13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 2428

WAVEFIELD ANALYSIS IN MEXICO CITY FROM THE VERTICAL ACCELEROMETRIC ARRAYS

Martín CÁRDENAS-SOTO[1] and Francisco J. CHÁVEZ-GARCÍA[2]

SUMMARY

The complex wavefield in Mexico City results from the interaction of regional seismic propagation (distances larger than 300 km) with the seismic response of the notorious soft clay layer in the lakebed zone. In order to understand this complex wavefield, we have analyzed data of four earthquakes ($7.0=M_E=7.6$) recorded in 10 vertical accelerometric array located in Mexico City. The analysis consisted of a correlation study of the records, as a function of time along the accelerogram and frequency. The results show fundamental site period (T_0) is a limit that separates two period regions, with different predominant phenomenon. For periods longer than T_0, the wavefield is composed of surface waves. Energy at periods longer than $2T_0$ is guided by the crustal structure in central Mexico; ellipticity, phase velocity and direction of propagation for the wavefield coincide with the fundamental mode of surface waves propagating from the epicenter. The wavefield at periods between T_0 and $2T_0$ also consists of surface waves, but they are guided by the upper 2-3 km of volcanic sediments in central Mexico. In this period range, the dominant propagation mode is still surface waves, but they do no longer come from the epicentral region. For periods smaller than T_0, ground motion is uncorrelated among the stations, and it becomes impossible to determine a propagation mode. At these short periods, response is dominated by the very local amplification due to the soft soils. The duration of seismic ground motion is similar for the four events (more that 200 s in lake zone), and the largest amplitudes at the surface are distributed over a long time. Our results indicate that seismic response of Mexico City results from the interaction of surface waves guided by the deep and intermediate crustal structure with the very local response of the soft surficial clay layer.

INTRODUCTION

Mexico City has experienced repeatedly destructive seismic motion from earthquakes occurring along the Pacific subduction zone, more than 300 km away. Several factors play a key role in this: the decay of amplitude for energy propagating perpendicular to the subduction zone (in the direction of Mexico City) is smaller than that observed along paths parallel to the coast (Cardenas *et al.* [1]); the very soft clay layer in the lakebed zone amplifies ground motion by up to a factor 40 in the frequency domain relative to ground

[1]Facultad de Ingeniería, UNAM, México. Email: martinc@servidor.unam.mx
[2]Instituto de Ingeniería, UNAM, México. Email: paco@hermes.iingen.unam.mx

motion observed on firm soil in Mexico City; and the very long duration of ground motion. A great many studies have dealt with these aspects in the past 17 years, since the occurrence of the great September 1985 earthquakes. However, our understanding is still incomplete. For example, while it is clear that the large amplification is due to the large impedance contrast between the soft sediments filling an ancient lake below Mexico City, this does not explain the large duration of ground motion, characterized by a succession of harmonic wave packages (Singh and Ordaz, [2]). This long duration was the object of several papers, where different hypothesis were advanced as possible explanations, from 2D or 3D site effects to gravity effects. These different hypotheses were rejected using numerical modelling by Chávez-García & Bard [3,4,5]. This forced a return to data analysis, in order to better understand the wavefield propagating in Mexico City during large earthquakes.

The main event in 1985 was recorded by only 8 digital accelerographs. The first analysis of these records used spectral ratios to quantify the amplification due to the soft soil layers in the lakebed zone (Singh *et al*., [6]). These same records were later reappraised by Chávez-García *et al*.[7], who were able to identify surface waves in two period bands. In the band 7 to 10 sec, these surface waves propagated along the direction epicenter-stations, with velocities predicted by deep crustal structure. In the period band 3 to 6 sec, surface waves were again observed, but they propagated with directions different from the epicentral one. Chávez-García *et al*. [7] hypothesized that the long seismic duration resulted from the interaction of waves guided by the deep structure of the basin with the 1D resonance of the superficial layers.

Characterization of the wavefield at Mexico was also at the center of a collaboration project between Mexico and France in 1994. During that project, a dense array of VBB stations was installed on firm soil in Mexico City. Barker *et al*. [8] analyzed 11 events recorded in this array, and showed that, in the period band 2.5 to 5 sec, long duration of seismic motion in Mexico basin is produced by late surface wave arrivals. They explained these late arrivals as wavetrains scattered from the boundaries of the Mexican Volcanic Belt (MVB). Recently, Iida [9] reached the same conclusion from the analysis of seismic records for one earthquake in four three-element, vertical arrays. This author proposed that the incident field in the basin of Mexico consists of Love waves diffracted by the lateral heterogeneities within MVB. The hypothesis by Iida was rejected by Shapiro *et al*. [10], who analyzed the records of 9 subduction events recorded in 5 vertical arrays in the lake zone of Mexico City. Shapiro *et al.* [10]proposed that the wavefield in the lake zone, around 3 sec period, is dominated by higher surface modes. However, they do not explain the long duration of ground motion.

Cárdenas-Soto and Chávez-García [11] analyzed strong ground motion data for three earthquakes (7.0=Mw=7.6) recorded at Roma Array (5 stations with absolute time, forming a small-aperture, dense array in the lake zone). The results showed that, for periods larger than 5 s, the seismic wavefield consists of surface waves propagating from the epicenter with phase velocities similar to those predicted by an average crustal model. In the period band between 3 and 6 s, incoming energy comes only partially from the epicenter, with significant contributions with different backazimuths. Phase velocities, however, were in good agreement with those predicted by the crustal model. Finally, for periods smaller than 3 s, they observed a strong resonance of the soft soil layers, with long duration of seismic motion, in addition to harmonic wave packets in the records at the surface. At these short periods, the correlation between stations drops sharply and Cárdenas-Soto y Chávez-García [11] interpret the wavefield as consisting of vertical propagation of body waves and slow, small amplitude local surface waves.

Thus, data analysis has increasingly suggested that ground motion in Mexico City cannot be interpreted in a piecewise fashion. All the different studies coincide in that it is necessary to consider together site effects and regional propagation effects (*e.g.*, Cárdenas *et al.* [12]) if we want to understand ground motion for large earthquakes from the subduction zone. The results of observation analysis are also backed by regional propagation in models of the 3D crustal structure (Furumura & Kennett, [13];

Furumura and Singh, [14]). An understanding of the physical causes of the destructive ground motion in Mexico City is required if we want to decrease our current dependence on statistical regressions of recorded data to predict ground motion in central Mexico for future large earthquakes.

STRONG MOTION DATA

We analyzed data from 10 accelerometric vertical arrays in Mexico City. Figure 1 shows the location of these arrays. Each array usually consists of three accelerometers at different depths; one at the surface and two at different depths (Table 1). Figure 1 also shows the zonation of Mexico City valley. Array CHA is located in the hill zone, arrays COY and IMP are located in the transition zone, and seven vertical arrays are located in the lakebed zone (EJP, RMC, SCT, UNK, ZAR, TLA, and CDA). In all the arrays of the lakebed zone, the deeper accelerometer is located at the interface where there is an high impedance contrast between the soft clay layer and more consistent substrata. Each array has a common time base for its three stations, which allows to measure delays among them by computing the crosscorrelation between traces. Each array has different time precision. We found that the time base of RMC array has a clock that is more precise than that of other arrays. For this reason, we have used the time at RMC as the basis from which we recomputed absolute time to the records of the other arrays, following the procedure of Chávez-García *et al.* [7].

Our dataset was complemented with records from three, independent stations located in the hill zone. We have chosen four events recorded in almost all of our stations, with M_E magnitudes comprised between 7 and 7.6 (Table 2). We first analyzed qualitatively the records filtered around different periods. Then, we examined the wavefield at each array using a correlation analysis. Finally, we have used *f-k* (frequency-wavenumber) analysis to determine directions and velocities of the wavefield that crosses Mexico City. Horizontal components have been rotated to Radial and transverse components relative to the epicenter and thus refer to different directions for each event.

WAVEFORM ANALYSIS

The records were filtered around 18 periods, from 1.5 to 8 sec, using a butterworth filter with a passing band whose width increases with frequency. The central frequency varies according to the expression

$$f_n = f_{\min}(1.1)^{i-1}$$

where $f_{min}=1.25$ Hz, and $i=1,2,...,18$. The bandwidth of the filter was determined for each central frequency f_n using

$$(1-w)\,f_n < f < (1+w)\,f_n$$

where $w=0.25$ is the relative bandwidth of the filter. Figure 2 shows, for example, the vertical components recorded at station C0 (the surface station at RMC array, topmost traces) for the events 1, 2 and 3 of Table 2. Below each recorded trace, Figure 2 shows the traces that result of applying our 18 band-pass filters. For periods larger than 4 sec, we observe some differences between the filtered traces for the different events. At such long periods, these differences must be due to differences in the source and in the crustal structure along the corresponding paths. For filters with central period between 4.1 and 8.0 sec, the filtered traces for event 1 show the arrival of energy during a long duration; at some periods, we distinguish several pulses arriving at different times, with similar amplitudes. This contrasts with that same record, filtered between 2.8 and 3.7 sec period, where a single pulse (between 50 and 75 sec) dominates the record. Event 2 shows different results, with a single pulse dominating the record between 3 and 8 sec period. The last column in Figure 2, corresponding to the record of event 3, shows an intermediate behavior; several pulses appear already at 8 sec period, but they are closer in time than the different pulses composing the record for event 1. In all the stations, we observe that the radial component is very similar to the vertical recorded at the corresponding location, for periods larger than 6 sec. Therefore, it is likely that these arrivals consist mainly of Rayleigh waves. Ground motion at long periods is dominated by wavetrains with wavelengths significantly larger than the distance between stations. Consider now the smaller period band. When the central period of the filter is smaller than 3 sec, several pulses dominate the filtered traces. The records show pulses whose amplitude contributes significantly to ground motion for a long duration, more than 100 sec in some cases. The shape of the traces becomes very different between the different stations, and it is no longer possible to identify common pulses between stations.

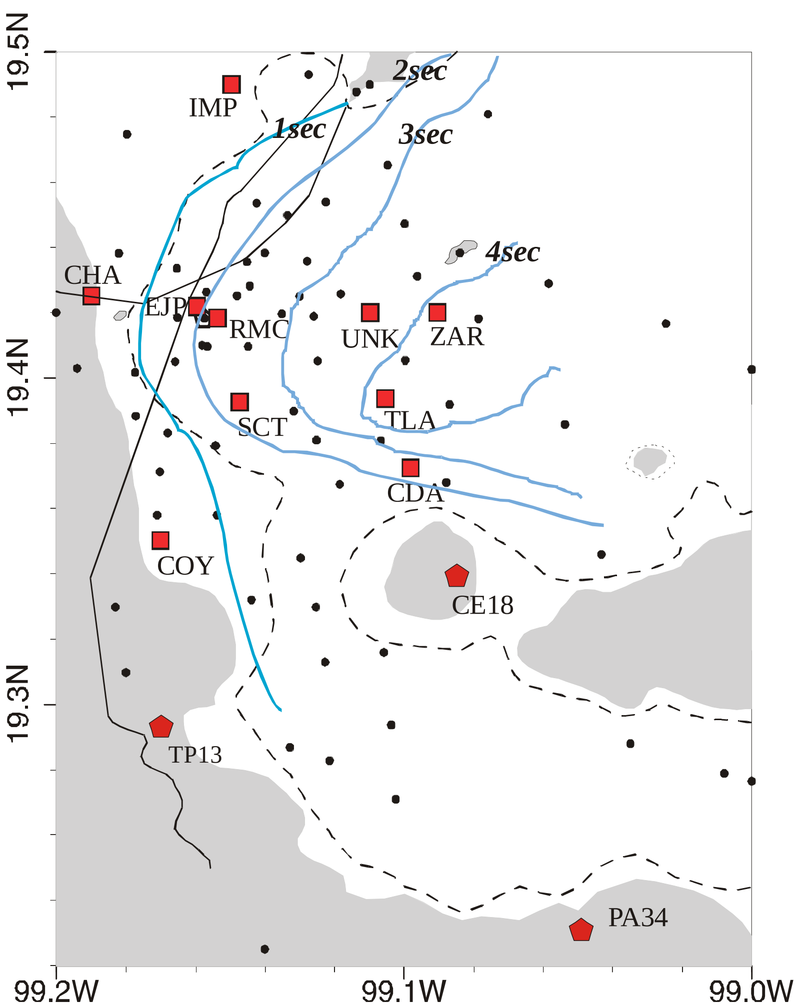

Figure 1. Map of Mexico City valley showing the locations of vertical accelerometric arrays (squares) and the three hill zone accelerometric stations (CE18, PA34, TP13). The solid circles indicate the locations of accelerometric surface stations of Mexico City. The grey zone represents the hill zone and the dashed line indicates the limits between transition and lakebed zone. Solid lines indicate main streets. The isoperiod lines of 1, 2, 3 and 4 s are also shown.

Consider now the records obtained at depth. Figure 3 shows the radial component recorded at the surface (C0), at 30 m depth (C1) and at 102 m depth (C2) for event 1 recorded at RMC. Below each recorded trace, we plot the traces obtained after filtering through 18 bandpass filters (the central period of the filter is indicated to the right of each trace). For periods larger than the dominant period (T_0) at RMC site (2.25 sec), the waveforms are very similar between each group of three traces, although the traces recorded at depth have smaller amplitudes. For periods shorter than T_0, 1D amplification by the soft soil layers between C0 and C2 makes the records very different, and correlation drops sharply. The surface trace (C0) and the trace at 30 m depth (C1) remain similar at periods shorter than do the traces at surface and 102 m depth. A recurrent subject regarding ground motion at Mexico City has been the late arrivals that we can observe in the recorded traces at the surface. The recorded trace at the surface in Figure 3, for example, shows such a late arrival at 120 sec time. Figure 3 shows that this late arrival has its energy around T_0, is present at C1 and are absent from C2. If we look at the vertical components, we observe similar late arrivals but they are not correlated with those observed in the radial components. Similar plots were drawn for the transversal component. We observed that the transversal component is not correlated with either the vertical or radial components in any period band. The observations for the data from the RMC array apply to the other lakebed zone arrays. In particular, we observe characteristics similar to those described for SCT and JAL arrays. In the arrays UNK, ZAR, TLA and CDA, the dominant characteristic is the lack of correlation between vertical components of intermediate and surface station close to site period at each array.

We have plotted time-distance profiles with the records filtered at different period band, for each ground motion component. The results show that, for periods larger than 6 sec, the wavefield that crosses Mexico valley is composed of surface waves coming from epicenter, and it is not affected by the local soil conditions. We identify a great similarity between vertical and radial components, which indicates the predominance of Rayleigh waves. For periods smaller than 6 sec, in particular between 3 and 4.5 sec, we have identified common wavetrains between vertical components of the deeper stations. Figure 4a shows, for example, the vertical component of event 1, filtered between 3 and 4.5 sec period, recorded at the deeper station of five arrays (CHA, COY, RMC, CDA y ZAR). We observe a common wavetrain in all the stations. The radial component (Figure 4b) is very similar to the vertical, which indicates the dominance of Rayleigh waves. The records for the transverse components (not shown) are not correlated either with the vertical or radial. Analyzing the records of the other stations (surface and intermediate depth) we observe that the wavetrains identified at the deeper stations are also observed at the stations CHA, IMP and COY, located in hill and transition zones, and in the lakebed zone arrays at JAL, RMC, SCT y CDA. In these latter stations, the dominant period at their sites is 2 sec, shorter than the period band of our analysis (3 to 4.5 s). Thus, the resonance of the clay layer does not occur, and its amplification does not mask the vertical correlation between stations at each site, or the correlation between the different arrays.

Figure 4c shows the vertical records at surface for the five stations shown in Figure 4a. We observe that the wavetrains recorded at depth are also observed in the surface records of stations CHA, COY, RMC and CDA, but not in station UNK, ZAR, and TLA. This is reasonable. At stations UNK, ZAR, and TLA, dominant period is larger than 3 sec. Thus, when we analyze the period band from 3 to 4.5 sec, we include the resonance of the clay layer for these stations. The comparison of these three sites with the previous ones shows that the surface waves that compose the incident wavefield in Mexico City excites the 1D resonance of the very soft clay layers when there is coincidence between the period content of the input motion and the dominant period at each site. The analysis of filtered traces shows clearly that T_0 at each site conditions the observed ground motion. For periods around T_0, the late arrivals, uncorrelated between stations or components, are responsible for the large amplitudes and long durations of ground motion. For periods longer than T_0, the traces are similar, with common wavetrains observed at the different stations.

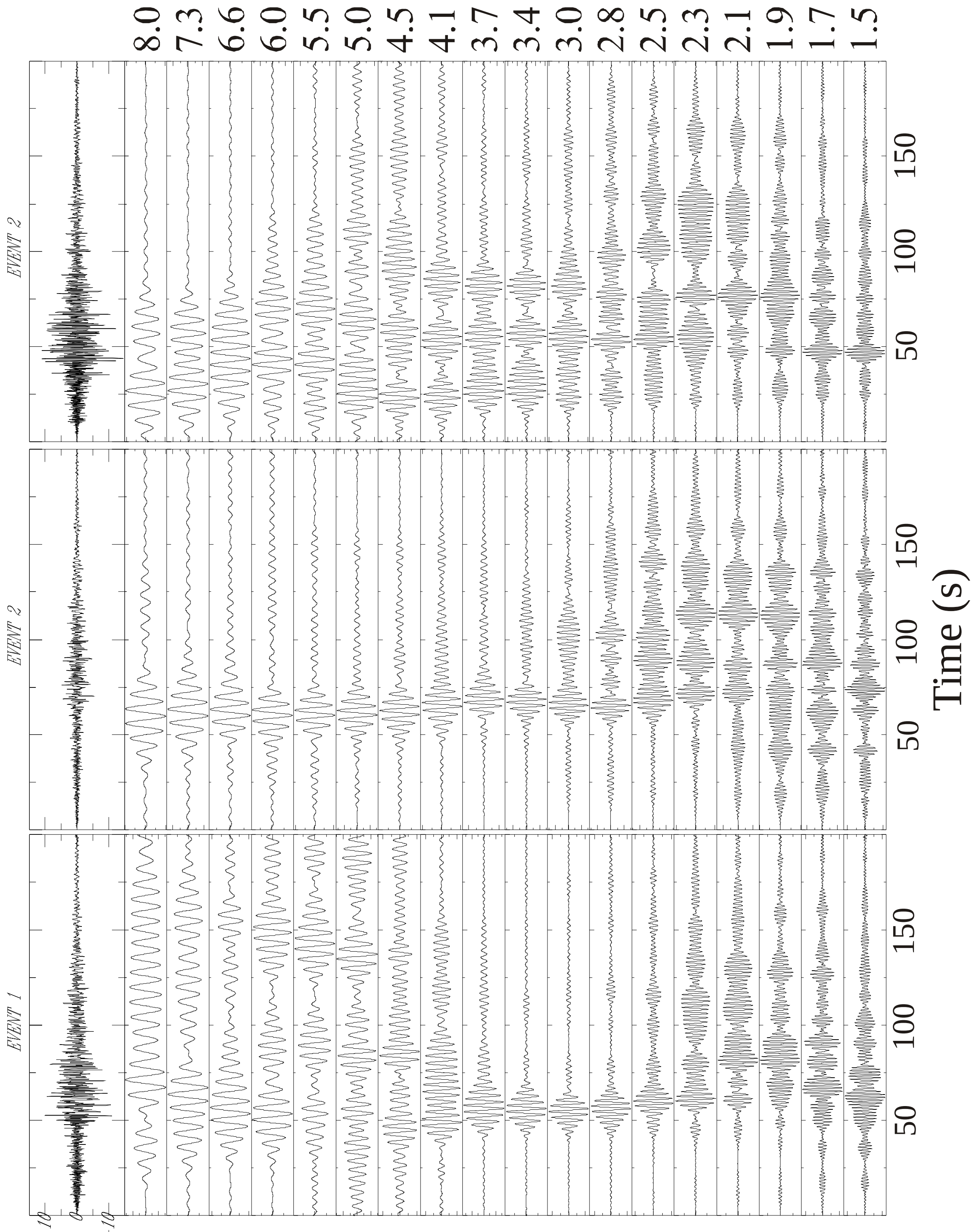

Figure 2. Top most trace of each column: recorded vertical component at the C0 surface station of Roma array for events 1, 2 and 3 of Table 2. The traces below each record result from 18 bandpass filters. The central period of each filter is given to the left of each trace in s. Each trace is scaled to its maximum amplitude.

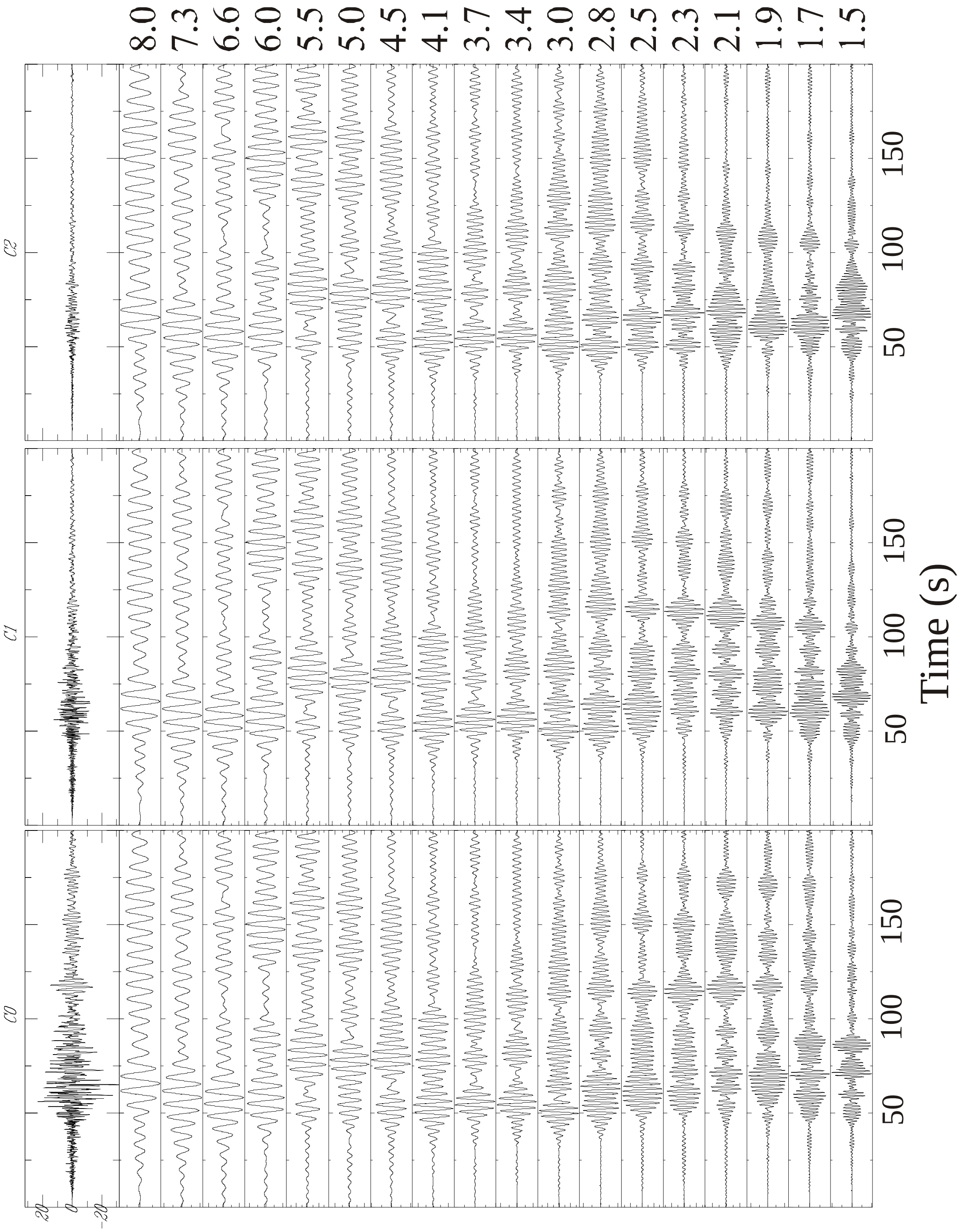

Figure 3. Top most trace of each column: recorded radial component at the three stations of Roma array that form a vertical line at location C, for event 2 of Table 2. C0 is the station at the surface, C1 is located 30 m below station C0, and C2 is located 102 m below the surface. The traces below each record result from 18 bandpass filters. The central period of each filter is given to the left of each trace in s. Each trace is scaled to its maximum amplitude.

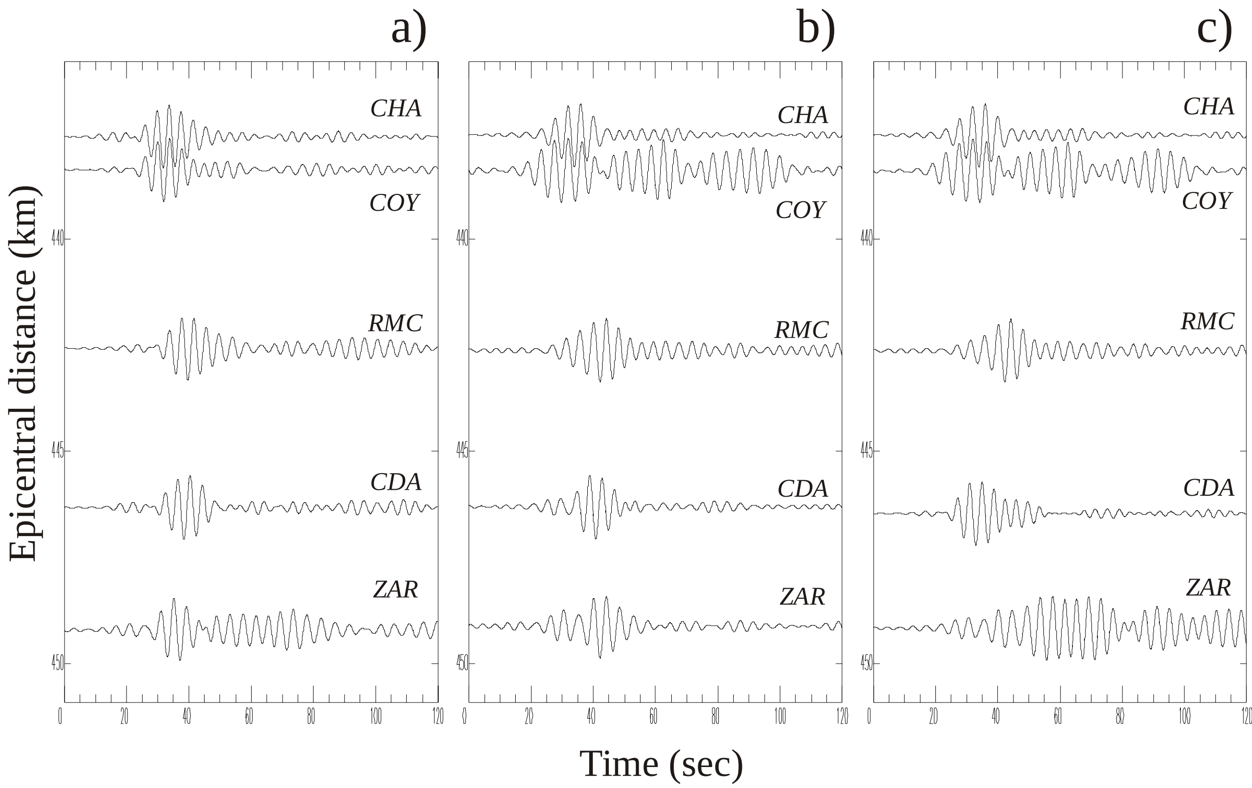

Figure 4. Time-distance record sections of vertical arrays for event 1 (Table 1). a) and b) Vertical and radial components, respectively, of the deepest stations. c) Vertical components at surface stations. The records are filtered between 3 and 4.5 sec period. The amplitude scale is common to all traces.

CORRELATION ANALYSIS

We have used a crosscorrelation analysis to measure delays of common wavetrains between stations. In addition, we compute the ellipticity for our records, for those time windows where we identified significant correlation between vertical and radial traces. We have used the same set of bandpass filters discussed above. Each filtered traces was windowed using time windows of duration equal to 3π times the central period of the bandpass filter. The overlap between successive windows was 1/4 of each window's length. Each time window was cosine tapered and a correlation coefficient (CC) was computed between the two waveforms (vertical and radial for surface wave identification) to be compared. If there is perfect correlation between the two windows, we obtain a correlation coefficient of 1 (for in-phase signals) or –1 (for opposition-of-phase signals).

We expect surface waves to show a similar correlation between radial and vertical components at surface and at depth, especially if the vertical distance between stations is smaller than the wavelength. For example, we computed the values of CC between radial and vertical components (for event 1) for the station RMC at 102 m depth, much deeper than the very soft clay layer. Figure 5 shows the difference between the CC values computed at the surface between radial and vertical components, and those at 102 m depth, also between radial and vertical. This figure shows that the correlation between radial and vertical components at the surface is very similar to the correlation between those two components at 102 m depth. The difference is close to zero for periods larger than 3 sec; if the correlation is large at the surface, it is also large at depth, all along the time duration of the records. This result supports the idea that surface waves are dominant at all times, for periods larger than 3 sec. The larger values in Figure 5, at periods smaller than 3 sec, indicate time-frequency windows where the correlation between radial and vertical components at the surface is different from that at depth, suggesting that body waves are important. The limiting period coincides with the dominant period of the very soft layers at RMC site. When we compare the CC values between radial and vertical components at the surface with those computed for the record at 30 m depth, we observe even larger similarities than those shown in Figure 5. The distinction for periods larger and smaller than 3 sec is blurred, which can be easily understood because the thickness of the soft soil layer at Roma is larger than 30 m. Thus, the correlation between radial and vertical components is similar between the records at the surface and at 30 m depth, even for body waves.

A similar analysis was done for events 2, 3 and 4 recorded also at RMC. The results are similar to those for event 1. Between the surface and 102 m depth, the CC values between vertical and radial components are similar. The difference between the two sets of CC values is close to zero for periods larger than 3 sec. The results between the surface and 30 m depth show again smaller differences. These results suggest that, for periods larger than 3 sec, the records are dominated by surface waves. For periods smaller than 3 sec, ground motion is correlated between the surface and 30 m depth, but not between the surface and 102 m depth, indicating that in this period band, the energy gets trapped in the soft layer.

Small correlation between radial and vertical components at any one station could indicate absence of Rayleigh waves, but could also result from Rayleigh waves propagating in a direction different from the radial one. We have tested this possibility by computing the correlation between vertical and horizontal ground motion in different directions. To this end, we rotated horizontal motion to different directions between 0 and 180 degrees azimuth, with a step of 15 degrees. The CC was computed between vertical motion and the resulting horizontal component for each rotation, at the three stations of RMC array. The results did not show any preferred direction for which the correlation between vertical and radial motion increased significantly, for any of the three events we analysed.

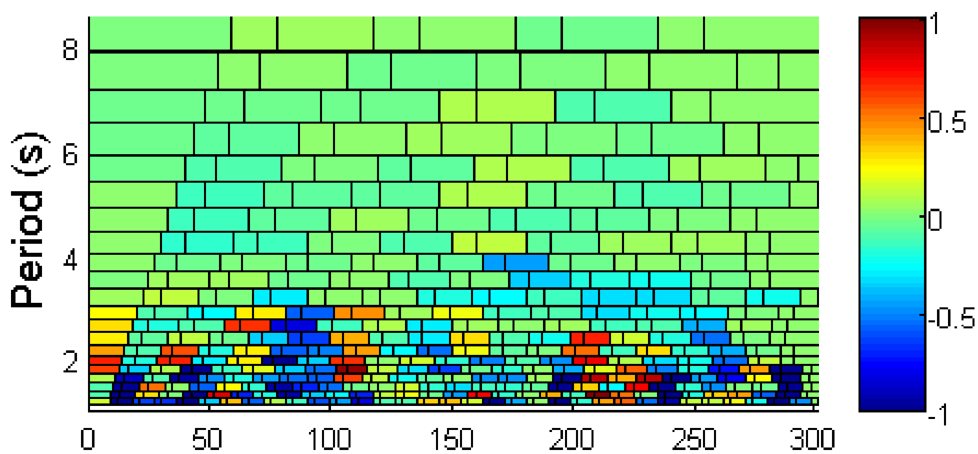

Figure 5. Correlation coefficient differences at RMC vertical array as a function of time along the record and central period of filter used for the analysis of accelerograms of event 1. We first computed the correlation coefficient between vertical and radial components at the surface and at 102 m depth. This figure shows the result of subtracting the resulting images. The rectangles indicate the time-frequency window analyzed. The color scale indicates the values of the difference between correlation coefficient.

Let us look now the values of ellipticity, computed as follows. We used the CC values between radial and vertical components computed before to select those time-frequency windows where the absolute value of the correlation coefficient was larger than 0.25. This makes sure that we are looking at the same wavetrain in the two components. For these windows, the envelope of the windowed, filtered traces was computed, and a value of Ur/Uz determined as the ratio of the maximum amplitudes of the envelope. Figure 6 shows, for example, the ratio Ur/Uz at the surface (Figure 6a) and at 102 m depth (Figure 6b) in RMC array for the larger amplitude portion of the records (time window 50-150 sec in Figure 2) for the four events. For periods larger than 4 sec, Ur/Uz values are similar at the surface and at 102 m depth. For periods smaller than 4 s there is a large scatter; Ur/Uz at the surface is in average an order of magnitude larger than at 102 m depth. We have included in Figure 6 the theoretical curves for the ellipticity of the fundamental and first higher modes of Rayleigh waves computed for the composite velocity profile at RMC (Table 3, taken from Yamashita Architects and Engineers Inc. Oyo Corporation [15], Gutiérrez *et al*. [16], Valdes *et al*. [17]). We observe that for periods larger 4 sec, Ur/Uz ratios at the surface and at 102 m depth follow the ellipticity of the fundamental mode. Between 2 and 4 sec period, Ur/Uz surface ratios suggest that the first higher mode becomes predominant. For periods smaller than 2 sec, Ur/Uz ratios show at surface exist significant correlation between waveforms of radial an vertical time windows in comparison to 102 m depth. We did the same computation for the coda of the records and found similar results. Ur/Uz ratios for the other events show that, for periods larger than 4 sec, seismic ground motion in the vertical and radial components at RMC array is dominated by the fundamental Rayleigh mode. For periods smaller than 4 sec, higher modes are possible, together with other propagation modes. Figure 6 also show a lack of the ellipticity values for some intervals of periods. This show that the response of the site is a function of the incoming wavefield.

F-K ANALYSIS

We have applied a conventional *f-k* (frequency-wavenumber) method [18] in order to study the predominant input ground motion in Mexico City. To this end, we use as array the deepest stations of each vertical array together with three surface stations (TP13, CE18 and PA34) located in the hill zone (Figure 1). The unit response of the spatial distribution of our stations (not shown) indicates that we cannot resolve wavelengths smaller than 6 km. Figure 7 shows the results for event 1, for the three components of motion. For periods larger than 7 s, surface waves propagate along the direction from the epicenter to the stations (Figure 7a). For periods smaller than 7 s, the dominant wavetrains seem to come from a backazimuth 45 larger than the epicentral one, indicating that the irregular 3D geometry of the crust plays a large role in this period band (this has been shown using numerical modelling in Furumura and Kennett [13]). Figure 7b shows that, for periods larger than 7 s, the phase velocities obtained are similar to those computed for the fundamental mode of Rayleigh waves. For periods less than 7 sec, we observe discrepancies between the phase velocities obtained from each ground motion component, and the phase velocities increases up to 6 km/s. This suggests that higher modes may control ground motion in this period range. Similar results are observe for the events 2, 3 and 4.

CONCLUSIONS

We have explored the nature of the seismic wavefield that propagates in the lakebed zone of Mexico City during large earthquakes. The data we used were accelerograms of four events recorded at 10 vertical arrays and three surface stations. The records were bandpass filtered around 18 periods, from 1.5 to 8 sec, using a butterworth filter with a passing band whose width decreases with frequency. In a first time, the compared the filtered traces qualitatively. In a second time, the filtered traces were analysed in detail computing the crosscorrelation among traces as a function of time (using time windows whose width was 3π times the central period of the corresponding bandpass filter) and period. Finally, we apply a *f-k* method in order to determinate the characteristics of the predominant input wavefield.

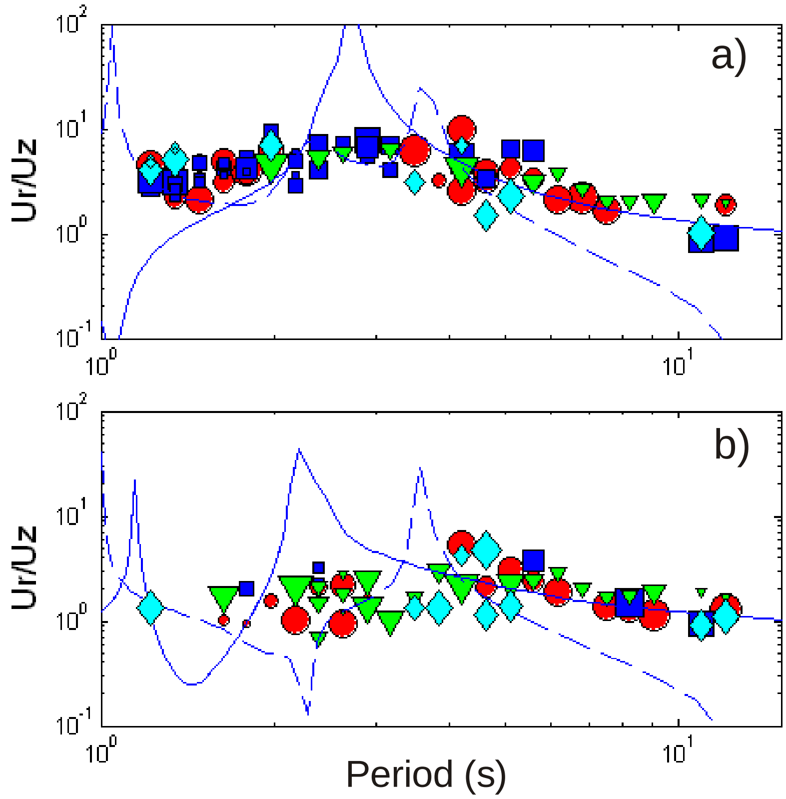

Figure 6. Ellipticity values (ratios of the amplitude of the envelope between radial and vertical components) at the surface (a) and at 102 m depth (b). The time window analyzed corresponds to the intense part of the records (the time window going from 50 to 150 s time in Figure 2). Circles, squares, triangles and diamonds correspond to the results for events 1, 2, 3 and 4, respectively (Table 1). The solid and dashed lines show the theoretical ellipticity curves of the fundamental and first higher mode of Rayleigh waves, computed for the soil profile given in Table 3.

The qualitative analysis of the traces showed that, at long periods larger than 6 sec the wavefield consists of surface waves efficiently guided by the crustal structure. The crosscorrelation analysis showed that these surface waves in the vertical and radial components correspond to the fundamental and first higher modes of Rayleigh waves, propagating from the epicentral region for the more intense part of the signals, while the coda shows the same propagation modes but with contributions from different backazimuths. We observed that seismic duration is independent of the backazimuth of the event. The recorded ground motion has large duration around the fundamental period of the very soft surficial layers for those arrays located in the lakebed zone. At this period, monochromatic wavetrains (the notorious beating) dominates the coda of the records at the surface, but is not observed at depth.

The cross correlation analysis among the traces allowed us to establish similarities among the records. We observed that the vertical component maintains a large correlation among all the stations for almost all the period range we analysed. In contrast, horizontal components are correlated only for periods larger than 5 sec. For periods smaller than 5 sec, the deepest station at the vertical arrays located in the lake zone becomes uncorrelated with the stations at the surface, which remain correlated down to 3 sec. When the correlation coefficient among vertical and radial components at each station was larger than 0.25, we computed the average Ur/Uz amplitude ratio as a function of period and time along the records. The results showed that, for periods larger than 5 sec, ground motion in the vertical and radial components is dominated by the fundamental mode of Rayleigh waves (the transverse component consists mainly of the fundamental mode of Love waves in this period band). For periods between 2 and 4 sec, the ellipticity values suggest that the first higher mode becomes important, while for periods smaller than 2 sec the ellipticity at the surface becomes an order of magnitude larger than that at deepest stations. For periods close to and smaller than that dominant period, the correlation between motion at the surface and at depth decreases sharply, indicating that ground motion at the surface is dominated by propagation within the soft clay layers.

All of our results suggest that, for periods larger than the dominant period (T_0) at vertical arrays of lake zone, surface waves dominate ground motion. At T_0, horizontal ground motion becomes uncorrelated between the surface and the soil layers more deeper than soil clay layer, with the notorious monochromatic beating appearing at the surface. This argues against the interpretation of that beating being a feature independent of the soil conditions, as proposed in Singh and Ordaz [2]. For periods smaller than T_0, we observe the coexistence of body and surface waves, propagating within the soft clay layers. Thus, in order to understand the long duration of ground motion in the lake zone of Mexico City, we need to consider together path and site effects. The results presented here support the hypothesis of the interaction of surface waves with the local 1D resonance as an explanation of the observed ground motion. Those surface waves do not appear to be simple modes, guided by a layered structure, but seem to result from contributions propagating from the source and also from diffractors along the path source-Mexico City.

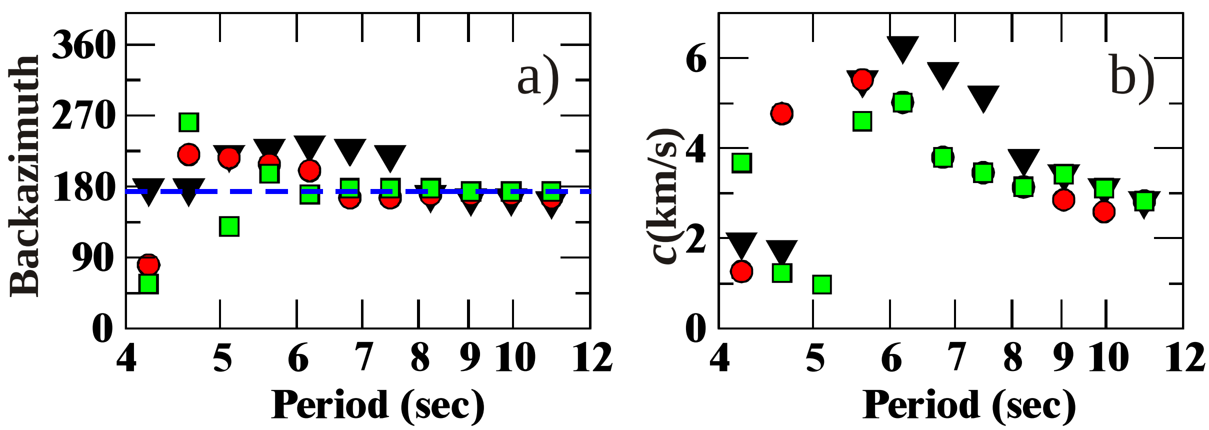

Figure 7. Backazimuth (a) and phase velocity (b) values obtained from *f-k* analysis of the records of event 1. The stations used for this analysis are the deepest accelerograph of each vertical array together with the surface stations CE18, PA34 and TL13. Triangles, circles and squares represent the results for vertical, radial and transverse components. The dashed line in Figure 7a represent the backazimuth of the epicenter for this event.

Acknowledgements

This research was supported by the División de Ingeniería en Ciencias de la Tierra, Facultad de Ingeniería, UNAM.

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Table 1. Some characteristics of the events used in this study. Epicentral distance and Backazimuth values are calculated to RMC array

No.	Date ddmmyy	Long.W	Lat. N	Epi. Dist. (Km)	Depth (Km)	Baz.	M_E
1	14.09.95	98.8	16.6	314	21	173°	7.3
2	11.01.97	103.0	17.9	442	33	248°	7.1
3	15.06.99	97.4	18.2	223	70	127°	7.0
4	30.09.99	97.03	15.95	445	16	149°	7.6

Table 2. Vertical arrays and events recorded by each station

Array	Depth (m)	Event Number			
		1	2	3	4
1 RMC	0	x	X	x	
	30	x	X	x	
	102	x	X	x	
2 UNK	0	x	X		x
	30	x	X		x
	83	x			
3 JAL	3	x	X	x	x
	20	x	X	x	x
	45	x	X	x	x
4 ZAR	0	x	X	x	x
	30	x	X	x	x
	83	x	X		
5 SCT	10	x	X	x	x
	25	x		x	x
	40	x		x	x
6 TLA	0		X	x	x
	30		X	x	x
	86		X	x	x
6 CDA	12	x	X	x	x
	30		X	x	x
	60		X	x	x
7 COY	0	x	X	x	x
	12	x	X	x	x
	70	x	X		
8 CHA	0	x	X		x
	22	x	X		x
	52	x	X		
9 IMP	0	x	X	x	x
			X	x	x
	85	x	X	x	x

Table 3.Subsoil models at RMC site

	Thickness (km)	Vp (km/s)	Vs (km/s)	ρ (g/cm3)
Yamashita Architects [15]	0.012	1.43	0.045	1.2
	0.018	1.43	0.06	1.2
	0.014	1.43	0.13	1.4
	0.021	1.68	0.35	1.5
	0.037	1.75	0.43	1.7
	0.075	2.0	0.6	1.8
	0.1	2.6	1.2	1.9
Gutierrez *et al.* [16]	0.5	2.6	1.2	2.0
	0.8	3.3	2.6	2.3
	1.9	4.5	2.8	2.4
Valdes *et al.* [17]	7	4.5	2.6	2.6
	12	5.4	3.2	2.7
	28	7.0	4.0	3.0
	-	8.3	4.8	3.3