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Discussions

On the behavior of site effects in Central Mexico (the Mexican Volcanic Belt – MVB), based on records of shallow earthquakes that occurred in the zone between 1998 and 2011

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Abstract

The Mexican Volcanic Belt (MVB) is a seismogenic zone that transects the central part of Mexico with an east–west orientation. The risk and hazard seismic of this seismogenic zone has not been studied at detail due to the scarcity of instrumental data as well as because seismicity in the continental regimen of Central Mexico is not too frequent, however, it is known that there are precedents of large earthquakes ($M_w > 6.0$) that have taken place in this zone. The Valley of Mexico City (VM) is the sole zone, within the MVB, which has been studied in detail; mainly focusing on the ground amplification during large events such as the 1985 subduction earthquake that occurred in Michoacan. The purpose of this article is to analyze the behavior of site effects in the MVB zone based on records of shallow earthquakes (data not reported before) that occurred in the zone between 1998 and 2011. We present a general overview of site effects on the MVB, a classification of the stations in order to reduce the uncertainty in the data to obtain attenuation parameters in future works, and some comparisons between the information presented here and that presented in previous studies.

A regional evaluation of site effects and Fourier Acceleration Spectrum (FAS) shape was estimated based on 80 records of 22 shallow earthquakes within the MVB zone. Data of 25 stations were analyzed. Site effects were estimated by using the Horizontal-to-Vertical Spectral Ratio (HVSR) methodology. The results show that seismic waves are less amplified in the northeast sites of the MVB with respect to the rest of the zone and that it is possible to classify two groups of stations: (1) stations with Negligible Site Amplification (NSA) and (2) stations with Significant Site Amplification (SSA). Most of the sites in the first group showed small (< 3) amplifications while the second group showed amplifications ranging from 4 to 6.5 at frequencies of about 0.35, 0.75, 15 and 23 Hz. With these groups of stations, average levels of amplification were contrasted for the first time with those caused by the subduction zone earthaquakes. With respect to the FAS shapes, most of them showed similarities at similar epicentral distances.

Finally, some variations of site effects were found when compared to those obtained in previous studies on different seismicity regions. These variations were attributed to the location of the source.

These aspects help to advance the understanding about the amplification behavior and of the expected seismic risk on the Central Mexico due to large earthquakes within the MVB seismogenic zone.

1 Introduction

The MVB is related to the subduction of the Rivera and Cocos plates below the continental North American plate (Singh et al., 2007; Ferrari et al., 2012). In general, the regional tectonics in the MVB have shown to be of extensional type with the minimum compressive stress in the north–south direction (Suter et al., 2001). The stress state of the MVB area, has been inferred largely from major structures such as alignments, faults, barrier of volcanoes and dikes (e.g. Suter et al., 1995), because of the scarcity of instrumental seismicity data (Zuñiga et al., 2003). Several studies have suggested that due to the morpho-tectonic composition of the MVB, there are significant differences in the behavior of seismic signals originated from subduction earthquakes, to sites within the MVB as opposed to other reception sites (e.g. Shapiro et al., 1997; Ferrer-Toledo et al., 2004; Cruz et al., 2009). These studies suggest that the site effects may differ within the entire MVB. However, at present time there are not detailed studies focusing on these characteristics. However, most of the studies (e.g. Singh et al., 1995, 1988a; Ordaz and Singh, 1992; Chávez-García et al., 1994; Sánchez-Sesma et al., 1995; Chávez-García and Cuenca, 1996; Reinoso and Ordaz, 1999; Montalvo et al., 2000; Chávez-García and Salazar, 2002) have focused on the ground response within and around the Valley of Mexico (where Mexico City is located, hereafter referred to as VM).

The MVB is a zone of low seismicity compared to other seismogenic sources in Mexico. Few studies have been focused on this region (e.g. Astiz-Delgado, 1980;

Suárez et al., 1994; Suter et al., 1996; Zúñiga et al., 2003; Quintanar et al., 2004). Earthquakes within the MVB which caused destruction include the 1568 Jalisco earthquake which had a magnitude M_w estimated between 7.5 and 7.8 (Suárez et al., 1994); the 1912 earthquake occurred in Acambay, State of Mexico, with $M_w = 7.0$ (Singh and Suárez, 1987) and the 1920 earthquake which occurred in Jalapa, Veracruz with $M_s = 6.4$ (Suárez, 1992) these types of earthquakes represent an important risk due to their proximity to urban areas.

Previous studies on seismic signal behavior within the MVB, which have been based on the analysis of small zones of the MVB (mainly in or around the VM) have observed that there is variability in the amplified signal depending on the trajectories of analysis (e.g. Cruz et al., 2009) being significantly higher in the VM (e.g. Singh et al., 1988a, b; Shapiro et al., 1997; Reinoso and Ordaz, 1999). In the VM, amplitudes decrease rapidly toward the north (Figueroa, 1986), and the ground motion is commonly associated with longer durations (Kawase and Aki,1989). The velocity of the seismic waves is slower when they propagate through the MVB, but higher velocities have been recorded in the north section of the MVB in comparison with the south (Shapiro et al., 1997). Attenuation values show a low Q ($Q(f) = 98f^{0.72}$), as compared to the regional Q values ($Q(f) = 273f^{0.66}$) (Ordaz and Singh, 1992), determined from analysis of seismic signals recorded at the extremes of a section of the MVB from south to north, including the VM (Singh et al., 2007).

Site effects are attributed to the response of shallow geology. In Mexico, several methods for the evaluation of site effects with the use of ambient noise and earthquake records have been carried out (e.g. Lermo, 1992; Lermo and Chávez-García, 1993, 1994a, b). In particular the so-called Standard Spectral Ratio (SSR) (Borcherdt, 1970) and the Horizontal-to-Vertical Spectral Ratio (HVSR) (Lermo and Chávez-García, 1993) have been used. The HVSR method with ambient noise data, has been employed for seismic microzonation studies worldwide, providing a reliable fundamental frequency (e.g. Nath et al., 2009; Abd El-Aal, 2010; Gosar et al., 2010). However, the HVSR method evaluated with data from earthquake signals, besides the fundamental frequency, allows for the estimation a reliable amplification (Lermo and Chávez-García, 1993). Based on the HVSR method with the use of earthquake data, two types of seismic stations can be identified: (1) rock-ground and (2) soft-ground stations. This is possible since negligible site amplification (NSA) values at sites on rock is expected, while significant site amplification (SSA) values at sites on soft-ground (Castro and Ruíz-Cruz, 2005) should be found. However, SSA have occassionaly been observed in rock sites (e.g. Tucker et al., 1984; Castro et al., 1990; Humphrey and Anderson, 1992). This classification of sites has been fundamental in several studies of seismic attenuation models in the world in order to confidently estimate how seismic amplitude decreases with distance (e.g. Joyner and Boore, 1981; Mandal et al., 2009). In Mexico, the evaluation of site effects has also helped to establish reliable attenuation models (e.g. Ordaz et al., 1989; García, 2006; Clemente-Chavez et al., 2012).

Several studies have included stations within the MVB that have been classified as with NSA, but they did not use the seismicity source types analyzed in this paper (e.g. Singh et al., 2006, 2007; Lozano et al., 2009; García et al., 2009), so currently there is no published study based on seismicity records within the MVB for sources also in the MVB. Even when there are seismic stations located within and around this region, which have been identified as having NSA (e.g. Castro and Ruíz-Cruz, 2005; Singh et al., 2006, 2007; García et al., 2009; Lozano et al., 2009), it is necessary to compare the level of amplification of each station due to local sources to the values observed for regional sources.

In this article, the evaluation of site effects and estimates of Fourier Acceleration Spectral (FAS) shapes focusing on the MVB seismogenic zone at regional level are presented for the first time. This was possible due to the existence of a growing number and better-quality of seismic stations (broadband seismometers and accelerographs) in the MVB zone. We study the behavior of site effects in the MVB zone based on records of shallow earthquakes (data not reported before) that occurred in this region between 1998 and 2011. We furthermore provide a general overview of site effects in the MVB. A classification of the stations is also given to help future studies of attenuation parameters.

Some site effect results based on the type of shallow seismicity of this study are compared with results of previous studies (e.g. Singh et al., 2006, 2007; Lozano et al., 2009; Castro and Ruíz-Cruz, 2005). These authors have reviewed only a few stations within or around the MVB based on inslab seismicity and interplate seismicity. None of these studies have focused on showing a regional site effect characteristics as presented in this study, much less with earthquakes occurring within the MVB. An exposition and discussion of some of the FAS shapes of the earthquakes also is presented. Finally, a comparison of these results was made with the amplification levels that García et al. (2009) reported for a zone outside the MVB (an area between the Mexican Pacific coast and the MVB); due to the interplate seismicity that occurs in the Mexican Pacific. It has been shown that this interplate seismicity represents the greatest seismic hazard for Central Mexico.

This study presents the first steps for the analysis of regional seismic hazard and risk due to the shallow seismicity present in this central zone of Mexico.

2 Data

A total of 80 records of 22 shallow earthquakes were used (see Table 1); of these, 77 records are of earthquakes with magnitudes between $4.0 \leq M \leq 4.3$ and the three remaining records correspond to two earthquakes of $M < 4$. These last three records were included for their contribution to a better evaluation of site effects at DHIG and JUR1 stations (located north of the MVB, see Fig. 1). All the selected earthquakes were recorded at epicentral distances within the range of 3.4–286 km and with depths of $H \leq 10$ km and occurred within the MVB during the period between 1990 and early 2011. The records were provided by the major seismic networks in Mexico (Tables 1 and 2).

For the purpose of obtaining a site effect average for each station, we selected only stations with at least two records. From this group, the first 13 stations in Table 2 were selected (12 seismographic stations and one acelerograph station). All records were converted to acceleration.

The remaining 12 stations in Table 2 (which have a single record) were analyzed trying to form groups of closely spaced stations to get their averages. Nine of these stations are located in the area of VM; and the three remaining stations are located in the states of Colima, Michoacan and Mexico. These nine stations were subgrouped according to the three known geotechnical zones within the VM (lakebed zone, transition zone and hill zone) (e.g. Reinoso and Ordaz, 1999) in order to obtain three representative H/V averages of each zone. It was not possible to group the last 3 stations due to their geographic dispersion, so the site effects were estimated separately.

The location of earthquakes and the stations are shown in Fig. 1, a division of the zone in four quadrants is also shown and will be discussed later.

3 Methodology

The Horizontal-to-Vertical Spectral Ratio (HVSR) method (Lermo and Chávez-García, 1993) was used to estimate the site effects. First, the records were visually inspected to select signals that are complete and that had a good signal-to-noise ratio $(S/N) \geq 2.0$. A baseline correction was applied to all the signals. For the spectral analysis only the strong ground motion was considered, taking different time-window lengths of 5–40 s starting from the S wave onset.

Two software packages were used for data processing: Degtra (Ordaz and Montoya, 2000) and Geopsy (Geophysical Signal Database for Noise Array Processing) (SESAME WP05, 2002). The results of these programs were compared because they have a different smoothing function in obtaining FASs, which are the basis to evaluate the H/V spectral ratios.

To determine the HVSR transfer functions, the FASs were calculated for the three components of each record. This is done automatically when estimating the H/V ratio with the Geopsy software. For the calculation of FAS for each selected window, a smoothing function defined in Eq. (1) (Konno and Ohmachi, 1998) was applied with a band width coefficient of $b = 40$ and a 5 % cosine taper-window. This type of smoothing function employs a different number of points at low and high frequency; its use is strongly recommended for frequency analysis (Konno and Ohmachi, 1998). The results are very similar in comparison with Degtra software results with a smoothing factor $F_s = 6$, which contains another type of smoothing function defined in Eq. (2). A comparison of these results is shown in Fig. 2.

$$A_s(f, f_c) = \left[\frac{\sin\left[\log_{10}(f/f_c)^b\right]}{\log_{10}(f/f_c)^b}\right]^4, \tag{1}$$

$$[A_s(f)]^2 = \frac{1}{N}\sum [A(f)]^2, \tag{2}$$

$$f_1 = f \cdot 2^{\left(-\frac{1}{2F_s}\right)} \quad f_2 = f \cdot 2^{\left(\frac{1}{2F_s}\right)} \tag{3}$$

In Eq. (1), $A_s(f, f_c)$ represents the smoothed amplitude; b, f and f_c are coefficients for band width, frequency, and center frequency, respectively. In Eq. (2), $A_s(f)$ represents smoothed amplitude based on frequency f. The sum is made in the range defined by frequencies f_1 and f_2, of Eq. (3) and N is the number of points between frequencies f_1 and f_2.

The results of both programs did not show significant differences. Each program had advantages according to the available tools. Geopsy software was used to evaluate spectral ratios H/V, and Degtra software to estimate FAS shapes separately for each horizontal component.

We obatained HVSR transfer functions for all the records of the 25 stations. For this purpose H was defined as the square average of FAS of the horizontal components.

Afterwards, for each group of earthquakes recorded at each station site, H/V averages were calculated with their standard deviations and plotted on a logarithmic scale.

Finally, FASs were obtained for each horizontal component of records of earthquakes with greater azimuthal coverage. This was performed with the aim of qualitatively analyzing the behavior of the shapes and amplitudes in the FASs for different trajectories of seismic wave propagation.

4 Results and discussion

Figure 3 shows averages and standard deviations of the H/V spectral ratios for the 13 stations analysed as well as for the three zones within the VM (Fig. 1) in order to estimate the site effects. Moreover, Table 3 shows all the estimated site effects grouped by quadrants in the MVB. Results are given for the fundamental frequency (f_o), the amplification factor (A_o) and values of other peaks in frequencies with smaller amplitudes.

Most of the ratios of Figs. 3 and 4 show a greater and more frequent variability at a frequency of about 0.5 Hz as compared to other frequencies. This coincides with the observations of Singh et al. (2007) which analyzed interplate earthquake data from two stations in order to estimate Q for a strip in the MVB. On the other hand, Table 3 and Fig. 5 show that stations LVIG, DHIG, JUR1 and MOIG can be considered as reference stations to estimate relative amplification in the MVB zone, due to a low A_o ($A_o < 2.7$), as well as an almost flat level in the H/V espectral ratio.

With the objective of providing a general overview of site effects in the MVB, in Fig. 5 we include the H/V spectral ratio averages show in Fig. 3, as well as three evaluations of site effects at stations with a single record (COMA, CANA and TXCR). This information is plotted as a function of period and according to its geographical position associated to each site. Information of this type is often used to relate with the structural periods in order to evaluate the expected damage due to an earthquake.

Figure 5 shows the following key points in each MVB quadrant:

1. The sites evaluated in quadrant II indicate lesser amplifications than the sites at other quadrants. On the contrary, the greatest amplifications of seismic signals occur – in decreasing order – at sites in quadrants I, IV and III, with an amplification factor of up to 6.2, mostly at low frequencies of 0.1–2 Hz (or 10–0.5 s);

2. All sites of the four quadrants have up to three peaks with amplitudes of around 2, except for PLIG, which presents a single well-defined peak. This could be a clear difference in site effects for stations within and outside the MVB, since PLIG is regarded as outside the MVB. CJIG station, also outside the MVB, shows similar behavior.

3. Important differences on the averages of site effects for two of the three zones within the VM were identified with respect to those given by Reinoso and Ordaz (1999) in their analysis based on large earthquakes (magnitude between 7.4 and 8.1) of the subduction type. In the transition zone our results are similar to those of Reinoso and Ordaz (1999). On the other hand, in the southern part of the lakebed zone, our results do not show large values (values between 50 and 75) of amplification in the range of 3–4 s as those obtained by these authors for this period. However, our results agree with them in a second peak at about of the period of 1.5 s with amplification of about 10.

The results of Table 3 were further used to classify the stations. This clasification is according to the criteria shown in previous studies on site effects in Mexico (e.g. Lermo and Chávez-García, 1993; Bard, 1999; Castro and Ruíz-Cruz, 2005; García et al., 2009). They consider a site as having a NSA when A_o is ≤ 2.5–3.0 at the fundamental frequency f_o (as it occurs for most hard-rock sites) and, conversely, they assign an SSA label to sites with $A_o > 3$. Thus, seven stations (JUR1, DHIG, LVIG, MOIG, CJIG, YAIG and PLIG) present NSA and six (ANIG, IGIG, CDGU, COIG, CUIG and PPIG) have SSA. However, in this study, YAIG and PLIG stations were placed in the group of stations with NSA, even though they showed amplifications between 3.35 and 3.81.

This is because: (a) they have a flat performance ($H/V < 2$) for most of the frequency range (0.01—30 Hz) (see Figs. 3 and 5); and (b) their site amplification values do not significantly alter the average for this group of stations (see Fig. 4).

In order to show the behavior and differences between the two groups of stations (with clasification NSA and SSA), we estimated the averages for both groups. These averages are shown in Fig. 4 which indicate that the main differences lie in the low frequency range of 0.1–1.0 Hz. The averages of the three zones within the VM were not considered in the above averages because they do not represent the general characteristics of the MVB, due to the large amplifications observed for that particular region. Only CUIG station has been included for such averages since its H/V ratio is close to those which represent site effects within the MVB.

Of the analized stations in this study it is clear that a low amplification occurs in quadrant II, compared to the rest of the MVB area. The causes of this behavior can be due to the wave velocity in the north being higher than in the southern part of the MVB as reported by Shapiro et al. (1997) for a strip in the zone. These authors associated this low velocity zone with the migration of volcanic activity from north to south, such as reported in Robin (1981). Recently, Singh et al. (2007) reported a higher attenuation, – low Q – in the northern part of the MVB with respect to the forearc (based on the station DHIG). Jödicke et al., 2006 also showed a correlation between this low Q and a low resistivity region. From the above arguments, and according to our results, this behavior might cover a larger area within the MVB, delimited by quadrant II.

With respect to FAS, several FAS shapes of the horizontal components were estimated, in order to compare the decay of the amplitudes at each signal frequency with respect to the epicentral distance. This was made for earthquakes 10, 17 and 18 in Table 1, which have the largest number of records in quadrants I, II and IV, besides having a similar magnitude. The location and FAS shapes of these earthquakes for each site are shown in Fig. 6. From this, the following aspects can be discerned:

1. In quadrants II and IV, the FAS estimated near the source of earthquakes 10 and 18, registered at YAIG and DHIG at distances of 37 and 3 km, respectively, show

that their largest amplitudes occur at high frequencies (the range of 15–20 Hz). This FAS are similar to FAS at the source according to the model presented by Haddon (1996);

2. In records at distances greater than 100 km, the highest amplitudes of the FAS shapes are in the range of frequencies from 1 to 10 Hz. This occurs at sites in quadrants I, II and IV, except for YAIG station, which retains its highest amplitudes at high frequencies of around 21 Hz;
3. The values of the maximum amplitudes are very similar between quadrants I, II and IV, except for the earthquake 17, recorded at stations IGIG, MOIG and PLIG. It showed greater attenuation at low frequencies ($f \leq 6$ Hz) than at high frequencies (about 15 Hz);
4. The FAS shapes obtained from each horizontal component for each record showed little variability between them. The largest difference takes place at low frequencies (less than 1 Hz).

In Fig. 7, an analogous analysis to that shown in Fig. 6 was made for earthquake no. 11 whose epicenter is in the center of the MVB, recorded in three sites located in quadrants II, III and IV. There was a fourth record at MOIG station, which is located at a close distance from the epicenter ($R = 8.5$ km). The three records are from DHIG, COIG and PLIG stations, with similar epicentral distances (with an average of $R = 247$ km). Key points from this analysis are:

1. The FAS obtained close to the source, from the record in MOIG station, shows its maximum amplitudes at about 1 Hz as opposed to previous cases, in which their maximum amplitudes appeared at high frequencies (the range of 15–20 Hz), for similar epicentral distances (3 and 12 km) as MOIG station ($R = 8.5$ km);
2. When the four FAS shapes are superimposed (Fig. 7g), it is clear that the signal at DHIG presents larger attenuation in the 0.3–10 Hz frequency range;

3. To better understand the latter point, the seismograms recorded in the four stations are shown in Fig. 7f. In DHIG record, smaller amplitudes are observed at high frequencies as well as, partially, at low frequencies compared to the other north–south records.

Comparing our results to those from previous studies, we find the following.

Chávez-García and Tejeda-Jácome (2010) presented an evaluation of site effects in Tecoman, Colima, Mexico, an area close to the MVB. These authors used interplate earthquake records with epicentral distances of about 100 km. In their results they reported two peaks. The first peak is the fundamental frequency of the site that varies between 0.5 and 0.7 Hz, with an amplification factor that varies between 6 and 8. A second smaller amplitude peak was also shown in their results, with an amplification of about 4 in the range of 1.2–2.1 Hz.

Of all the sites analyzed in the present study, the closest to Tecoman is the COIG station. In the present study three well-defined peaks instead of only two were identified for that site. The first peak corresponds to a fundamental frequency $f_o = 0.28$ Hz with amplification factor $A_o = 4.64$; these values differ from those reported in the Tecoman study. The two other peaks ($f_1 = 1.30$ Hz with $A_1 = 3.72$ and $f_2 = 2.17$ Hz with $A_2 = 3.37$) are similar to the second peak values reported in the Tecoman study.

Site amplification averages from the MVB are contrasted for the first time to averages for other trajectories (within the zone know as subduccion) which do not cross the MVB. The latter was reported by García et al. (2009). The results of these authors were based on records of interplate seismicity that occurred at the Mexican Pacific Coast. They obtained H/V averages for two groups of stations with NSA: (a) a group of inland stations and (b) a second group made up of coastal stations (see Fig. 8). Figure 8 shows the differences in site amplification averages of stations on rock at regional level, classified with NSA, outside and inside of the MVB. As seen in Fig. 8, an amplification factor of up to 1.5 times at a frequency of 0.36 Hz, is shown for MVB stations with respect to the amplification level of inland stations. On the other hand, when compared with coastal stations averages, the behavior is similar. This similarity may be due to the proximity to the seismic source. In frequency ranges from 1 to 5 Hz, the average levels of amplification at MVB station sites are very similar to the levels of both groups of stations (inland stations and coast stations).

Finally, Table 4 shows other comparisons of A_o and f_o from previous studies (which were based on interplate seismicity), with the results of this study. This is for specific stations. In general, the main differences are in A_o with an increment to up a 150 % compared to previous studies.

5 Conclusions

The Mexican Volcanic Belt (MVB) is a seismogenic zone that has not been studied at detail in terms of its hazard. This is due to the scarcity of data and the low seismicity in the continental regimen of Central Mexico. However, there are precedents of large earthquakes ($M_w > 6.0$) within the MVB. Now, in this study, seismic data from this seismogenic zone were gathered in order to advance the understanding about the expected regional hazard and seismic risk in Central Mexico. Eighty records of 22 shallow earthquakes (obtained of 25 station of the main seismic networks of Mexico during the last 13 yr) that occurred within the MVB zone were used to determine site effects and Fourier Acceleration Spectra (FAS). The purpose of this study was to show the behavior of site effects in the zone through a general overview, a classification of seismic stations and comparisons with previous studies.

In general, our study yielded the following:

1. A difference in the level of amplification in the MVB zone was identified. The results show that site effects in the northeastern part of the MVB present a lesser level of amplification compared to the rest of the zone. This difference coincides with the results of Shapiro et al. (1997) in their study of a strip (north to south) of the MVB across the Valley of Mexico. However, in the present study the results showed that this behavior covers a greater area of the MVB, corresponding to approximately a quarter of the total MVB area. The average H/V spectral

ratios indicate an amplification factor of 2.5 at a frequency of 0.38 Hz. On the other hand, the attenuation of the signals was analyzed qualitatively with FAS shapes to examine the difference in behavior (e.g. frequency ranges in the maximum amplitudes) between different propagation trajectories within the MVB. FAS shapes obtained for the horizontal component records showed a uniform behavior within the MVB, mainly for frequencies $f \geq 1$ Hz. However, only one trajectory showed greater attenuation in the northeast part of the MVB. This trajectory starts from the center to the northeast of the zone (see Fig. 7).

2. From the 13 stations analyzed on rock two groups were identified: (1) seven stations with negligible site amplification (NSA) and (2) six stations with significant site amplification (SSA). The first group of stations in general presented amplification factors of 4–6.5 at frequencies of about 0.35, 0.75, 15 and 23 Hz. From this classification, the first group shows an amplification average similar to the sites analyzed by García et al. (2009) for coastal stations, which were also classified as negligible.

3. NSA and SSA average levels of amplification based on shallow seismicity within the MVB region are analyzed for the first time. We observed amplification differences with respect to the zones outside of the MVB (in particular between the Mexican Pacific coast and the MVB). The most important difference is that in the MVB there is an amplification of up to 1.5 times more that found by García (2009) for the Pacific coast in the frequency of 0.36 Hz. This result highlights the relevance of further studying the hazard within the MVB.

Finally, the dependence of site effects results with the characteristics of the source was analyzed. Variations of site effects were found when compared to those obtained in previous studies on different seismicity regions. These variations were attributed to the location of the source. Moreover, we identified more than one peak as the fundamental frequency (we attribute such behavior as typical of the MVB), as opposed to previous studies, in which only one peak was identified.

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Table 1. Earthquakes analyzed in this study.

Earthquake No.	Date	Latitude (° N)	Longitude (° W)	H (km)	M^*	Epicentral Location (State)	Number Records	Epicentral Distance R (km)
1	18 Mar 1998	20.10	99.23	5	4.3	Hidalgo	6	69–85
2	27 Apr 1998	19.04	98.51	2	4.0	Puebla	1	13
3	4 Mar 2000	18.84	98.57	4	4.1	Puebla	3	26–110
4	12 Mar 2000	20.10	99.29	5	4.1	Hidalgo	3	134–190
5	5 Aug 2001	20.47	103.67	10	4.3	Jalisco	2	143 and 180
6	3 Nov 2002	19.26	98.04	2	4.0	Tlaxcala	2	65 and 182
7	16 Nov 2002	19.17	98.49	9	4.1	Puebla	5	18–226
8	4 Feb 2003	18.92	98.51	2	4.1	Puebla	2	21 and 120
9	28 Apr 2003	19.55	103.46	4	4.0	Jalisco	2	47 and 166
10	16 Nov 2003	19.18	98.97	7	4.0	Distrito Federal	13	11–242
11	5 Dec 2003	19.72	101.25	7	4.3	Michoacán	4	8–263
12	15 Dec 2003	20.35	99.07	4	4.0	Hidalgo	7	7–286
13	7 Oct 2004	20.81	103.48	5	4.2	Jalisco	2	219 and 268
14	5 Jun 2005	19.44	103.55	5	4.2	Colima	2	32 and 157
15	5 Dec 2007	18.64	102.22	4	4.1	Michoacán	2	27 and 153
16	29 Nov 2009	19.36	103.76	5	4.0	Colima	2	50 and 136
17	17 Apr 2010	20.38	98.96	2	4.1	Hidalgo	8	12–251
18	18 May 2010	20.27	99.04	3	4.3	Hidalgo	9	3–281
19	18 May 2010	20.35	98.92	5	3.6	Hidalgo	2	44 and 195
20	20 May 2010	20.34	98.89	2	3.9	Hidalgo	1	167
21	3 Oct 2010	19.48	103.52	6	4.0	Jalisco	3	25–203
22	8 Feb 2011	19.73	104.51	5	4.0	Jalisco	1	147

M^* = Magnitude reported by Servicio Sismológico Nacional (SSN) (http://www.ssn.unam.mx/).

Table 2. Classification of the database by seismic network with its stations.

Institution	Seismic network	Station name	Site geology	Number of records			Instrument type
				/Station	/Network	/Network %	
Servicio Sismológico Nacional (SSN), Instituto de Geofísica (IG) Universidad Nacional Autónoma de México (UNAM)	SSN (IG-UNAM)	PPIG	Rock	10	62	77.5	Broadband seismographs. Most of them are composed of a STS-2 sensor and Q330 digitizer. Most of their recordings are at 80 samples per second (sps), while a few are at 100 sps.
		YAIG	Rock	9			
		PLIG	Rock	8			
		MOIG	Rock	7			
		CUIG	Rock	6			
		DHIG	Rock	6			
		CJIG	Rock	5			
		COIG	Rock	4			
		LVIG	Rock	3			
		IGIG	Rock	2			
		ANIG	Rock	2			
Centro de Geociencias (CGEO) in Juriquilla, Querétaro, Campus UNAM	CGEO (UNAM)	JUR1	Rock	4	4	5.0	Broadband seismograph. Composed of a Trillium 120P sensor and a Taurus digitizer. All its records are at 100 sps.
Instituto de Ingeniería (II), UNAM	II-(UNAM)	CDGU	Rock	2	5	6.3	Accelerographs. With Etna episensor. Their records are at 100, 200 or 250 sps.
		COMA	Rock	1			
		CANA	Rock	1			
		TXCR	Rock	1			
Centro de Instrumentación y Registro Sísmico A.C. (CIRES)	CIRES	CI05	Clay	1	8	10	Accelerographs. Models SSA-1 and RAD-851. Most of their recordings are at 200 sps, while a few are at 100 sps.
		GR27	Clay	1			
		UI21	Sand	1			
		DX37	Clay	1			
		SI53	Clay	1			
		TH35	Clay	1			
		TP13	Sand	1			
		XO36	Clay	1			
Centro Nacional de Prevención de Desastres (CENAPRED)	CENAPRED	CNPJ	Rock	1	1	1.2	Accelerograph. Model Altus K2. Its record is at 100 sps.
					80		

Table 3. Results of the estimation of site effects grouped by quadrants in the MVB. It shows the following: fundamental frequency identification (f_o), amplified factor (A_o), the classification of the amplification level at each seismic station site, values of other peaks at frequencies with smaller amplitudes and the number of records used in each evaluation of the sites.

Quadrant no.	Station name or zone	f_o (Hz)	A_o	Classification of the site amplification level	f_1 (Hz)	A_1	f_2 (Hz)	A_2	f_3 (Hz)	A_3	Number of Records
I	ANIG	16.58	4.97	S	0.25	3.36	0.35	3.29	–	–	2
	IGIG	0.75	6.20	S	23.59	5.80	14.82	5.80	–	–	2
II	JUR1	0.37	2.52	N	0.92	2.20	2.10	2.45	4.56	2.40	4
	DHIG	0.50	2.46	N	0.25	2.13	0.35	1.78	–	–	6
	LVIG	0.45	2.23	N	1.65	1.95	2.89	2.16	5.06	2.00	3
	MOIG*	0.20	2.65	N	0.13	2.43	0.40	2.31	1.00	2.07	7
III	CDGU	0.35	4.02	S	8.19	2.95	9.85	3.31	–	–	2
	CJIG	1.94	2.26	N	0.67	2.23	0.23	2.19	–	–	5
	COIG	0.28	4.64	S	1.30	3.72	2.17	3.37	–	–	4
IV	CUIG	0.17–0.22	5.05–4.93	S	0.70	3.40	10.75	2.54	–	–	6
	PPIG	12.52–14.01	5.53–5.61	S	0.67	4.20	0.05	4.19	0.35	4.05	10
	YAIG	0.70	3.35	N	0.40	2.75	4.05	2.37	–	–	9
	PLIG	0.35	3.81	N	–	–	–	–	–	–	8
	HILL	0.60	5.83	S	1.07	3.98	–	–	–	–	3
	TRANSITION	1.33	11.56	S	1.07	11.11	0.33	3.82	0.13	3.16	2
	LAKEBED	0.67	9.48	S	–	–	–	–	–	–	4

S = Significant, N = Neglible.

* Considered in quadrant II, due to its behavior in H/V spectral ratio, in addition to its central location in the MVB.

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Table 4. Comparisons of A_o and f_o (at sites of stations), reported in previous studies with the results of this study.

Authors	ID Station	Previous studies f_o (Hz)	Previous studies A_o	This study f_o (Hz)	This study A_o	Increase in A_o
Castro and Ruíz-Cruz (2005)	YAIG	≈ 5.0	≈ 2.5	0.7	3.35	34 %
Singh et al. (2007)	PLIG	≈ 0.7–0.8	< 2.0	0.35	3.81	91 %
	DHIG	≈ 0.5–0.6	< 2.0	0.5	2.46	23 %
Lozano et al. (2009)	CUIG	0.2–0.7	1.0–3.0′	0.17–0.22	5.05–4.93	68 %
	PLIG	≈ 4.0–5.0	< 1.5	0.35	3.81	154 %

(≈ results observed in their results).

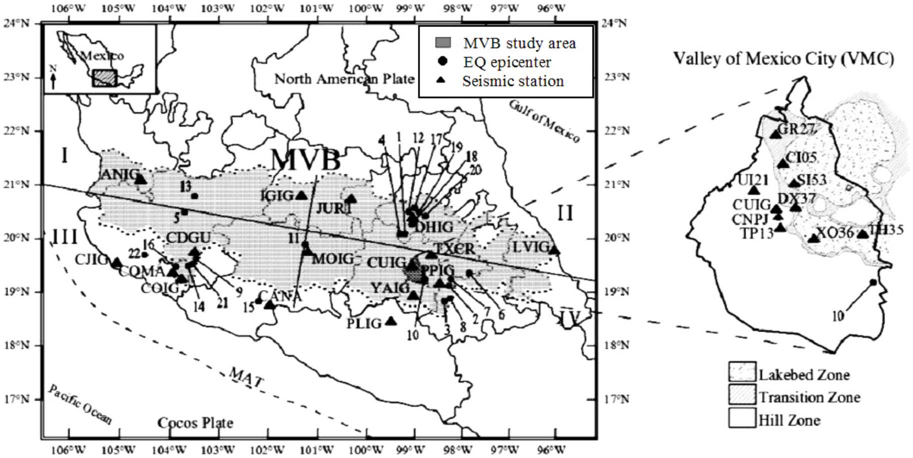

Fig. 1. Map of the Mexican Volcanic Belt (MVB) according to Gómez-Tuena et al. (2005); location of: epicenters in Table 1, seismic stations in Table 2, and the zone divided in quadrants (this in solid straight lines) are shown. To the right, the VM located within the Distrito Federal, stations and the classification of the three geotechnical zones are also shown.

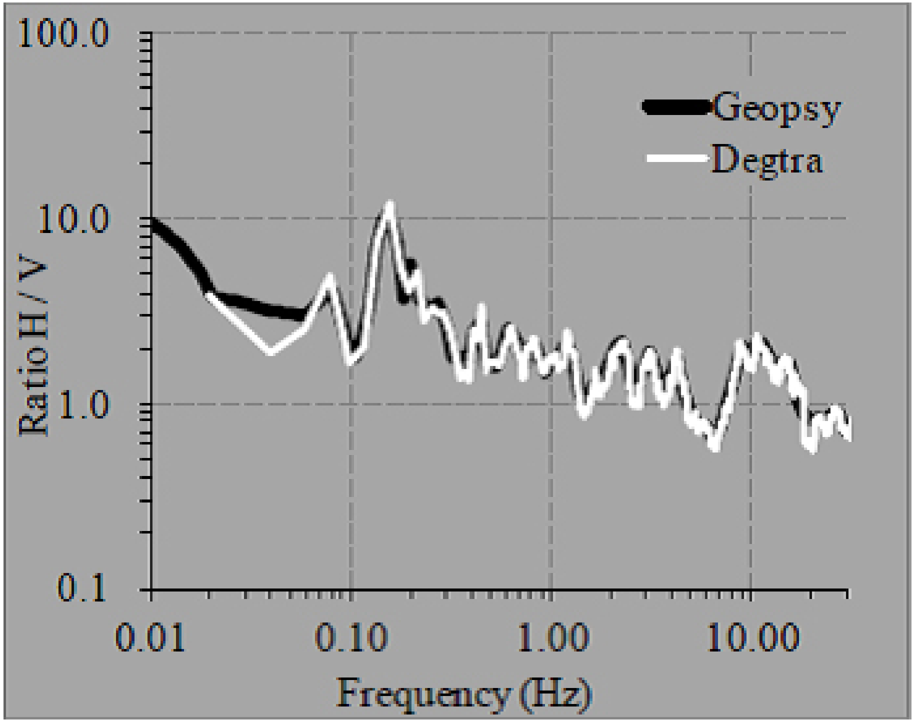

Fig. 2. Comparison of H/V results of the Geopsy and Degtra softwares are shown. Observe that the ratios are similar although the smoothing functions are different.

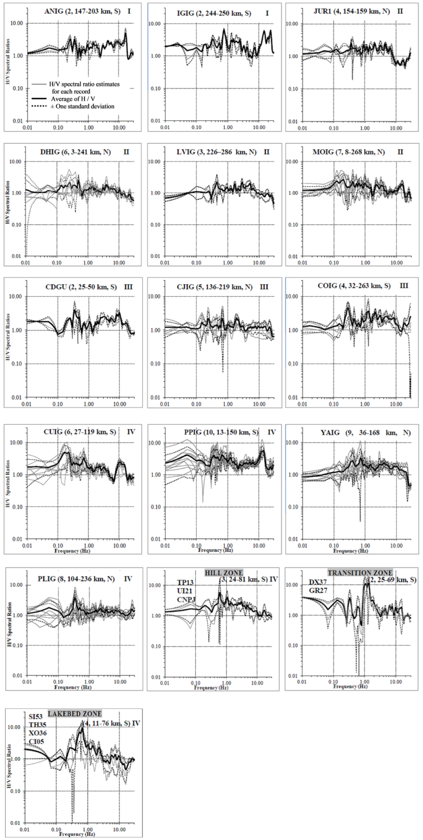

Fig. 3. Averages of H/V spectral ratios ± one standard deviation for all stations are shown. The headers in each graph correspond to the following nomenclature: station (number of records, epicentral distance range in km, site classification: N = negligible site amplification or S = significant site amplification) and quadrant number. The last three graphs correspond to averages of grouped stations within each geotechnical zone in the VM, this according to Fig. 1.

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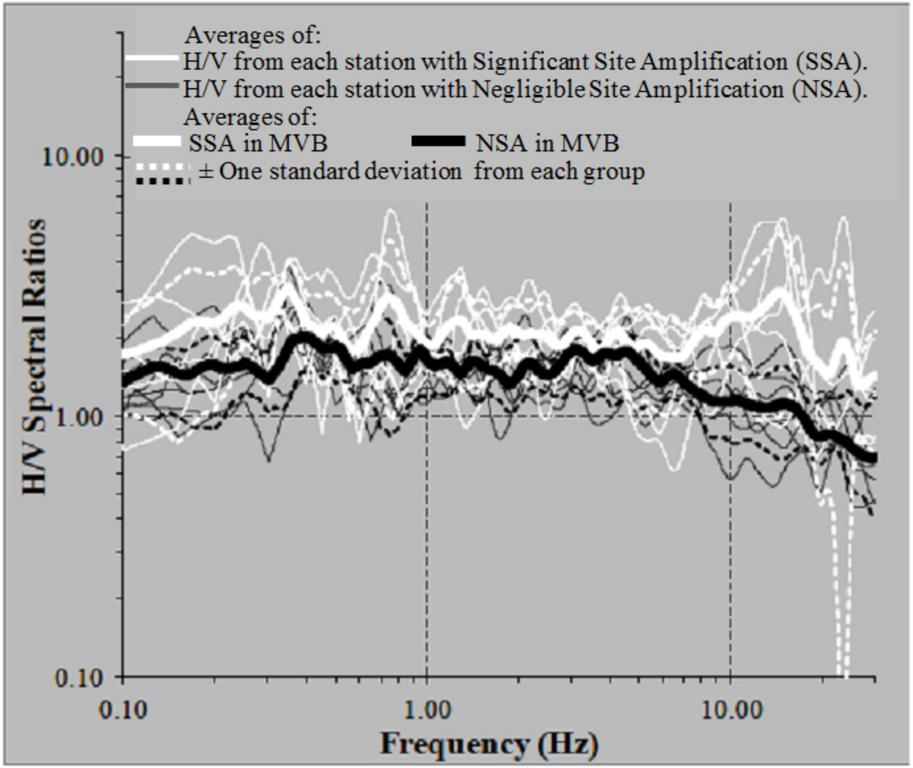

Fig. 4. Comparison of the behavior and differences of site amplification between the two groups of stations within the MVB: (1) with SSA and (2) with NSA. Both groups are shown with ± one standard deviation. Observe that the main differences are in the low frequency range of 0.1–1.0 Hz. Averages of all the stations, which form each group, are also shown.

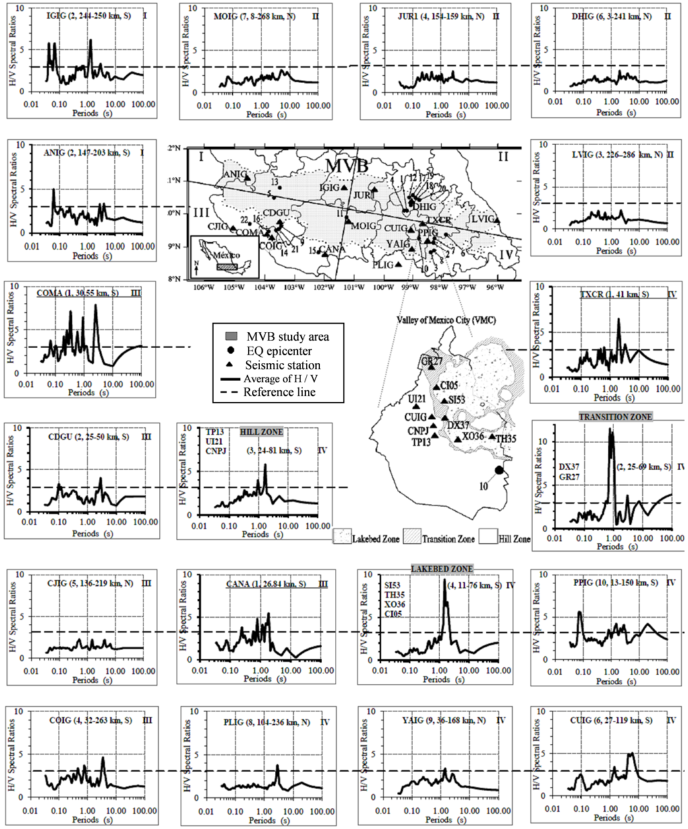

Fig. 5. A general overview of site effects in the MVB is shown. Note: A smaller site amplification in the northeast part of the MVB (quadrant II) than those of the other quadrants. (The three stations with a single record: COMA, CANA and TXCR are also included).

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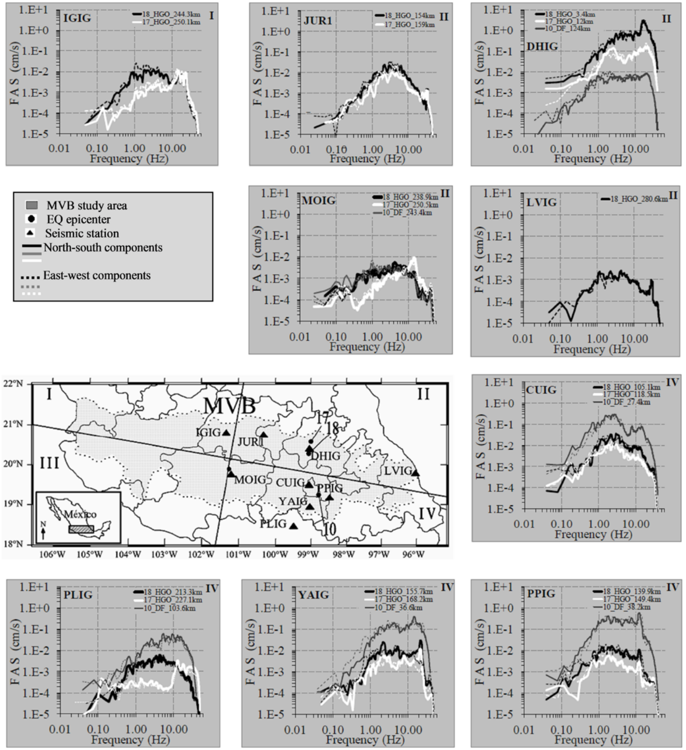

Fig. 6. Comparisons of the decay of the amplitudes among the Fourier acceleration spectra (FAS) of the earthquakes 10, 17 and 18 (with the largest number of records and of similar Magnitude $M \approx 4$) in Table 1 of site differents within the MVB are shown. FAS shapes are of the horizonal components. The legends in each graph indicate: earthquake no., epicenter location, and epicentral distance (HGO = Hidalgo State, DF = Distrito Federal).

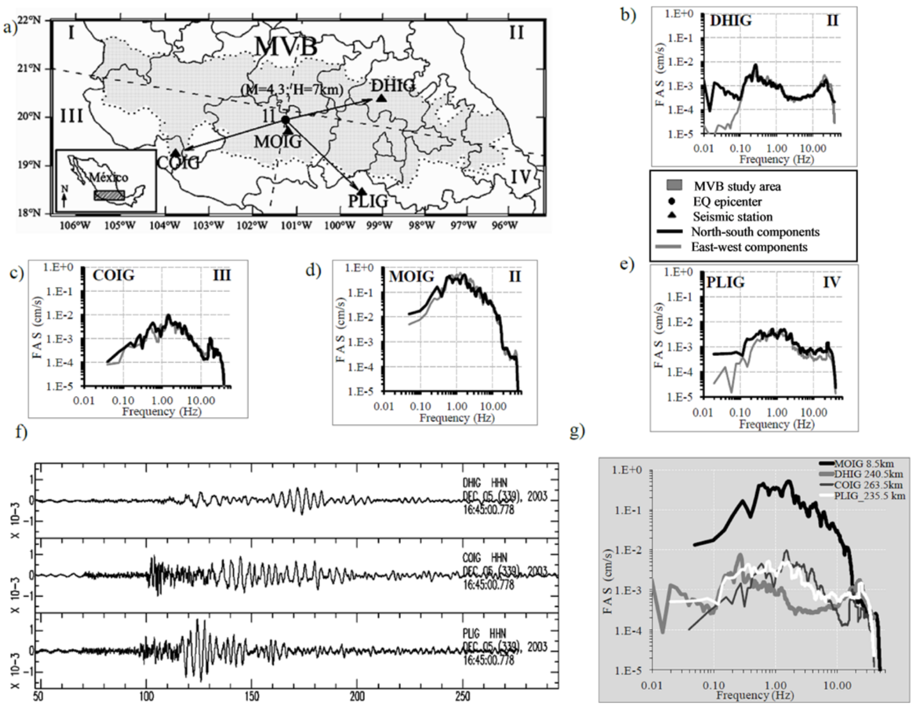

Fig. 7. In **(a)–(e)**, Fourier acceleration spectra (FAS) of the earthquake 11 in Table 1 for the station sites MOIG, COIG, PLIG and DHIG (with similar epicentral distances) are shown; in **(f)** seismograms of the north–south component of the COIG, DHIG and PLIG stations are also shown; and in **(g)** FAS shapes of the north–south components of the four stations are superimposed, where the greater attenuation is observed at DHIG site (at frequencies of 0.3–10 Hz) with respect to COIG and PLIG sites.

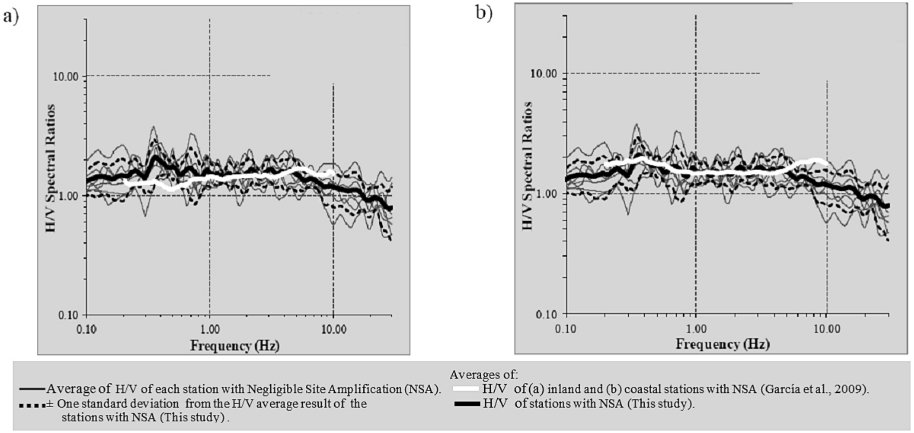

Fig. 8. Comparisons of averages of site effects with NSA between those reported by García et al. (2009) – sites with trajectories in the subduccion zone – and the results of this study are shown. The results of García et al. (2009) are shown for **(a)** inland stations and **(b)** coastal stations, this based on records of the interplate seismicity of the Mexican Pacific Coast. Observe: **(a)** an higher amplification factor in MVB sites than the amplification level of inland stations, this of up to 1.5 times at the frequency of 0.36; and **(b)** the comparison between the MVB sites with averages of the coastal stations, the behavior is similar.