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GROUND MOTION IN CENTRAL MEXICO. PATH EFFECTS DUE TO THE TRANSMEXICAN VOLCANIC BELT.

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SUMMARY

In this work the influence of the Transmexican Volcanic Belt on the propagation of surface waves with periods between 1 and 10 s is studied. The data used are acceleration records of 13 events recorded along two lines of stations. We considered different paths epicenter-Mexico City. The results show that, for periods smaller than a given value, the seismic motion that propagates towards Mexico City from earthquakes that occur in the subduction zone of the Pacific coast are affected by presence of the TVB. This period value depends on the path.

INTRODUCTION

Mexico City (MC) can be severely affected by earthquakes originated in the subduction zone of the Mexican Pacific coast more than 300 km away. The damages caused by the earthquake of Michoacan in 1985 spurred the research on the different topics that played a role in that catastrophe. The more important factor was the amplification of the ground motion caused by the presence of a very thin, extremely soft clay layer, deposited in an ancient lake (e.g. Singh *et al*. [21]; Bard *et al.*, [2]). Site effects amplified the peak ground acceleration by a factor of 3, relative to nearby firm ground. In the frequency domain, amplification reached a factor of 40 at the dominant frequency of the clay layer (Singh *et al*., [21]). However, in addition to the observed amplification, ground motion observed in the lakebed zone (where the soft clay layer conditions earthquake ground motion) showed a very large increase in the duration of strong ground motion, relative to that in the hill zone. Duration of ground motion was also a significant factor in the damages observed in 1985, given its importance in the non linear response of structures (e.g. Trifunac and Westermo [23]). While the observed amplification was rapidly explained in terms of the impedance contrast between the soft clay layer and its substratum, the observed long duration of ground motion has not yet received a generally accepted explanation. Several models have been proposed, from

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1D site effects (e.g. Seed *et al.*, [20]) to effects of gravity on surface waves (Lomnitz, 1990), but were shown to be unable to explain the observations (Chávez-García and Bard [7], [8]). Singh and Ordaz [22] hypothesized that the long duration of the ground motion was already present on firm soil and that the accelerographs were not sensitive enough to record it. Chávez-García, *et al.* [9] and Chávez-García and Salazar [10] analyzed the records of two events in MC and showed the contribution of late arrivals with large amplitudes. Based on simple models, Chávez-García and Salazar [10] proposed that the long duration of ground motion is originated outside the valley of Mexico.

In addition to the observed site effects, the analysis of strong motion records from the 1985 earthquake showed that ground motion on rock in central Mexico was already amplified relative to sites at similar epicentral distances, but located along the Pacific coast (Singh *et al.*, [21]). Ordaz and Singh [17] computed attenuation curves for earthquakes on the Pacific subduction zone and showed that ground motion on rock in central Mexico was amplified by a factor around 10 in the period band from 1 to 3.33 s. This regional amplification was further analyzed by Cárdenas *et al.* [5] and Cárdenas and Chávez-García and Salazar [10]. It is clear that it is not possible to dissociate the observed long duration of ground motion from the regional amplification that conditions the incident motion to MC.

It is likely that the regional amplification is related to the heterogeneous geological structure of central Mexico. The largest geological structure is the Transmexican Volcanic Belt (TVB), the volcanic arch created by the subduction of plates Rivera and Cocos under the Northamerican plate. The variable dip of the subduction along the trench has been used to explain the obliqueness of the TVB relative to the subduction zone (Pardo and Suarez [18]). The TVB shows a large variability in its volcanic style and chemical composition, as well as remarkable variations in its width (Ferrari [12]). Several authors have tried to relate this heterogeneity with observed ground motion either by analysis of recorded data (e.g. Barker *et al.* [3]; Shapiro *et al.* [19]; Yamamoto *et al.* [25]; Cárdenas and Chávez-García [6]) or using numerical modeling (Furumura and Kennett [13]).

In this paper we tackle this problem using analysis of recorded data. Previous studies have made it clear that path effects affect the ground motion incident to the valley of Mexico in the range 1 to 5 s period, a range that is critical because it coincides with the periods amplified locally by the soft clay layer. We have chosen acceleration data from 13 earthquakes recorded at 22 stations, most of them on rock. We have computed the attenuation and duration of ground motion for our dataset. In addition we have computed group velocity dispersion for all the traces. We verified that site effects were not important using as measure the horizontal to vertical spectral ratios (Lermo and Chávez-García [15]). Our results allow us to point where the regional amplification becomes important and to show its relation with the TVB. In addition, we show the relation between regional amplification and duration of strong ground motion. Our results allow us to better understand the incident motion into MC.

DATA

Our data was chosen from the Mexican Database of Strong Earthquakes (Alcantara *et al.* [1]). A total of 13 events between 1990 and 2003 ($4.6 \leq Mc \leq 7.6$, Table 1) recorded by 22 stations (Table 2) were selected from the database. The data were chosen in order to be able to compare the behavior of the surface waves inside and outside of the TVB. All the epicenters of the selected events are outside of the TVB and they were ordered in 5 groups, according to their location with regard to our stations (Figure 1). Each of those groups defines a path between epicenters and stations. Not all of the records were of high quality.

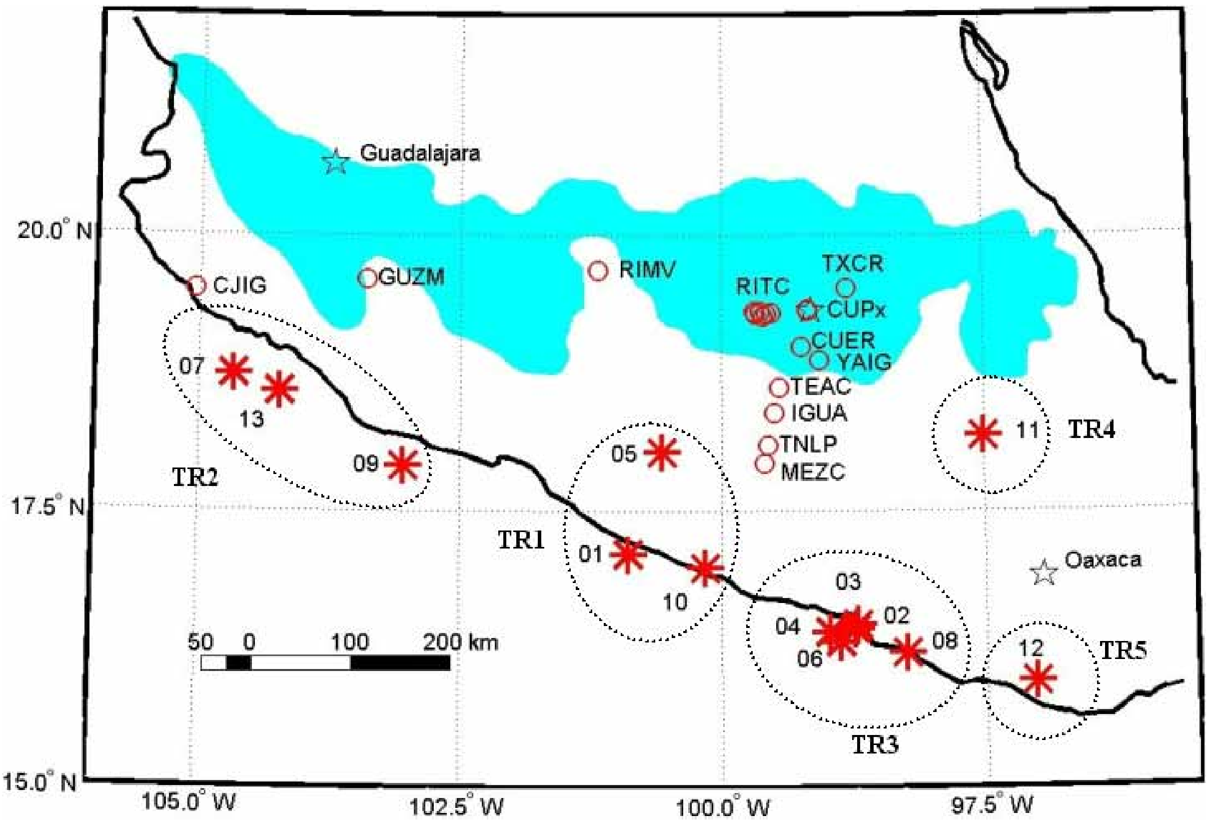


Fig. 1. Distribution of epicenters (stars) and stations (circles) used in this work. The TVB is shown by the gray area. IGUP and IGUP are very close to IGUA. CENA, CNPJ and CUPx stations are on a single point at the scale shown, in the south of MC.

Table No 1. Seismic events used in the analysis.

Event	Date (GMT)	Location		Mc	Depth (km)
		Latitude N	Longitude W		
01	31.05.1990	17.106	100.893	5.5	16
02	15.05.1993,1	16.430	98.740	5.8	20
03	15.05.1993,2	16.470	98.720	6.0	< 5
04	24.10.1993	16.540	98.980	6.5	19
05	23.05.1994	18.030	100.570	5.6	23
06	14.09.1995	16.310	98.880	7.3	22
07	09.10.1995	18.740	104.670	7.5	16
08	27.03.1996	16.210	98.250	4.6	7
09	11.01.1997	17.910	103.040	6.5	16
10	17.07.1998	16.980	100.160	4.6	27
11	15.06.1999	18.180	97.510	7.6	69
12	30.09.1999	15.950	97.030	5.2	16
13	22.01.2003	18.220	104.600	7.6	10

The stations we selected define approximately two lines: one along a direction North-South, from Mezcala, Gro., to MC, and the second in a direction East-West, from Colima to MC. In both lines some stations are inside the TVB and others are outside it. The chosen location of the epicenters and stations allows to compare the behavior of surface waves inside and outside the TVB.

In University City, UNAM, there are several seismic stations. We have used five of them. These stations, named CUP1, CUP2, CUP3, CUP4, and CUP5, have the same coordinates. In order to simplify, in table 2 and figure 1, we have used the name CUPx.

Table No. 2. Seismic stations used in this analysis.

Name	Location		Altitude (m)	Site conditions	Instrument
	Lat. N	Long. W			
TXCR	19.5180	98.8050	2570	Metamorphic rock	ADN-4/N102/FBA-23
CUPx	19.3300	99.1830	2240	Basaltic rock	DCA-333
CENA	19.3143	99.1762	2270	Basaltic rock	ADII-4
CNPJ	19.3143	19.3143	2270	Basaltic rock	ALTUS-K2
CUER	18.9840	99.2370	1542	Rock	ALTUS-ETNA
YAIG	18.8620	99.0667	1340	Limestone	Q680LT/G
TEAC	18.6180	99.4530	1000	Rock	DSA-1
PLIG	18.3920	99.5020	875	Limestone	Q680LT/G
IGUA	18.3912	99.5038	1350	Rock	SMAC-MD
IGUP	18.3870	99.5020	900	Rock	DCA-333
TNLP	18.0980	99.5590	740	Rock	PDR-1
MEZC	17.9300	99.5910	1660	Rock	SMAC-MD
RITB	19.2809	99.5744	2590	Soil clay-sand	SSA-2
RITC	19.2830	99.6764	2705	Rock	SSA-2
RITE	19.2985	99.5288	2131	Soil clay-sand	SSA-2
RITL	19.3135	99.6936	2709	Soil clay-sand	SSA-2
RITP	19.2601	99.6115	2665	Soil clay-sand	SSA-2
RITS	19.3084	99.6378	2625	Soil clay-sand	SSA-2
MOIG	19.6780	101.189	1275	?	Q680
RIMV	19.6800	101.180	2020	Rhyoltic tuff	SSA-2
GUZM	19.6000	103.400	N/E	?	SSA-2
CJIG	19.4990	105.043	129	Andesite	Q680LT/G

One problem in our records was the lack of a common time base. This problem prevents the search of pulses common to several stations. For this reason, we have used the technique described by Chávez-García *et al.* (1995) to assign a common time. The records were filtered in a long period band, from 7 to 12 s. At such long periods, the fundamental mode of Rayleigh waves is the dominant feature in the vertical and radial components. Moreover, they are not affected by the irregular crustal structure. If we assume a group velocity for that mode, we can impose a common time to the records using their epicentral distance. The group velocity chosen was that computed at 9 s period from the crustal model for central Mexico proposed by Campillo *et al.* [4]. Prior to the analysis, the records were baseline corrected, glitches were eliminated, and horizontal components were rotated to radial and transverse directions, which are different for each record.

DATA ANALYSIS.

The analysis of our data was carried out in three stages. The first one consisted of the qualitative analysis of the wave forms in each record, after filtering them in different frequency bands. The second consisted of a dispersion analysis using the Multiple Filter Technique (MFT) described by Dziewonski *et al.* [11] and Herrmann[14]. The results of MFT were stacked with the aim of enhancing features common to records from various events. Finally spectral ratios H/V were computed for each station.

Qualitative analysis of waveforms.

The records were filtered in different frequency bands and the amplitudes and shapes of the traces were compared among the different stations. An example is shown in Figure 2, where the records of the 14.09.95 event are shown, lowpass filtered with a cutoff frequency of 1.0 Hz. The amplitudes do not decrease with increasing distance, but rather show significant amplitude increases in all three components of motion. This amplitude increase with distance is observed for periods smaller than 6 s, starting from station CUER and independently of the location of the epicenter. The amplification factor, however, seems to depend on the path. For example, in the period range from 1 to 6 s, amplification at CUER is a factor of 2 relative to IGUA, for events in the group TR2. This same station is amplified by a factor of 2 relative to TEAC or epicenters in group TR3, and by a factor of 4 also relative to TEAC for the events in group TR4. These factors depend on the frequency band analyzed. In general the larger amplifications were observed between 2 and 5 s at CUER (a factor of 4 relative to TEAC), and between 3 and 6 s at CUP1 (a factor of 5 relative to TEAC).

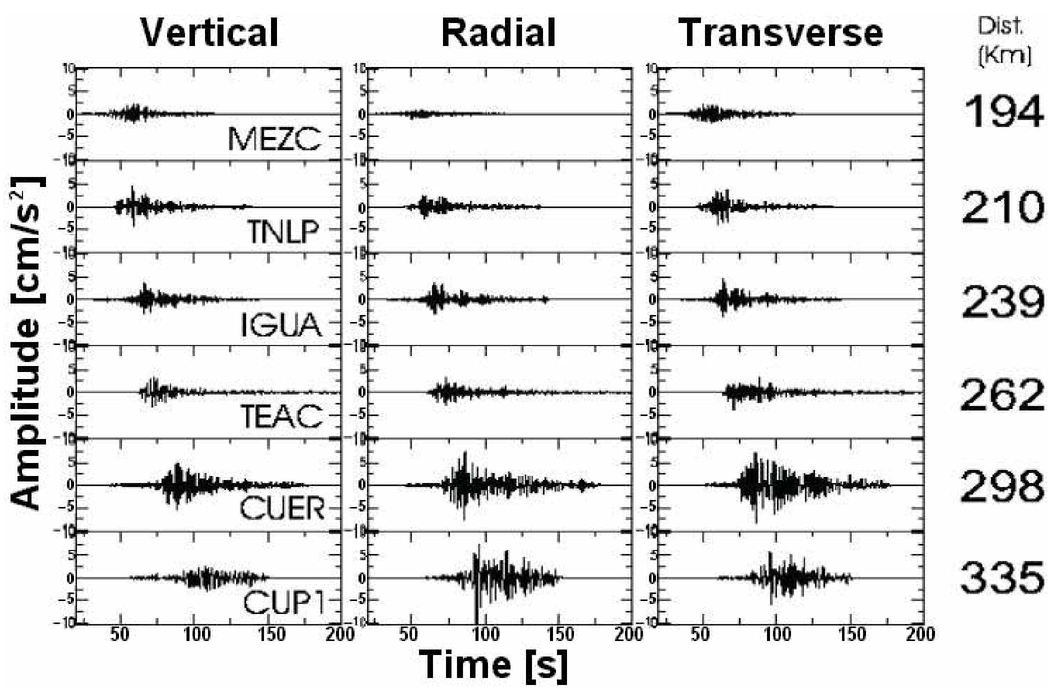
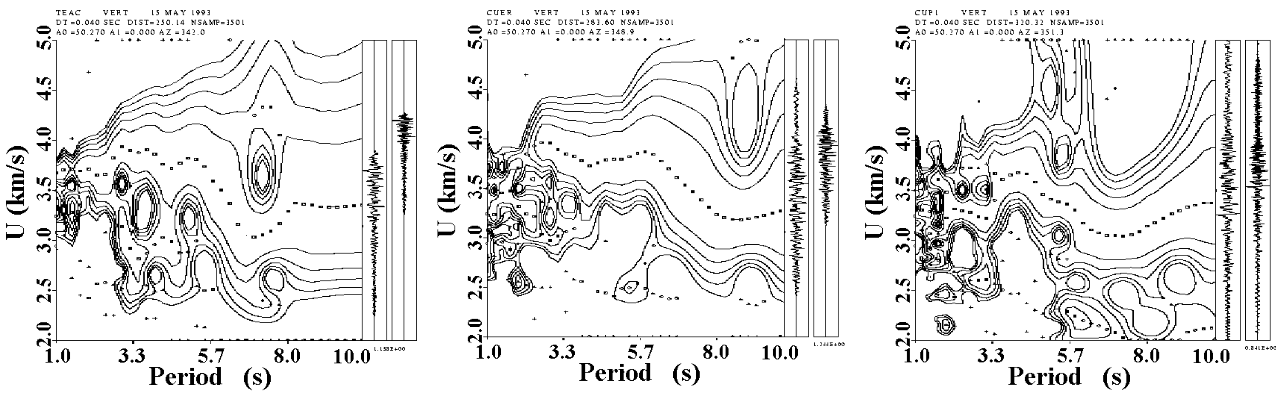


Fig. 2. Vertical, radial and transverse components of the 14.09.1995 event, lowpass filtered with a cutoff frequency of 1 Hz. To the right of each trace the corresponding epicentral distance is shown.

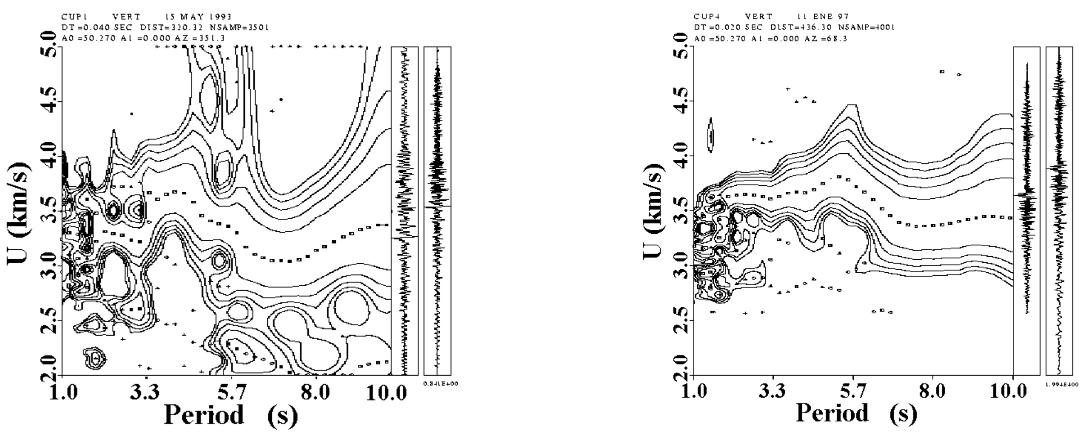
Group velocity dispersion analysis.

The multiple filter analysis by Dziewonski *et al.*[11] allows to plot the energy of a signal as a function group velocity and period. The traces are bandpass filtered using a series of filters in a given period range. Then, the envelope of the resulting trace is plotted at the period of the corresponding filter, converting time into group velocity through the epicentral distance of the station. Finally, contours are drawn in the plane group velocity-period (U-T). Different symbols indicate, for each period value, the location of the four values of U for which the amplitudes are the largest.



a) *b)* *c)*

Fig. 3. Dispersion curves of event 03 (05.15.1993-2), vertical component for stations a) TEAC. b) CUER. c) CUP1.



a) *b)*

Fig. 4. Group velocity dispersion diagrams obtained from MFT for the vertical components of station CUP1, for two different events. a) Event 04 (24.10.1993). b) Event 09 (11.01.1997).

We have analyzed the three components of motion recorded at each station in the period range 1 to 10 s. The range of group velocities used was 2 to 5 km/s. We observed that the U-T diagrams for radial and vertical components were similar, and that those for the transverse component were not, as expected.

Figure 3 shows the U-T diagrams obtained for the vertical components recorded at stations TEAC, CUER, and CUP1 for event 03 (Table 1). In the long period range (periods larger than 5 s) the overall picture is similar for these three records; they are dominated by the fundamental mode of Rayleigh waves propagating from the epicenter. For periods smaller than 5 s, significant differences appear among the records. For example, in the range between 1 and 3.3 s, TEAC shows contours that are concentrated in the group velocity range between 3.1 and 3.7 km/s. In CUER, for that same period range, the maxima appear distributed in a larger range of U, between 3 and 3.8 km/s. This suggests that several arrivals at different times contribute to the energy in this period band. This hypothesis is supported by the results for CUP1, where at least two, maybe three, distinct arrivals may be identified: one with group velocity between 2.6 and 2.8 km/s, one with velocity around 3.3 km/s, and maybe another with group velocity larger than 3.5 km/s. The absence of these arrivals in TEAC indicates clearly that they were generated at some location between TEAC and CUER, and thus, the observed group velocities are probably overestimated.

Figure 4 shows the group velocity-period diagrams for two different events recorded at station CUP1, vertical component. One event comes from the SSE, with epicenter on the coast of Guerrero, while the second (event 04) has a backazimuth of 249.5°. The two diagrams are similar for periods larger than 6 s, and are very different for smaller periods. The results for event 09 indicate that, for periods between 2 and 6, a single wavetrain contributes most of the energy for this record, with group velocity going from 3.8 km/s at 5.7 s to 3.6 km/s at 2 s. At smaller periods, many different contributions appear in the record with apparent velocities between 2.7 and 3.6 km/s. The picture is very different for event 04. For this event, in the period range 2 to 6 s, the energy arrives at different times, with apparent group velocities between 2 and 4 km/s. This suggests that the incident angle of the waves on the TVB is important in the generation of diffracted pulses. This had been suggested by Furumura and Kennett [13] based on numerical simulation of ground motion in a 3D model of central Mexico. Our results lend observational support to that result.

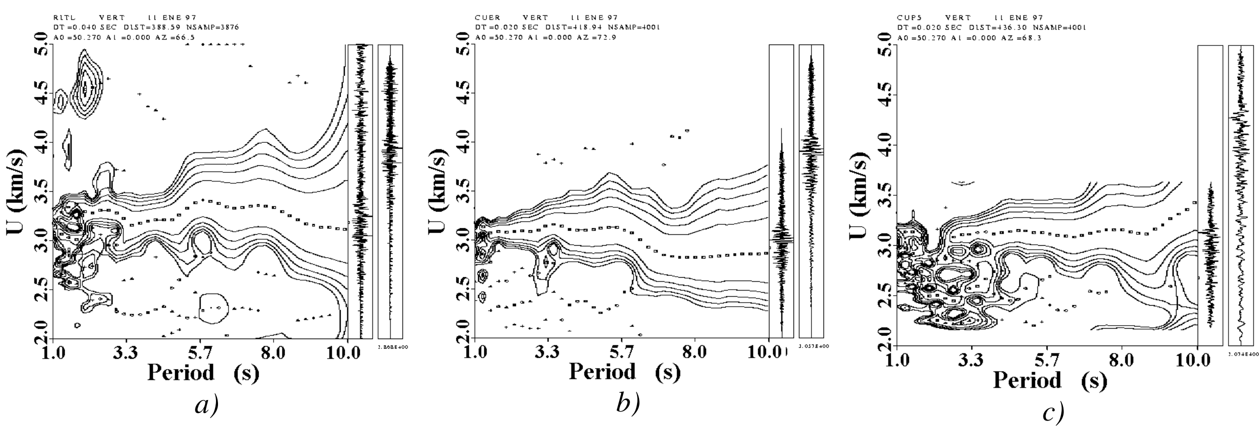


Fig. 5. Dispersion curves, vertical component, of event 09 (11.01.1997) TR2, for station a) RITL. b) CUER. c) CUP5.

Figure 5 shows the U-T diagrams, vertical component, for the same seismic event recorded in three stations. The stations correspond to the line West-East. For station CUP5, for periods between 1.0 and 4.5 s, the contours indicate that contributions with similar amplitude arrive with apparent group velocities in the range between 2.2 and 3.2 km/s (Figure 5.c). However for stations RITL and CUER, group velocity varies in a smaller range, between 2.9 and 3.4 km/s, and between 2.9 and 3.2 km/s, respectively (Figures 5.a and 5.b).

Consistently, analyzed dispersion curves show that for periods smaller than a given value (depending on the path) for stations inside the TVB, the energy arrives during a larger time window. Stations outside the TVB have U-T diagrams with maxima in a smaller velocity range. Our analysis showed that the periods affected vary as a function of the analyzed direction of propagation. For events with a path nearer to the line South-North (TR3) this period (T_{cr}) reaches values of 6 s, while for the rest of the path it reaches values of 3.33 s and until of 4.5 s.

Stacking of the group velocity dispersion diagrams.

The group velocity for periods smaller than 6 s shows great variability from one event to another. With the purpose of obtaining a more stable estimate of U in this period range, we stacked the dispersion diagrams. This procedure allows to emphasize the characteristics common to several diagrams T-U and to eliminate those details that are not consistent for several events. The stack was made for all dispersion diagrams that were similar for each station were stacked, independent of the path.

The diagrams obtained from the stack for CUP1 station, show that results are similar to those for CUER, except for event 09 (Fig. 5.b). For periods larger than a given value the contours in the U-T diagram define a single value for U. For periods smaller than that value, the contours define several maxima for each period with similar amplitude. In the case of station CUP1 the limiting value of period is 6.5 s for events in TR3, while it is 4 s for events in TR5, and 3.5 s for events in TR1 (Figures 6 and 7).

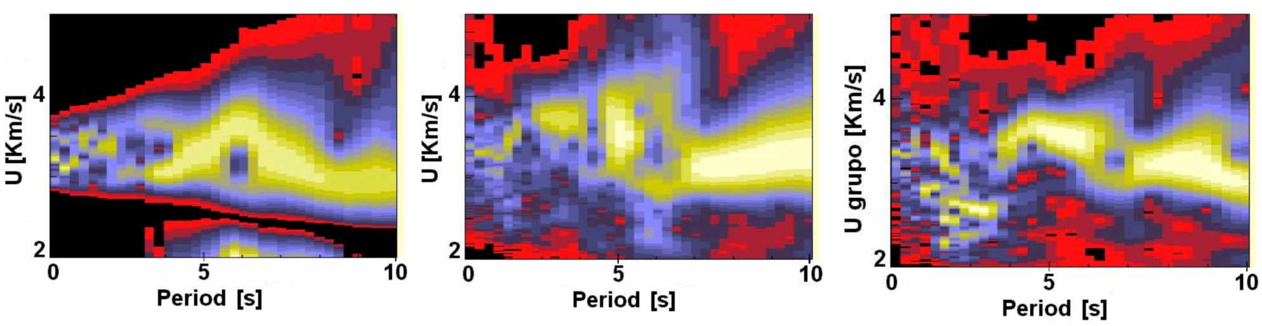


Figure. 6. Staking of the curves T-U of the station CUP1 a) Path TR1. b) Path TR3. c) Path TR5.

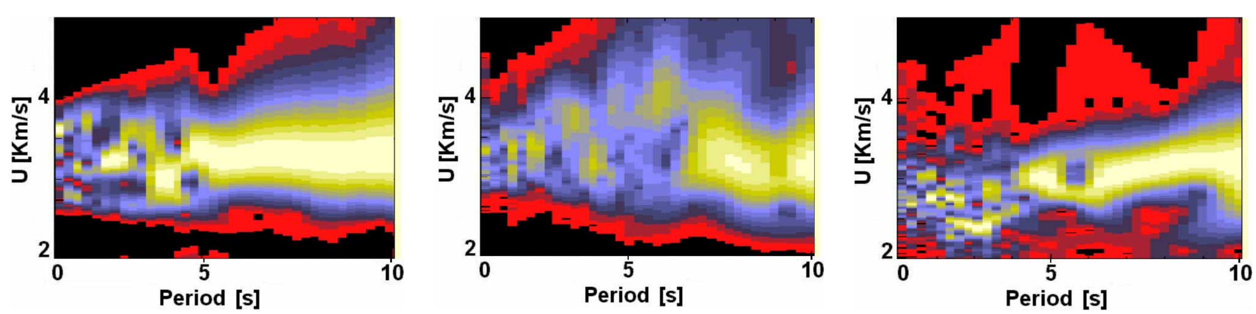


Figure 7. Staking of the curves T-U of the station CUER a) Path TR1. b) Path TR3. c) Path TR5.

Figure 6 shows that for station CUP1, the dispersion diagrams are very similar for periods larger than 6 s, independently of the path. For periods around 5 s group velocity takes values around 4 km/s. These values are larger than the other maxima displayed in the same curve. This support that there are several arrivals at different times. In the same station, for TR3, the stacked diagram shows single U values for periods larger than 6 s. For TR1 and TR5, T_{cr} is close to the 3.5 s. An example of what occurs with the dispersion curves stacked for the stations outside of the TVB is the station TEAC. The diagrams are very stable and the maxima of group velocity occur in a small time window, for periods smaller than 6 s. For the stations CUP1 and CUER, in the same periods range, the group velocity is not easy defined. For station RITL we have not determined if there are variation with the other trajectories exists, because although three events are had, all you belong to TR2.

H/V spectral ratios.

Site effects are caused by the impedance contrast between a very soft soil over another more rigid. On surface rock there is not impedance contrast. In order to verify that our results are not affected by local conditions, we have computed H/V spectral ratios (Lermo and Chávez-García [15]) using our records. We discarded all stations that only had one record. For each record, we took a time window where the stronger ground motion were. The Fourier amplitude spectra, computed from the traces, were smoothed using a triangular, 5-point filter. The average of the two horizontal components was computed for each record, and the resulting curves were averaged for all events recorded by each station. The results are shown in Figure 8, in two groups according to their location relative to the TVB.

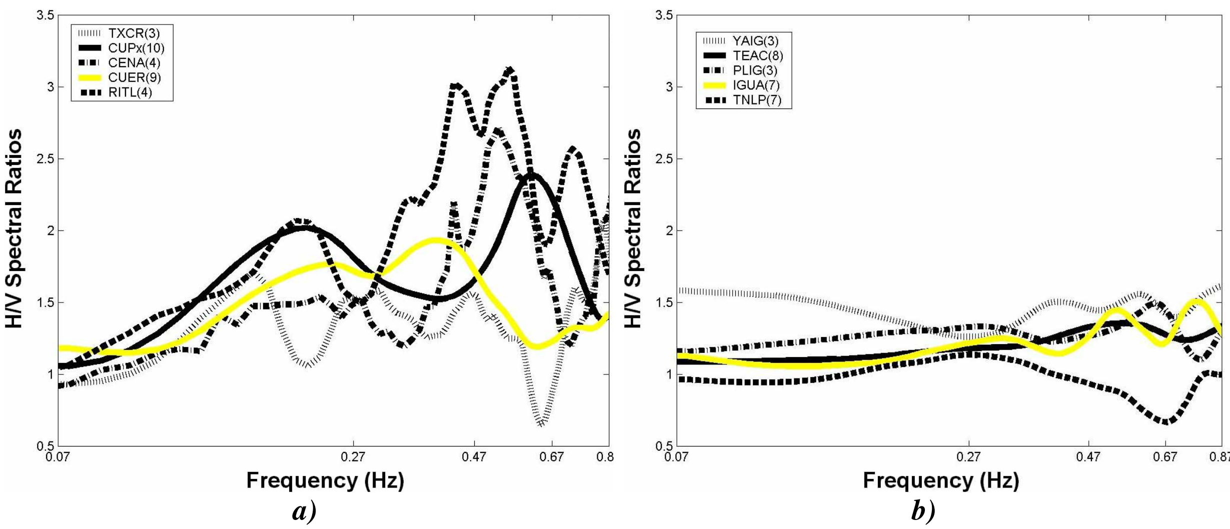


Figure 8. Average H/V spectral ratios for station in a) the TVB, and b) the North-South line, outside the TVB. The number in parenthesis to the right of each station's name gives the number of events that were averaged.

Figure 8a shows the results for 5 stations close to Mexico City. This figure shows two maxima at each station, with exception of TXCR. The first one is close to 0.2 Hz, and the second one around 0.47 Hz. For TXCR we observe values H/V close to 1 but the ratio increases to 1.5 at 0.195 Hz.

The H/V ratios for the stations outside the TVB are shown in Figure 8b. The average H/V spectral ratios for the station YAIG was included in this figure due to the similarity with spectral ratios for stations outside of the TVB. This is probably due to its closeness with the southern limit of the TVB. The results show that the average H/V spectral ratios are close to 1, for all the frequencies analyzed.

Figures 8.a and 8.b show that there are amplification in the stations located on the TVB. For CUPx and CUER the results coincide with the qualitative analysis of the wave form. Both analysis shown that the larger amplifications are between 0.2 and 0.5 Hz. All the station inside the TVB, independently of the site characteristics, show H/V maxima between 0.17 and 0.33 Hz (Figure 8.a). For 0.2 Hz, surface wave velocity is about 3.2 km/s. Thus the wavelength is about 16 km and it cannot be modified by site conditions function of a layer a few m stack. That wavelength could be affected by the TVB. Then, two maxima observed are not appropriated to be related with site effects. If we related these maxima to site effects, it could seem that the installation of those stations was made on not-firms soils, which contradicts the geology reported by the institutions in charge of the stations. This suggest that this phenomenon can be associated to regional effect, probably caused by the TVB.

CONCLUSIONS

We have presented an analysis of the characteristics of the surface wave propagation in central Mexico by means of the TFM, stacking of T-U diagrams and H/V spectral ratios. 22 stations and 13 seismic events were used with epicenters distributed in the country. The data set was taken from the Mexican Database of Strong Earthquakes (Alcántara *et al.* [1]) and were chosen according with its epicentral location relative to the TVB. The qualitative wave form analyses of the records has shown that the signals, for station CUER and CUP1, are amplified mainly in the periods band from 2 to 6 s. The dispersion analysis has shown different group velocities for periods smaller than a value given. This suggests that several arrivals at different times contribute to the energy in this period band. In addition, for paths with azimuth around zero, the group velocity for surface waves with periods smaller than 6 s are affected in a region between PLIG and CUER. The surface waves are refracted and arrive at different times. For paths with azimuths between 60° and 120° or between 240° and 300°, the signal with period between 3 and 4 s are strongly affected. This indicates that the incident angle of the waves on the TVB is important in the generation of diffracted pulses. This had been suggested by Furumura and Kennett [13] based on numerical simulation of ground motion in a 3D structure of central Mexico. Our results lend observational support to that result. The incident angle of the waves on the TVB is important on the generation of diffracted pulses, and the period from as the signals are affected depending on the direction of propagation. The H/V spectral ratios analysis shows maxima around 0.2 and 0.5 Hz for stations inside the TVB, most of them located on rock. For these frequencies the wavelengths are more than 10 km and they cannot be affected by site conditions. That wavelength could be modified by the TVB. For stations located outside the TVB, H/V spectral ratios were around 1. The results obtained from the different analyses, point out that between stations CUER and PLIG, a geologic boundary exists, capable of modifying surface wave with periods smaller than 6 s. This geologic boundary generates waves with different group velocities. These waves are the cause of the long durations recorded in firm areas of Mexico City. It is possible that, in the southern limit of TVB, the pulses are affected by the 3D structure.

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