Dear Referee # 2

We thank you for your revision and comments done for our paper, which has improved the paper. Therefore, we have done the corrections according to his comments as follow and at end displayed the corrected complete paper. In the paper, the corrections are in red text (this due to the corrections of the Referee 3, mainly) and the blue text the new text, this due to his corrections/comments/observations.

Your questions	***Answers, about your corrections or comments***
1) Are the authors aware that HVSR and other estimates of site amplification could have significantly different amplitudes at frequency higher than the fundamental even when earthquakes are used? (see e.g., for theoretical explanation, Parolai and Richwalski, 2004, The Importance of Converted Waves in Comparing H/V and RSM Site	Yes, We are aware about this shift, however the possible shift of site amplification that could occur in our study, do not affect our main contributions, because we are looking at: 1) Average fundamental frequency (fo) in the MVB zone, 2) The average level of amplification (Ao) around fo. The main diference between HVSR and RSM is that the HVSR method generally provide**, at frequencies higher than the fundamental one, a lower level of amplification than the RSM results** (*Parolai and Richwalski, 2004*). We did this study based on HVSR methodology because the majority of studies used for comparison also employed the same methodology (*e.g. Singh et al., 2007; García et al., 2009*). However, the revision of the site amplification with other metodology (RSM o GIT) might be interesting in other study.

Your questions	***Answers, about your corrections or comments***
2) Which is the need to convert the velocity data in acceleration and not accelerometric data into velocimetric?	There are two reasons: 1) Our focus of investigation is to find an attenuation model which can be applied in other studies for which the majority of data is acceleration. This is to estimate the risk and seismic hazard of a zone according to construction regulations. 2) In addition, this conversion of velocity data in acceleration is well known and it is more stable than the opposite case, but it is not impossible to do. The main point is that the H/V ratio results are the same with both types of input.

Your questions	*Answers, about your corrections or comments*
3) More details should be given about instrumentation at each station. Was instrument response corrected using factory data or single instruments' calibration sheets? This is important also for HVSR because vertical and horizontal response with frequency might be different. Moreover, For frequencies below 1-0.5 Hz accelerometers do not have a flat response if the motion is weak.	The information about the instrumentation at each station is shown in Table 2; no more detailed information is available to us. Regarding the instrumental response correction, it was done based on the generic value of Station Gain provided by Servicio Sismológico Nacional (SSN Station Gain) from an instrument calibration sheet (station with STS-2 sensor and Q330 digitalizer). On the other hand, we did some tests about instrumental response correction (deconvolution process) in two ways, this in order to compare and validate our H/V results. First, we performed a deconvolution process (with use of the constant, poles and zeros; factory information) and second, with use of the value of Station Gain; it was done for the JUR1 station (Trillium 120 –TR120-broadband seismograph with similar instrumental flat response to the SSN stations, see Fig. 9a), for which we have the complete information from factory (see technical information in Figueroa et al., 2010). The H/V results are shown in the Fig. 9, where we can see the H/V shapes are identical; and this is because the range of frequency content of the analyzed earthquakes in our study (0.01-40Hz) are within the flat range of the typical instrumental response for broadband seismographs (see Fig. 9a). Thus, we did the same procedure for all the SSN stations. Finally, with respect to the H/V response for frequencies below 1-0.5 Hz with accelerometers could be different; Your observation is correct, if the ambient noise level is similar to amplitude of electronic noise of the instrument; this situation was studied by Chávez-García and Tejeda-Jácome (2010), in their study they report that the accelerometers (like K2) have problems to giving good H/V results at frequencies below 2 Hz. However, if the ambient noise level is higher than the amplitude of the electronic noise of the instrument, then the H/V results are excelent. In our study case, we have data of accelerometers, but these are records at close epicentral distances (11-81km) within the Mexico City area, where the ambient noise is much higher than the electronic noise level; furthermore our H/V result are acceptable because (in last three graphics of the Fig. 3) we

	can identify fundamental frequencies of 0.6-1.33 Hz without any problem. We have added the following paragraph to this respect in the part of results and discussion: Regarding the instrumental response correction, it was done based on the generic value of Station Gain provided by Servicio Sismológico Nacional (SSN) from an instrument calibration sheet (station with STS-2 sensor and Q330 digitalizer). On the other hand, we did some tests for the instrumental response correction (deconvolution process) in two ways, in order to compare and validate our H/V results. First, we performed a deconvolution process (with use of the constant, poles and zeros; from factory information) and second, with the use of the value of Station Gain; this was performed for the JUR1 station (Trillium 120 – TR120-broadband seismograph with similar instrumental flat response to the SSN stations), for which we have the complete information from factory (see technical information in Figueroa et al., 2010). The H/V results are shown in the Fig. 9, where we can see that the H/V shapes are identical. This is due to the range of frequency content of the analyzed earthquakes in our study (0.01-40Hz) which are within the flat range of the typical instrumental response for broadband seismographs. Thus, we performed the same procedure for all the SSN stations. We also dealt with the difficulty obtaining reliable H/V results for low frequencies (< 2 Hz) with accelerometer data, which is a common problem for these instruments. This problem was studied in detail by Chávez-García and Tejeda-Jácome (2010), where they reported that accelerometers (like K2) have problems providing good H/V results at frequencies below 2 Hz. However, if the ambient noise level is higher than the amplitude of the electronic noise of the instrument, then the H/V results are excelent. In our study, we have data of accelerometers, but these are records at close epicentral distances (11-81km) within the Mexico City area, where the ambient noise is much higher than the electronic noise level; furthermore our H/V results are acceptable because we can identify clear peaks for the fundamental frequencies of 0.6-1.33 Hz (this in last three graphics of the Fig. 3).

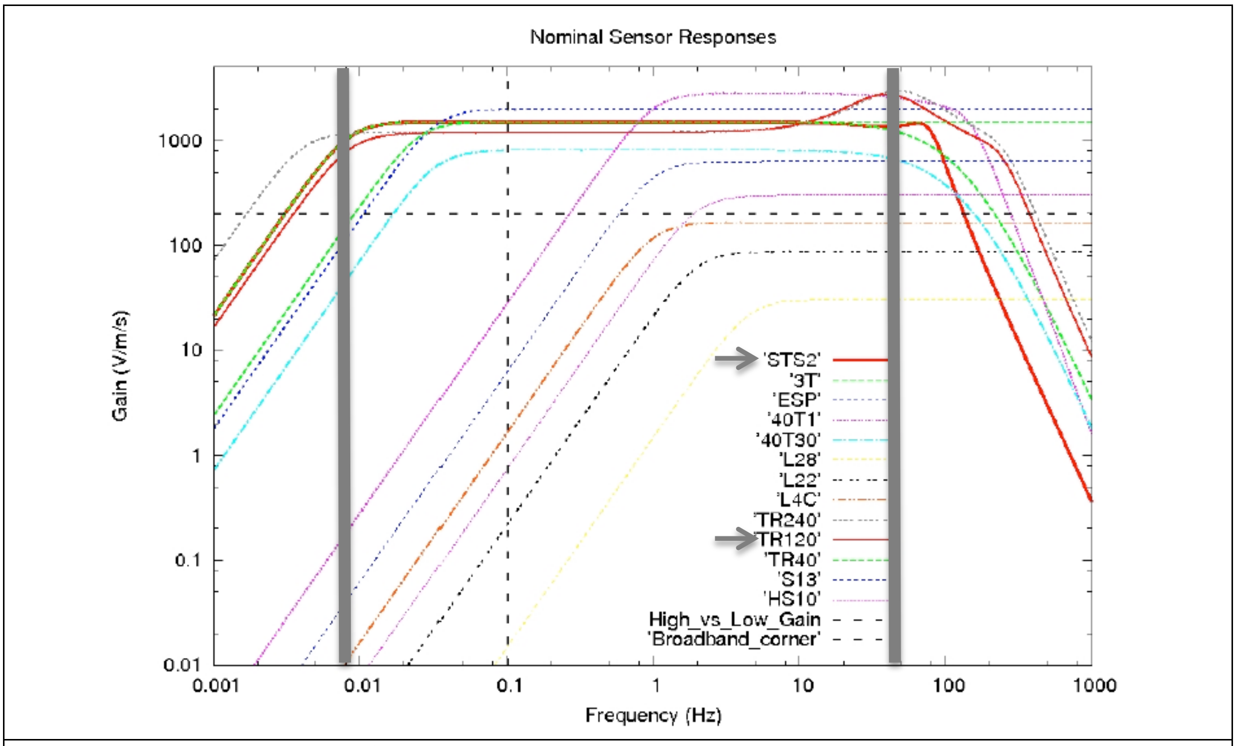

Figure 9a. Nominal response for some typical sensors reported by PASSCAL web site. The curves of interest are STS2 and Trillium 120 (TR120); these indicated with arrows. The range of flat response part (range between gray lines) of both sensors are similar and includes the frequency range analyzed in our study (0.01-40Hz).

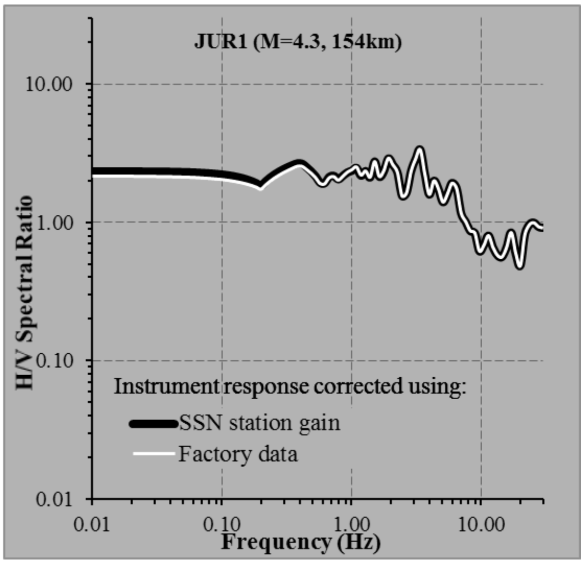

Figure 9. Example of instrumental response correction with two ways: SSN station gain and factory data. The H/V results show identical shapes. The earthquake record used correspond to the number 18 of the Table 1 with magnitude 4.3 and epicentral distance of 154 km.

Your questions	*Answers, about your corrections or comments*
4) Why the authors decided not to use the GIT approach for absolute amplification?	As pointed out before, we used HVSR methodology because the majority of studies that are used for comparison also employed the same methodology (*e.g. Singh et al., 2007; García et al., 2009*).

Your questions	*Answers, about your corrections or comments*
5) Fig. 7 shows predominant amplitude and length due to surface waves. Tab. 4 shows a decrease of fo in this study with respect to previous ones. Could it be due to different window selection in recordings? Selecting the whole recording or the Swave window alone could lead to different results (see e.g., Castro et al., 1997, Swave site-response estimates using horizontal-to-vertical spectral ratios; Bulletin of the Seismological Society of America, v. 87, p. 256-260)	Your comment and observation is pertinent. However, we decided to clarify it at general way. According to Parolai and Richwalski (2004) fo doesn't shift, the shift must be in the amplitudes (Ao); where the tendency is that the amplitudes are lower than with analysis of S-wave window alone. This tendency happens at low frequencies if there is the presence of surface waves inside the analyzed signal windows (Castro, et al., 1997) and at high frequencies if there is the presence of diffracted wave (Triantafyllidis et al., 1999; Castro et al., 2000) or seismic noise (Lachet et al., 1996) inside the analyzed signal windows. In our study, we did the selection of S-wave windows according to (cite), where they recommend taking only the part of the strong motion for the H/V analysis in order to obtain correct results. In spite of the above-mentioned points, we decided to do a test of the analysis that you mention: Selecting the whole recording and Selecting S-wave window alone We have taken the same record of the JUR1 station that was shown in Figure 2. The H/V results are shown in Figure 3; for an S-wave window alone and for the complete record, they show the same frequency peaks; the only difference was lower amplitudes at low frequencies. We forgot to reference Castro et al. (1997), then, we have added the following paragraph to this respect in the part of methodology: In line 19, page 6: (this according to the criterias recommended by

	Castro et al., 1997), Also, We have added the following paragraph to this respect in the part of results and discussion: Another point worth discussing is the possibility that the different choice of the window employed in our analysis might bias the estimation of the fundamental frequency, in particular with reference to the results shown in Table 4. Thus, we performed a test with two different windows. We selected only the S-wave trend, with the criteria according to Castro et al. (1997), and compared it to our results from the whole record. The record used was the same from JUR1 station shown in Fig. 9. The H/V results are displayed in Fig. 10. Using an S-wave window alone as opposed to the complete record, we can see that both show the same frequency peaks; the only difference being lower amplitudes at low frequencies. This effect is similar to the reported by Parolai and Richwalski (2004) when the choice window is different.

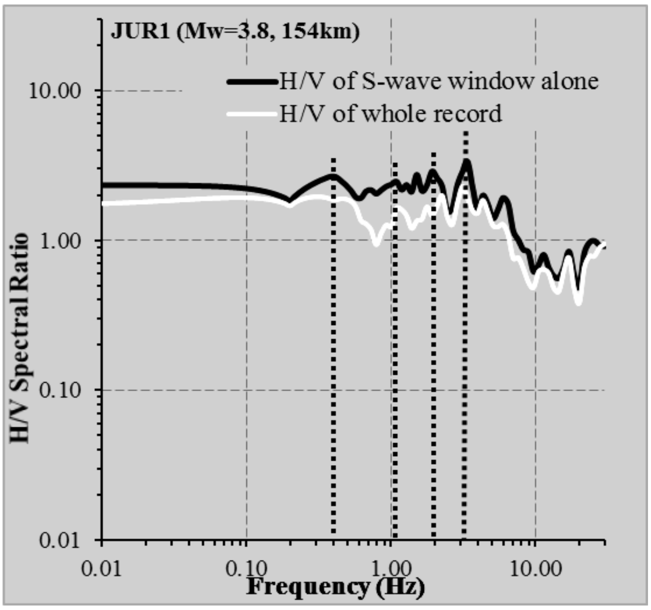

Figure 10. Comparison of H/V results with the use of different window longitude to analysis. The dotted lines show the same peaks at same frequencies in both H/V shapes.

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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

A. Clemente-Chavez[1], F. R. Zúñiga[2], J. Lermo[3], A. Figueroa-Soto[2], C. Valdés[4], M. Montiel[1], O. Chavez[1] and M. Arroyo[1]

[1]División de Investigación y Posgrado, Facultad de Ingeniería, Universidad Autónoma de Querétaro, Centro Universitario, Cerro de las Campanas s/n, Querétaro, Querétaro, C.P. 76010, México

[2]Centro de Geociencias (CGEO), Juriquilla, UNAM, P.O. Box 1-742, Querétaro, Querétaro, C.P. 76001, México

[3]Instituto de Ingeniería, UNAM, Ciudad Universitaria, Coyoacán, México D.F., C.P. 04510, México

[4]Instituto de Geofísica, UNAM, Ciudad Universitaria, Coyoacán, México D.F., C.P. 04510, México

Correspondence to: A. Clemente-Chavez (aclemente09@alumnos.uaq.mx)

Abstract

The Mexican Volcanic Belt (MVB) is a seismogenic zone that transects the central part of Mexico with an east-west orientation. The seismic risk and hazard of this seismogenic zone has not been studied in detail due to the scarcity of instrumental data as well as because seismicity in the continental regime of central Mexico is not too frequent, however, it is known that there are precedents of large earthquakes (Mw greater than 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 off coast of 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 when obtaining attenuation parameters in future works, as well as 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. Most of the studies in the region (e.g. Singh et al., 1988a; Ordaz and Singh, 1992; Chávez-García et al., 1994; Sánchez-Sesma et al., 1995; Singh et al., 1995; Chávez-García and Cuenca, 1996; Reinoso and Ordaz, 1999; Montalvo et al., 2000; Chávez-García and Salazar, 2002) have emphasized 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 dealing with its seismicity characteristics in this region have been published (e.g. Astiz-Delgado, 1980; Suárez et al., 1994; Suter et al., 1996; Zúñiga et al., 2003; Quintanar et al., 2004). However, earthquakes have occurred in the past within the MVB which caused destruction including the 1568 Jalisco earthquake which had a magnitude Mw estimated between 7.5 and 7.8 (Suárez et al., 1994); the 1912 earthquake occurred in Acambay, State of Mexico, with Mw=7.0 (Singh and Suárez, 1987) and the 1920 earthquake which took place near Jalapa, Veracruz with Ms = 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, 1988b; 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 as 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, 1994b). 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 which makes use of 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 when employing 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 acelerographs) 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.

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 regional site effect characteristics as presented in this study, much less with earthquakes occurring within the MVB. A discussion of some of the FAS shapes found is also given. 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 the 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 to 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 (Table 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 (this according to the criteria recommended by Castro et al., 1997), taking different time-window lengths of 5 to 40s 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 Fs= 6, which contains another type of smoothing function defined in Eq. (2). A comparison of these results is shown in Fig. 2.

$$As(f, fc) = \left[\frac{sin\left[log_{10}(f/fc)^b\right]}{log_{10}(f/fc)^b} \right]^4, \quad (1)$$

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

$$f_1 = f * 2^{(-\frac{1}{2Fs})} \quad f_2 = f * 2^{(\frac{1}{2Fs})}$$

In Eq. (1), *As* (*f, fc*) represents the smoothed amplitude; *b, f* and *fc* are coefficients for band width, frequency, and center frequency, respectively. In Eq. (2), *As* (*f*) represents smoothed amplitude based on frequency *f*. The sum is made in the range defined by frequencies f_1 and f_2; 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 obtained 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 (fo), the amplification factor (Ao) and values of other peaks in frequencies with smaller amplitudes.

Most of the ratios of Fig. 3 and Fig. 4 show a greater and more frequent variability at a frequency of about 0.5Hz as compared to other frequencies. This coincides with the observations of Singh et al. (2007) who 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 Ao (Ao < 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 to 2 Hz (or 10 to 0.5s);

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 to 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 1.5s with amplification of about 10.

The results of Table 3 were further used to classify the stations. This clasification is consistent with the criteria proposed 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 Ao is ≤2.5-3.0 at the fundamental frequency fo (as it occurs for most hard-rock sites) and, conversely, they assign an SSA label to sites with Ao>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 response (H/V < 2) for most of the frequency range (0.01 to 30Hz) (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 0.1-1.0Hz. 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 (range 15 to 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 100km, 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 15Hz);

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=8.5km). The three records are from DHIG, COIG and PLIG stations, with similar epicentral distances (with an average of R=247km). 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 (range 15 to 20 Hz), for similar epicentral distances (3 and 12 km) as MOIG station (R= 8.5km);

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 to 10Hz 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 100km. In their results they reported two peaks. The first peak is the fundamental frequency of the site that varies between 0.5 and 0.7Hz, 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 to 2.1Hz.

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= 0.28Hz with amplification factor A_o= 4.64; these values differ from those reported in the Tecoman study. The two other peaks (f_1= 1.30Hz with A_1 = 3.72 and f_2= 2.17Hz 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 subduccion zone) which do not cross the MVB. The latter observations were 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). Fig. 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 Ao and fo 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 Ao with an increment to up a 150% compared to previous studies.

Regarding the instrumental response correction, it was done based on the generic value of Station Gain provided by Servicio Sismológico Nacional (SSN) from an instrument calibration sheet (station with STS-2 sensor and Q330 digitalizer). On the other hand, we did some tests for the instrumental response correction (deconvolution process) in two ways, in order to compare and validate our H/V results. First, we performed a deconvolution process (with use of the constant, poles and zeros; from factory information) and second, with the use of the value of Station Gain; this was performed for the JUR1 station (Trillium 120 –TR120- broadband seismograph with similar instrumental flat response to the SSN stations), for which we have the complete information from factory (see technical information in Figueroa et al., 2010). The H/V results are shown in the Fig. 9, where we can see that the H/V shapes are identical. This is due to the range of frequency content of the analyzed earthquakes in our study (0.01-40Hz) which are within the flat range of the typical instrumental response for broadband seismographs. Thus, we performed the same procedure for all the SSN stations.

We also dealt with the difficulty obtaining reliable H/V results for low frequencies (< 2 Hz) with accelerometer data, which is a common problem for these instruments. This problem was studied in detail by Chávez-García and Tejeda-Jácome (2010), where they reported that accelerometers (like K2) have problems providing good H/V results at frequencies below 2 Hz. However, if the ambient noise level is higher than the amplitude of the electronic noise of the instrument, then the H/V results are excelent. In our study, we have data of accelerometers, but these are records at close epicentral distances (11-81km) within the Mexico City area, where the ambient noise is much higher than the electronic noise level; furthermore our H/V results are acceptable because we can identify clear peaks for the fundamental frequencies of 0.6-1.33 Hz (this in last three graphics of the Fig. 3).

Another point worth discussing is the possibility that the different choice of the window employed in our analysis might bias the estimation of the fundamental frequency, in particular with reference to the results shown in Table 4. Thus, we performed a test with two different windows. We selected only the S-wave trend, with the criteria according to Castro et al. (1997), and compared it to our results from the whole record. The record used was the same from JUR1 station shown in Fig. 9. The H/V results are displayed in Fig. 10. Using an S-wave window alone as opposed to the complete record, we can see that both show the same frequency peaks; the only difference being lower amplitudes at low frequencies. This effect is similar to the reported by Parolai and Richwalski (2004) when the choice window is different.

5 Conclusions

The Mexican Volcanic Belt (MVB) is a seismogenic zone that has not been studied in 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 (Mw magnitude greater than 6.0) within the MVB. 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 from 25 stations belonging to the main seismic networks of Mexico during the last 13 years) 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 a general overview of the behavior of site effects in the zone, a classification of seismic stations and to compare with previous studies.

In general, our study yielded the following results:

1) A difference in the level of amplification in the MVB zone was identified. Our 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 0.38Hz. 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 for 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 ≥ 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 on rock sites analyzed, 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 showed amplification factors of 4 to 6.5 at frequencies of about 0.35, 16 0.75, 15 and 23Hz. 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 than 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 (yyyy/mm/dd/)	Latitude (°N)	Longitude (°W)	H (km)	M*	Epicentral Location (State)	Number Records	Epicentral Distance R (km)
1	1998/03/18	20.10	99.23	5	4.3	Hidalgo	6	69 - 85
2	1998/04/27	19.04	98.51	2	4.0	Puebla	1	13
3	2000/03/04	18.84	98.57	4	4.1	Puebla	3	26 - 110
4	2000/03/12	20.10	99.29	5	4.1	Hidalgo	3	134 - 190
5	2001/08/05	20.47	103.67	10	4.3	Jalisco	2	143 and 180
6	2002/11/03	19.26	98.04	2	4.0	Tlaxcala	2	65 and 182
7	2002/11/16	19.17	98.49	9	4.1	Puebla	5	18 - 226
8	2003/02/04	18.92	98.51	2	4.1	Puebla	2	21 and 120
9	2003/04/28	19.55	103.46	4	4.0	Jalisco	2	47 and 166
10	2003/11/16	19.18	98.97	7	4.0	Distrito Federal	13	11 - 242
11	2003/12/05	19.72	101.25	7	4.3	Michoacán	4	8 - 263
12	2003/12/15	20.35	99.07	4	4.0	Hidalgo	7	7 - 286
13	2004/10/07	20.81	103.48	5	4.2	Jalisco	2	219 and 268
14	2005/06/05	19.44	103.55	5	4.2	Colima	2	32 and 157
15	2007/12/05	18.64	102.22	4	4.1	Michoacán	2	27 and 153
16	2009/11/29	19.36	103.76	5	4.0	Colima	2	50 and 136
17	2010/04/17	20.38	98.96	2	4.1	Hidalgo	8	12 - 251
18	2010/05/18	20.27	99.04	3	4.3	Hidalgo	9	3 - 281
19	2010/05/18	20.35	98.92	5	3.6	Hidalgo	2	44 and 195
20	2010/05/20	20.34	98.89	2	3.9	Hidalgo	1	167
21	2010/10/03	19.48	103.52	6	4.0	Jalisco	3	25 - 203
22	2011/02/08	19.73	104.51	5	4.0	Jalisco	1	147

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

Table 2. Classification of the database by seismic network and station name.

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 site effect estimation by quadrants in the MVB. The table shows: fundamental frequency identification (fo), amplification factor (Ao), classification of the amplification level at each seismic station site, values of other peaks at frequencies with smaller amplitudes and number of records used in each evaluation.

Quadrant no.	Station name or zone	fo (Hz)	Ao	Classification of the site amplification level	f1 (Hz)	A1	f2 (Hz)	A2	f3 (Hz)	A3	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

Table 4. Comparisons of Ao and fo (at each seismic station) reported in previous studies with the results of this study.

Authors	ID Station	Previous studies fo (Hz)	Previous studies Ao	This study fo (Hz)	This study Ao	Increase in Ao
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%

(≈ values observed in their studies)

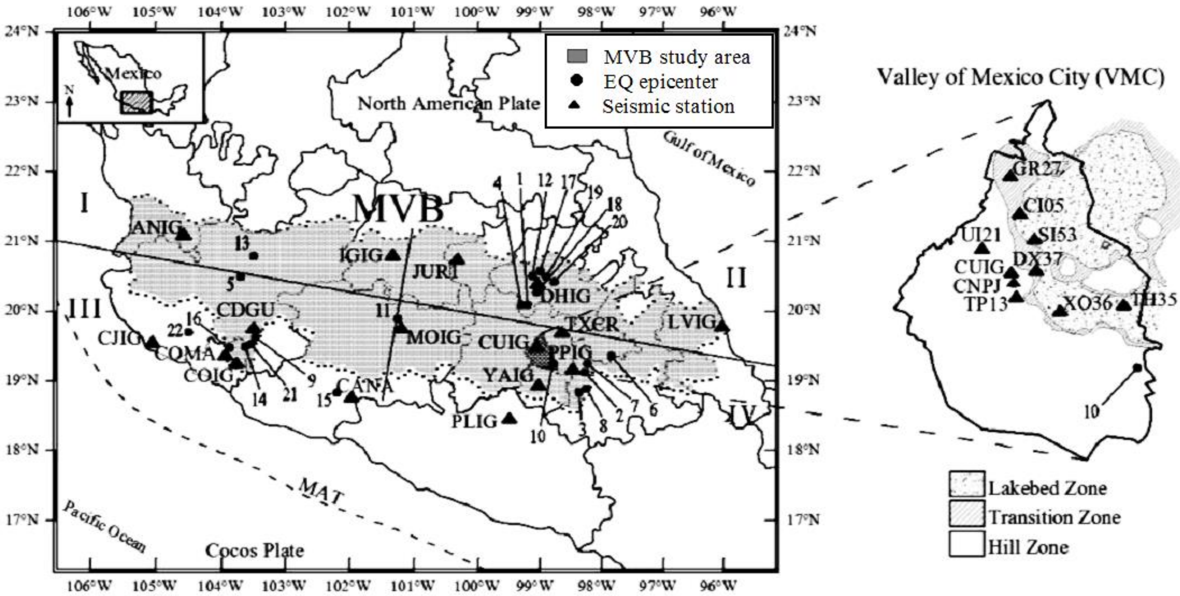


Figure 1. Map of the Mexican Volcanic Belt (MVB) according to Gómez-Tuena et al. (2005); Location of: epicenters in Table 1, seismic stations in Table 2, and the zone divided in quadrants (solid straight lines) are shown. To the right, the map of the VM located within the Distrito Federal, the stations,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

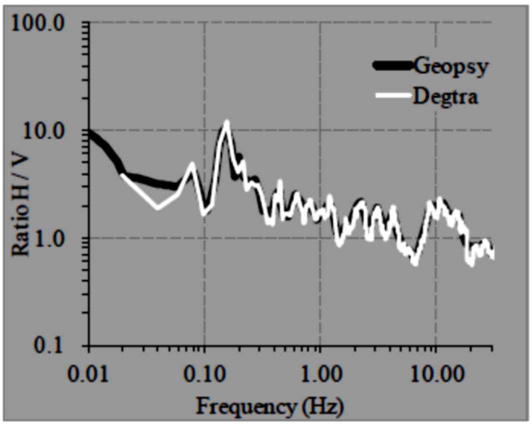


Figure 2. Comparison of H/V results of the Geopsy and Degtra softwares are shown. Observe that the ratios are similar although the smoothing functions are different.

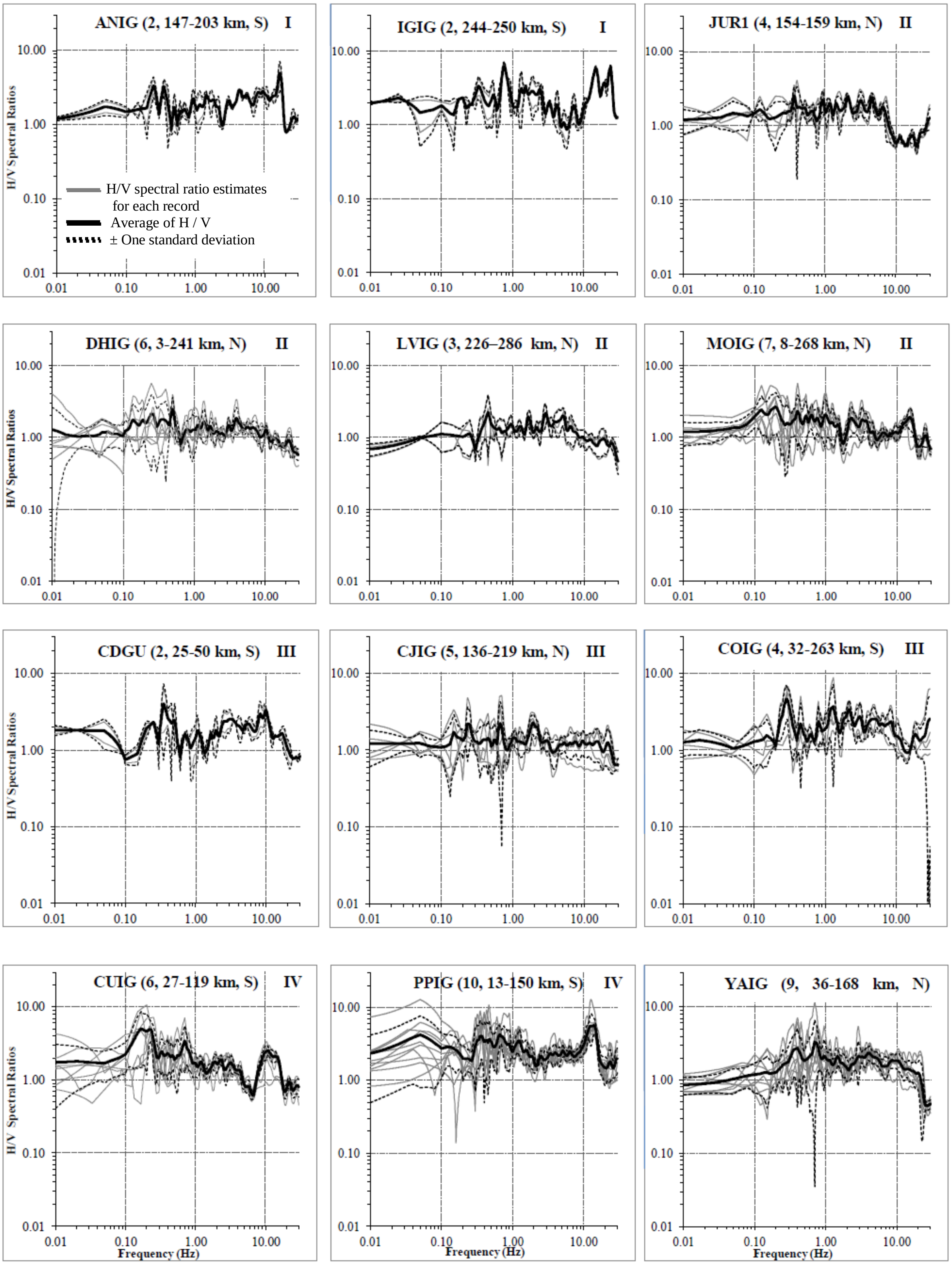
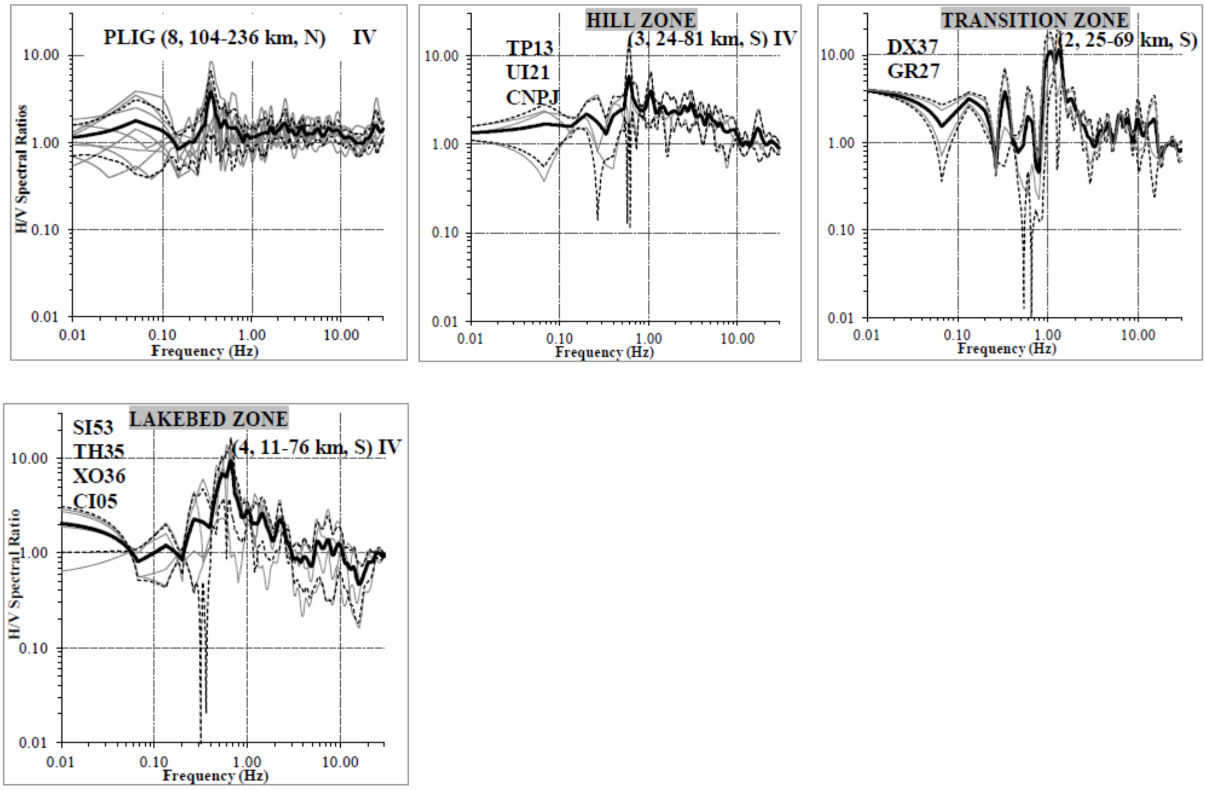


Figure 3. Averages of H/V spectral ratios ± one standard deviation for all stations are shown. The headers in each graph correspond to the following nomenclature: Station (Number of records, epicentral distance range in km, site classification: N = negligible site amplification or S = significant site amplification) and quadrant number.



Continuation of Fig. 3. The last three graphs correspond to averages of grouped stations within each geotechnical zone in the VM, this according to the Figure 1.

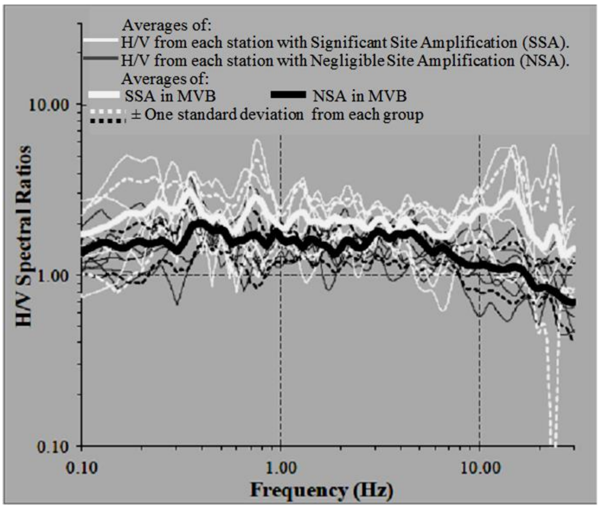


Figure 4. Comparison of the behavior and differences of site amplification between the two groups of stations within the MVB: 1) with SSA and 2) with NSA. Both groups are shown with ± one standard deviation. Observe that the main differences are in the low frequency range of 0.1-1.0 Hz. Averages of all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

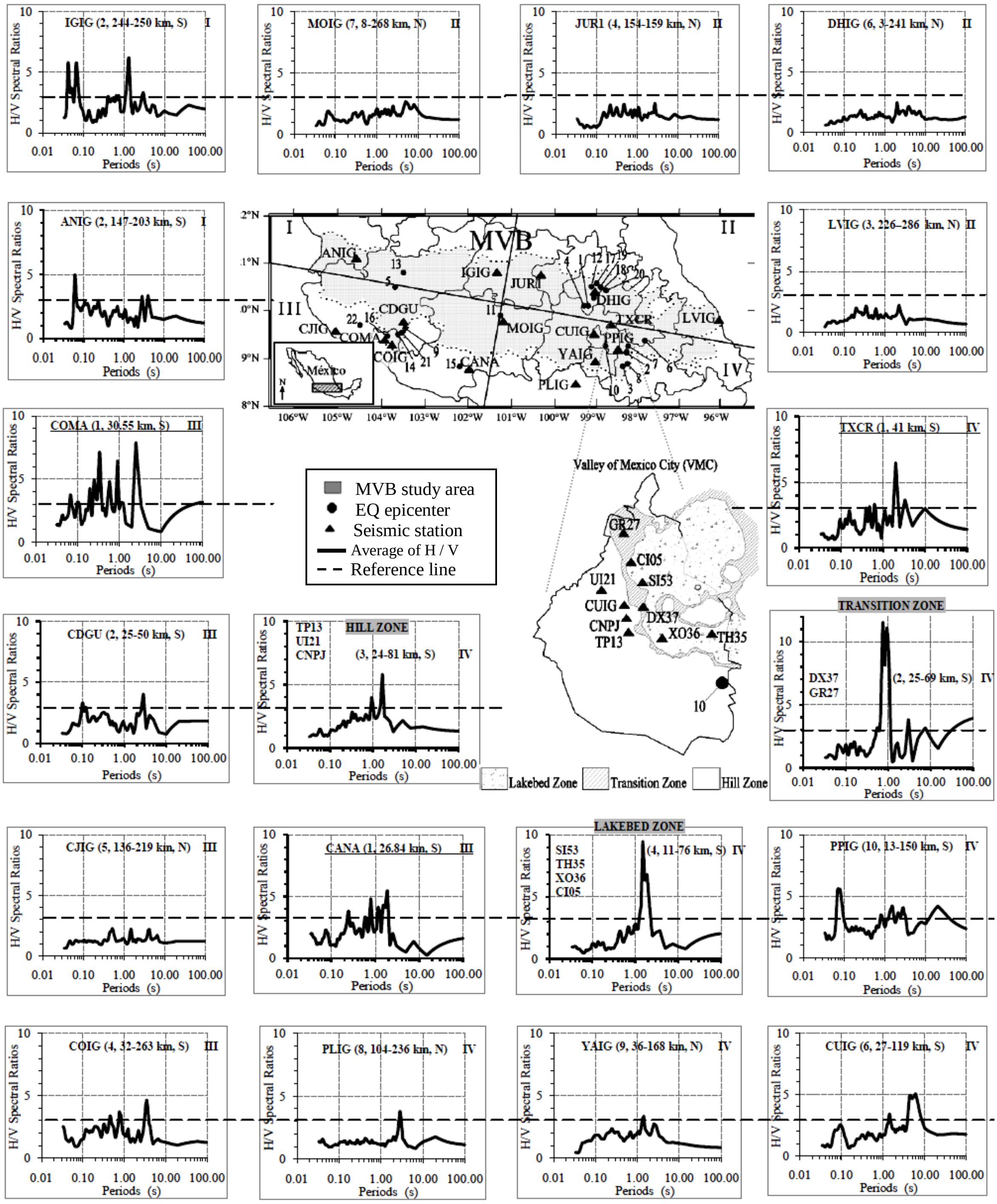


Figure 5. A general overview of site effects in the MVB is shown. Note: A smaller site amplification in the northeast part of the MVB (quadrant II) than those of the other quadrants. (the three stations with a single record: COMA, CANA and TXCR are also included).

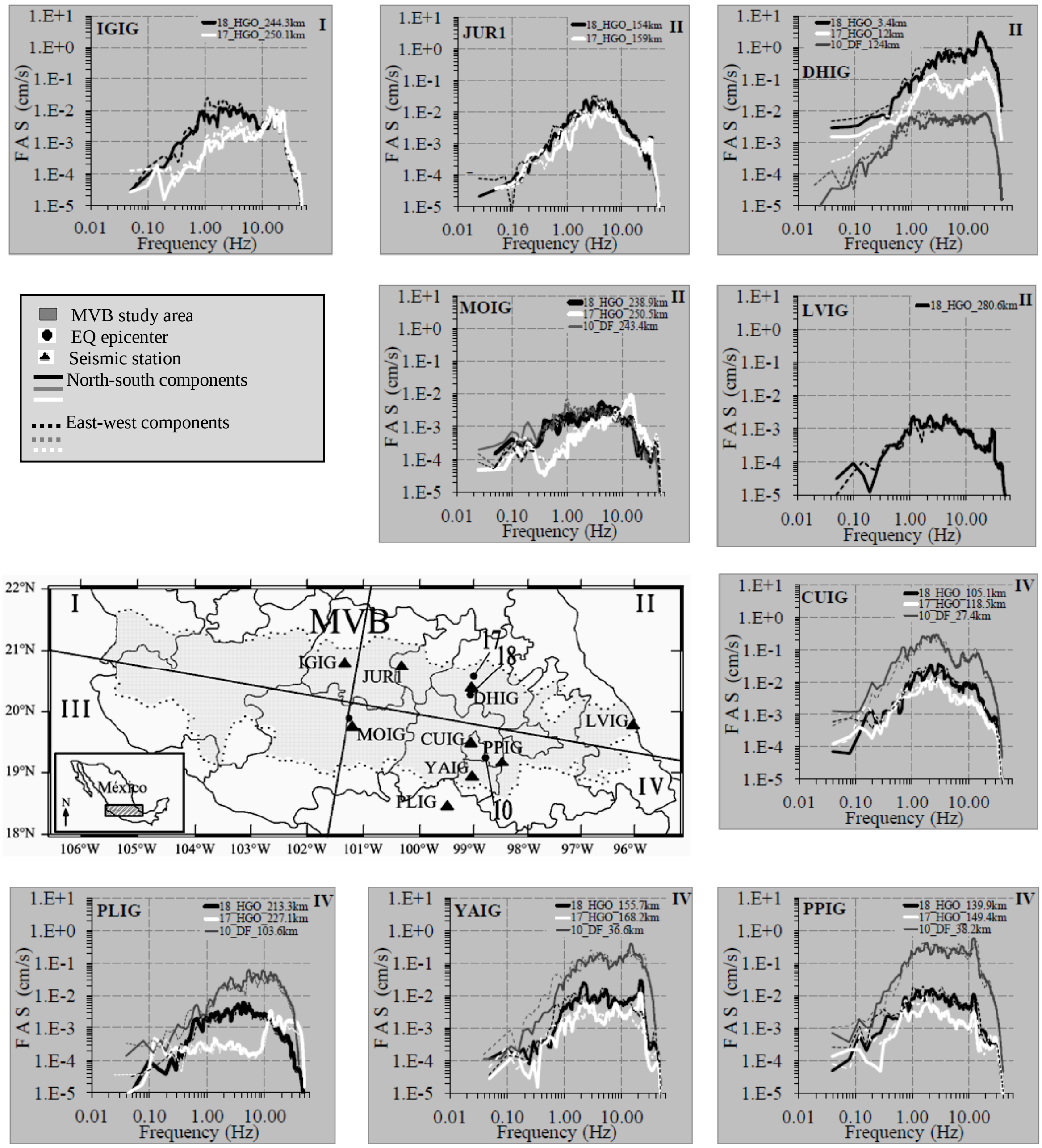


Figure 6. Comparisons of the amplitudes decay among the Fourier acceleration spectra (FAS) of the earthquakes 10, 17 and 18 (earthquakes in Table 1 with the largest record number and similar Magnitud $M \approx 4$) with site differents within the MVB are shown. FAS shapes correspond to the horizonal components. The legends in each graph indicate: earthquake number, epicenter location, and epicentral distance. (HGO = Hidalgo State, DF = Distrito Federal).

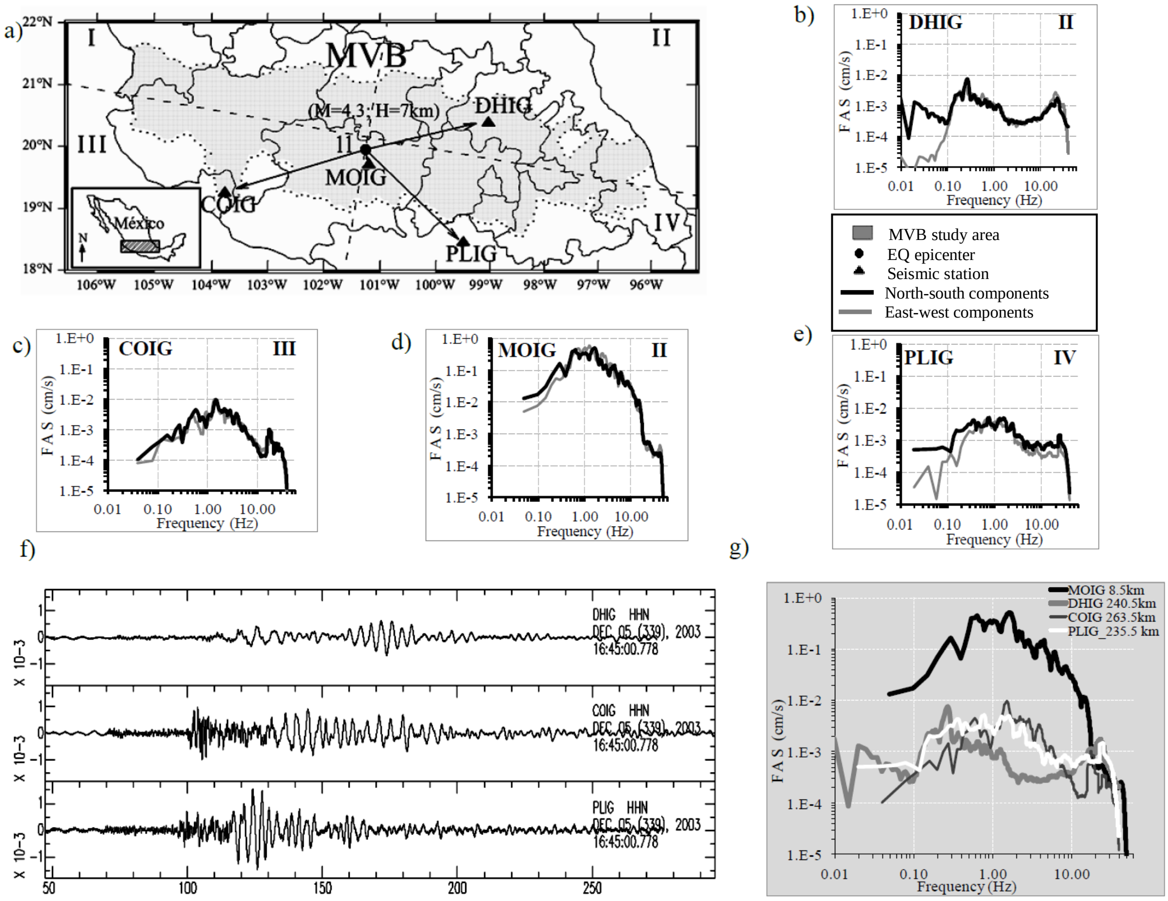


Figure 7. In the Figures a) to e) Fourier acceleration spectra (FAS) of the earthquake 11 for the station sites MOIG, COIG, PLIG and DHIG (with similar epicentral distances) are shown; In Figure f) seismograms of the north-south component of the COIG, DHIG and PLIG stations (where the DHIG station shows longer periods than the other stations) are also shown; and in Figure 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 to 10Hz) with respect to COIG and PLIG sites.

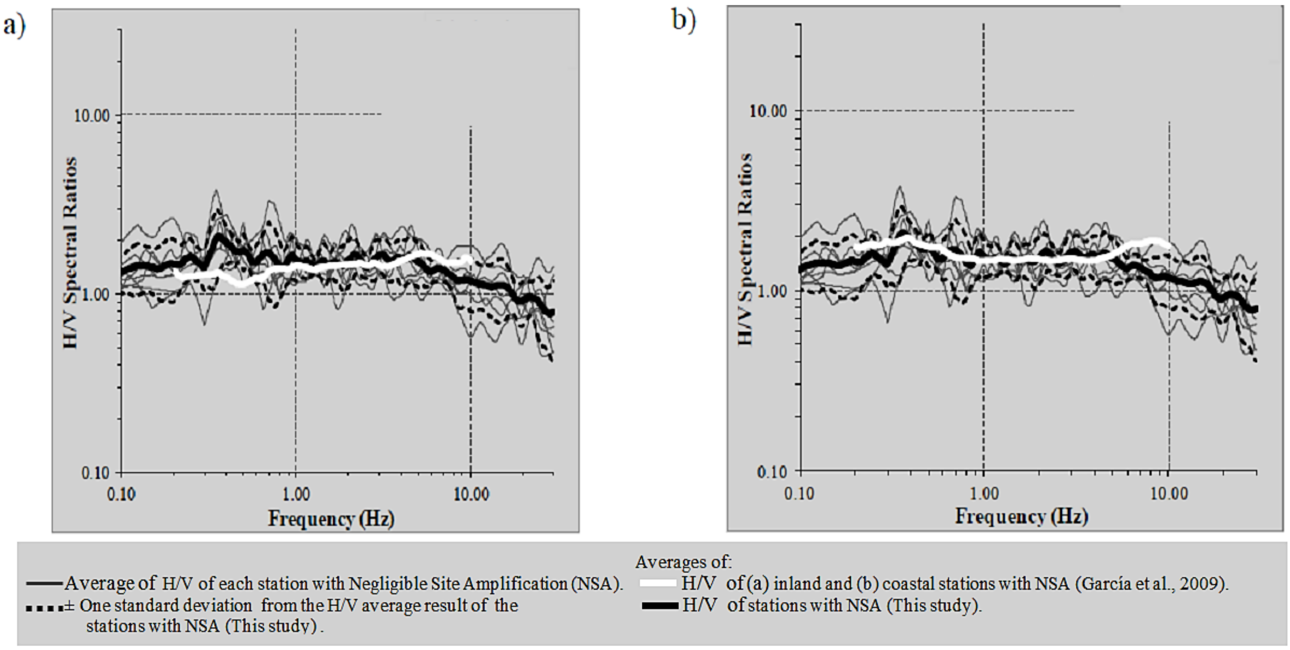


Figure 8. Comparisons of averages of site effects with NSA between those reported by García et al. (2009) –sites with trajectories in the subduccion zone– and the results of this study are shown. The results of García et al. (2009) are shown for a) inland stations and b) coastal stations, this based on records of the interplate seismicity of the Mexican Pacific Coast. Observe: in Fig. 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 in Fig. b) the comparison between the MVB sites with averages of the coastal stations, the behavior is similar.

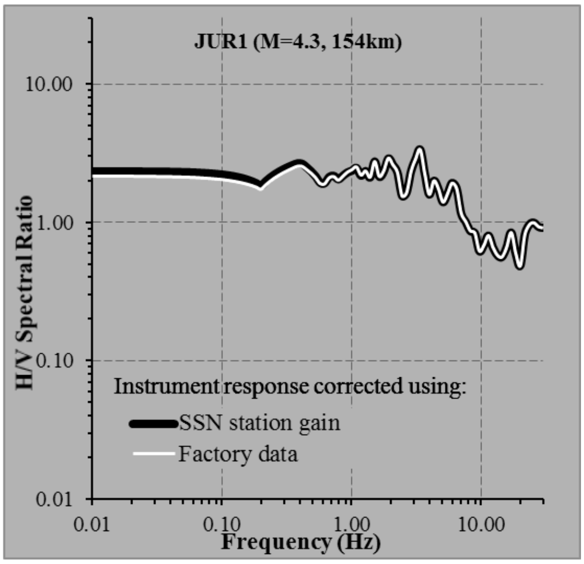


Figure 9. Example of instrumental response correction with two ways: SSN station gain and factory data. The H/V results show identical shapes. The earthquake record used correspond to the number 18 of the Table 1 with magnitude 4.3 and epicentral distance of 154 km.

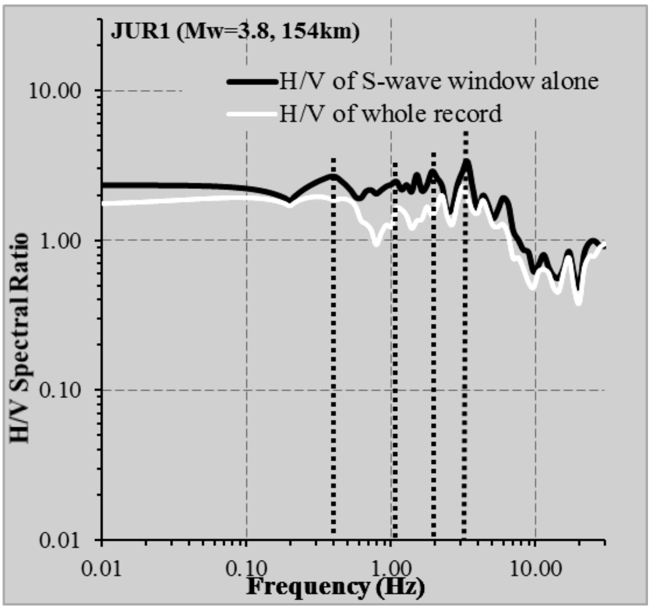


Figure 10. Comparison of H/V results with the use of different window longitude to analysis. The dotted lines show the same peaks at same frequencies in both H/V shapes.