$c_1 + c_2 M - c_3 \ln h$" is replaced by $\sum d_i l_i$, where l_i is a dummy variable and d_i a coefficient for the i th earthquake. The sum is taken over the total number of earthquakes, n. Thus, the coefficient c_4 is obtained in the first step as the least-square solution of the linear inversion problem described by Equation (2).

The second stage consists of the evaluation of the coefficients c_1, c_2, and c_3 in Equation (1). The terms c_2 and c_3 are both related to the source scaling of the acceleration observation. However, these two terms can be considered independently, and these define an initial acceleration that decreases as distance increases. Fukushima and Tanaka (1990) proposed to compute the coefficients c_2 and c_3 from the statistics of the correlation among the variables. According to them, these coefficients can be evaluated from the linear equation composed with standard deviations and correlation coefficients of the variables. Finally, c_1 is determined as a function of the other coefficients and the mean values of ground acceleration, focal depth, distance, and magnitude. The equations we have used here follow the procedure proposed by Fukushima and Tanaka (1990), in the form given by Chang et al. (2001). Those formulas are

$$c_3 = \left(c_4 \sigma_{\ln R} R_{\ln h, \ln R} + \sigma_{\ln A} R_{\ln h, \ln A}\right) \big/ \sigma_{\ln h} \tag{3}$$

$$c_2 = \left(c_4 \sigma_{\ln R} R_{M, \ln R} + \sigma_{\ln A} R_{M, \ln A}\right) \big/ \sigma_{M} \tag{4}$$

$$c_1 = \ln \overline{A} - c_2 \overline{M} + c_3 \ln \overline{h} + c_4 \ln \overline{R} \tag{5}$$

In these equations, σ_M, $\sigma_{\ln R}$, $\sigma_{\ln A}$ and $\sigma_{\ln h}$ are the standard deviations with respect to M, ln R, ln A, and ln h, respectively; $R_{\ln h, \ln R}$, $R_{\ln h, \ln A}$, $R_{M, \ln A}$, and $R_{M, \ln R}$ are the correlation coefficients between ln h and ln R, between ln h and ln A, between M and ln A, and between M and ln R, respectively; and the symbols $\ln \overline{A}$, $\overline{M}$, $\ln \overline{h}$, and $\ln \overline{R}$ represent the average values for ln A, M, ln h, and ln R, respectively. The derivation of these equations is given in detail in Chang et al. (2001). It may be argued that there is no need to include a depth term. However, results shower less scatter when it is included, and the data distribution shown in Figure 4 suggests that epicentral distance and depth are not simply correlated. In addition, our database suggests that deep events have slower attenuation with distance than shallow events. We are aware, however, that a larger database is required to substantiate this term better.

We could not correct the records obtained at the four stations on soft soils (i.e., 23% of all stations) by their transfer functions because we do not have enough data to compute those transfer functions. In addition, our dataset is not large enough to divide our stations in two groups. For this reason, we will pay special attention to the residuals of those four stations, while searching for a significant bias.

RESULTS

The coefficients and their standard deviations determined from the regression analysis are given in Tables 2 and 3. An analysis of the signal-to-noise ratio led us to limit the estimations of PSA to periods up to 1 s for the horizontal motion and up to 0.8 s for the vertical motion. This is expected for the small-magnitude earthquakes. The residuals for average PGA for the horizontal motion are plotted in Figure 5. Although some data points are far from the predicted value, the standard deviation for the whole dataset is 0.28. We observe that our attenuation relation shows no significant bias. The apparent decrease in the residuals for large distances reflects only the decreasing amount of data available. We have verified that the residuals for the four stations on soft soils are not different from those for the rock stations (see Figure 5). This suggests that site effects do not impose a significant bias in our results, thus confirming the indication provided by the H/V spectral ratios.

Table 2: Regression Coefficients Computed for Average Horizontal Motion

T (s)	c_1	c_2	c_3	c_4	σ
0.00	–0.5342	2.1380	0.4440	1.4821	0.28
0.07	–0.3924	1.9554	0.4200	1.3033	0.27
0.13	–0.4821	2.5676	0.6412	1.6630	0.28
0.19	–0.6559	3.1780	0.9306	2.1734	0.30
0.25	–1.3836	3.5738	1.0681	2.4317	0.32
0.32	–1.6473	3.7029	1.1530	2.5281	0.33

0.38	–1.9799	3.7442	1.1694	2.5511	0.34
0.50	–2.6537	3.7623	1.1801	2.5224	0.36
0.62	–2.9776	3.6381	1.1821	2.4148	0.36
0.80	–3.3181	3.5824	1.2055	2.3725	0.35
0.99	–3.6962	3.4723	1.1664	2.2806	0.35

Table 3: Regression Coefficients Computed for Vertical Motion

T (s)	c_1	c_2	c_3	c_4	σ
0.00	–0.5231	1.9876	0.5502	1.4038	0.27
0.07	–1.0294	2.1996	0.5626	1.2653	0.27
0.13	–2.0317	2.9507	0.7211	1.9181	0.27
0.19	–2.6411	3.4305	0.8501	2.3413	0.31
0.25	–2.9134	3.5597	0.9267	2.4426	0.33
0.32	–3.0510	3.5220	0.9349	2.4435	0.34
0.38	–3.1475	3.4945	0.9533	2.4438	0.36
0.50	–3.4057	3.3324	0.9290	2.3391	0.36
0.62	–3.4724	3.2640	0.9733	2.3142	0.36
0.80	–3.9437	3.1458	0.8821	2.2571	0.35

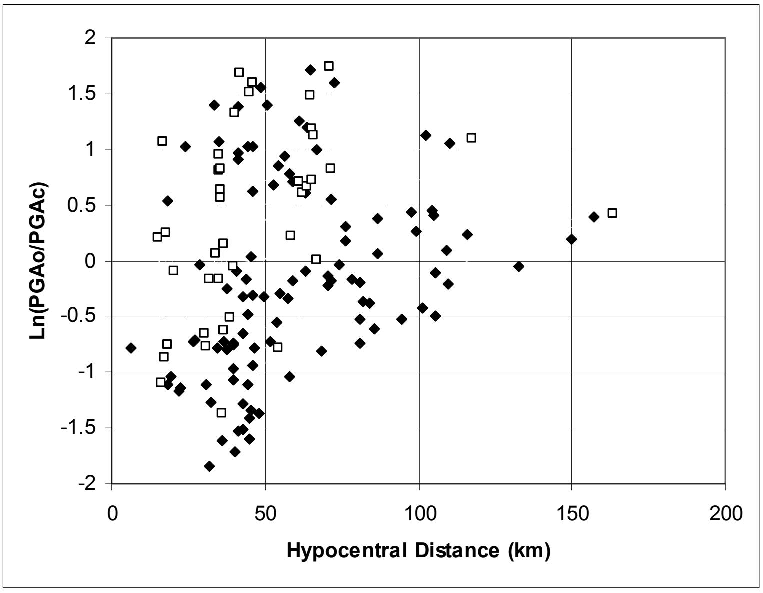

Fig. 5 Ratios between the predicted and observed horizontal PGAs for our dataset (solid diamonds correspond to the stations on firm soil; open squares show the residuals for the four stations on soft soils; the scatter is similar to that observed in the previous studies; we observe that our relation shows no significant bias)

Figure 6 compares our predictions for PGA for a $M = 5$ earthquake (with the focal depth of 15 km) with those from the previous attenuation relations developed for the subduction zones in Mexico (García et al., 2005), Japan (Fukushima and Tanaka, 1990), and elsewhere (Youngs et al., 1997; Atkinson and Boore, 2003). This comparison is limited by the small overlap in the magnitude range used in those studies (i.e., between 4.6 and 5.2) with ours. However, we observe that, at close distances from the source (i.e., up to 50 km), our predicted values are similar to those of Fukushima and Tanaka (1990), Youngs et al. (1997), and Ordaz et al. (1989), and are larger than those of Garcia et al. (2005) and Atkinson and Boore (2003). However, as the distance increases, the PGA values predicted by our ground-motion estimation equation decrease more slowly than those by the other authors. As a consequence, for distances larger than 100 km, we predict larger PGA values. This is important because Colima city is located at 120 km from the subduction zone. Therefore, the use of attenuation relations derived with the data from other subduction regions may underestimate the seismic hazard for Colima city.

Using the same regression procedure, we also derived the coefficients for 10 period values of pseudo acceleration response spectra for 5% damping. García et al. (2005) also derived these coefficients. Figure 7 shows the comparison between our results and those of García et al. (2005), again for a $M = 5$ earthquake at 15 km depth and at a distance of 50 km. We observe that our estimation equation predicts larger horizontal PSA in the entire period range.

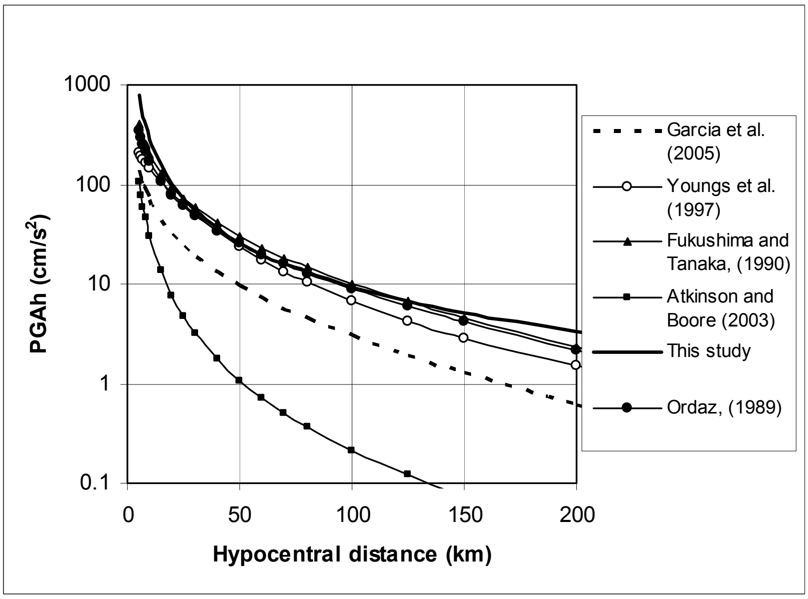

Fig. 6 Comparison between different attenuation relations (horizontal PGA is shown as a function of distance for a magnitude 5 earthquake, at 15 km depth; at short distances, our relation shows smaller PGA values, but it crosses over the other relations and predicts larger PGAs for distances larger than 100 km)

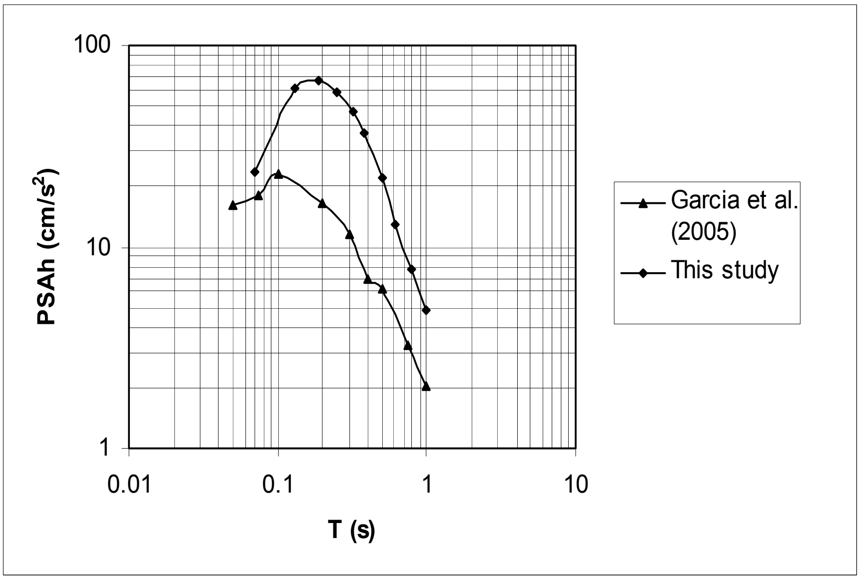

Fig. 7 Comparison between Garcia et al. (2005) and our study in terms of predicted average horizontal (5%-damping) PSA as a function of period T (these results correspond to a magnitude 5 earthquake at 15 km depth and 50 km hypocentral distance; in the period range between 0.07–1.0 s, our relation predicts larger PSAs than those of García et al. (2005))

CONCLUSIONS

We used data from a network of 12 autonomous digital accelerographs that operated for eight months in the state of Colima, to obtain the first attenuation equations validated with data for this region. The data of the temporary array was complemented with data from the five permanent digital accelerographs recently installed in Colima. We used the two-stage procedure proposed by Joyner and Boore (1981), as modified by Fukushima and Tanaka (1990) and Chang et al. (2001), to develop attenuation equations for average horizontal PGA, vertical PGA, horizontal PSA (at 10 period values between 0.07 and 1 s), and vertical PSA (at 9 period values between 0.07 and 0.8 s).

We have observed that, at close ranges, our predicted values are similar to those predicted by Ordaz et al. (1989), Fukushima and Tanaka (1990), and Youngs et al. (1997) and larger that those predicted by García et al. (2005) and Atkinson and Boore (2003). For distances larger than 100 km, our results predict larger values. Thus, our relations predict higher accelerations at Colima for the subduction zone earthquakes and suggest that the ground motion models derived using data from Guerrero may not be appropriate for other sections of the subduction zone.

We do not have data to validate our results for large earthquakes. However, the 2003 event provides an indication that supports these results. This event (M_w = 7.6) was recorded by a single accelerograph located in Manzanillo, 100 km from the epicentre. The attenuation relation by García et al. (2005) predicted a horizontal PGA of 1.05 m/s^2 (105 gal) and a horizontal PSA of 1.51 m/s^2 (151 gal) at a period of 0.4 s at that location. The observed average horizontal PGA at Manzanillo was 3.29 m/s^2 (329 gal) and the observed average horizontal PSA was 4.70 m/s^2 (470 gal) at 0.44 s period. This suggests that García et al. (2005) underpredict PGA and PSA in the region of Colima.

Our results are a first estimate of the attenuation for the western part of Mexico; however, they have some limitations. One of them is that we did not explicitly consider site effects for the four stations (out of 17) that we had installed on soft soils. However, H/V spectral ratios have suggested that the local amplification may not be important at those four stations in the frequency band where our data is useful. In addition, analysis of the residuals has indicated that soft soil stations do not show a systematic bias and that these residuals are indistinguishable from those computed for the firm soil stations. Site effects are important though, and future studies may not neglect them safely. In addition, our results are strongly limited by the small magnitudes that we could record during the field experiment. Possible differences between the ground motion models derived from weak and strong motions have been discussed by, for example, Douglas (2003), and Bragato and Slejko (2005). It may also be useful to compare ground motion models for different sections along the subduction zone in terms of variance (Douglas, 2004). However, currently there is not enough data for this. The small magnitudes of the earthquakes recorded over the eight-month period show how small is the seismic activity in the northern section of the subduction zone, as compared to that in the Guerrero region where more than 25 earthquakes with magnitudes larger than 3.5 are recorded every month. However, despite the low seismicity levels, large earthquakes do occur in this section. As some permanent instruments have been installed recently, we expect that our estimates will be improved in the near future with the help of new data and that this will allow a better understanding of the seismological character of the subduction zone and its variation along the trench.

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