Geophys. J. Int. (2001) **147**, 517–527

Evidence of the dominance of higher-mode surface waves in the lake-bed zone of the Valley of Mexico

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Accepted 2001 May 4. Received 2001 April 2; in original form 2000 July 4

SUMMARY

We compare ground motions recorded at the surface and in boreholes at five different locations of the lake-bed zone of the Valley of Mexico with theoretical dispersion curves and eigenfunctions calculated for the first two modes of Rayleigh and Love waves. We find that (1) the maximum in the horizontal-to-vertical displacement ratio, which occurs at the dominant frequency of the site (0.4 Hz), corresponds to the higher mode rather than to the fundamental mode of the Rayleigh waves, (2) borehole records at depths from 0 to 100 m show that the normalized vertical displacement does not decrease rapidly below the superficial clay layer, as should be the case for the fundamental mode, but remains ≈ 0.8, and (3) the measured phase velocity at a period of about 2.5 s (2.0 ± 0.5 km s^{-1}) is too fast for the fundamental mode predicted for the known crustal velocity structure. These observations lead us to conclude that the wavefield in the lake-bed zone in Mexico City is dominated by higher-mode surface waves. This provides a plausible explanation for the long duration of the coda in the lake-bed zone. Although shear wave Q is very small (10–20) in the clay layer, the higher modes of surface waves do not propagate in the superficial clay layer but in the underlying structure where Q-values are likely to be relatively high. Thus, while the clay layer plays the passive role of amplifying the ground motion, its contribution in damping out the motion is insignificant. The results have two important practical implications. (1) The strain estimate from recorded ground velocity differs significantly for the fundamental mode as compared to the higher-mode surface waves. (2) If the ground motion is dominated by the fundamental mode, then knowledge of the superficial layer and the velocity contrast with the underlying structure is sufficient for understanding and modelling of the ground motion. If, however, the higher-mode surface waves dominate, then a detailed knowledge of the deeper structure is required.

Key words: higher nodes, strong motion duration, surface waves, Valley of Mexico.

1 INTRODUCTION

The great 1985 Michoacan earthquake ($M_w = 8.0$) was probably unique in the sense that it caused major destruction to Mexico City located more than 350 km away from the epicentral area. It is well known that this damage was provoked by strong amplification of the ground motion because of the very unfavourable characteristics of the subsoil of the Valley of Mexico. The importance of the site effects is evident in the distribution of the damage in Mexico City, where many buildings were destroyed in the so-called lake-bed zone (Fig. 1), while the hill zone suffered almost no damage (Esteva 1988). Since the Michoacan earthquake, the amplification in the lake-bed zone of the Valley of Mexico has been the subject of numerous studies and the main features of the ground motion are well documented. In addition to the strong amplification, the ground motion in the lake-bed zone is characterized by very long-duration monochromatic waves (e.g. Anderson *et al.* 1986; Bard *et al.* 1988; Singh *et al.* 1988a,b; Campillo *et al.* 1988; Chávez-García & Bard 1994).

The subsoil of the Valley of Mexico is divided into three regions (Fig. 1): (1) the hill zone, which is formed by a surface layer of lava flows and volcanic tuffs; (2) the lake-bed zone, which consists of 30–100-m-thick deposits of highly compressible, high-water-content clay, underlain by sands; (3) the transition zone, composed of alluvial sandy and silty layers with occasional clay layers. The extremely low rigidity of the clay layer provides a very strong impedance contrast relative to

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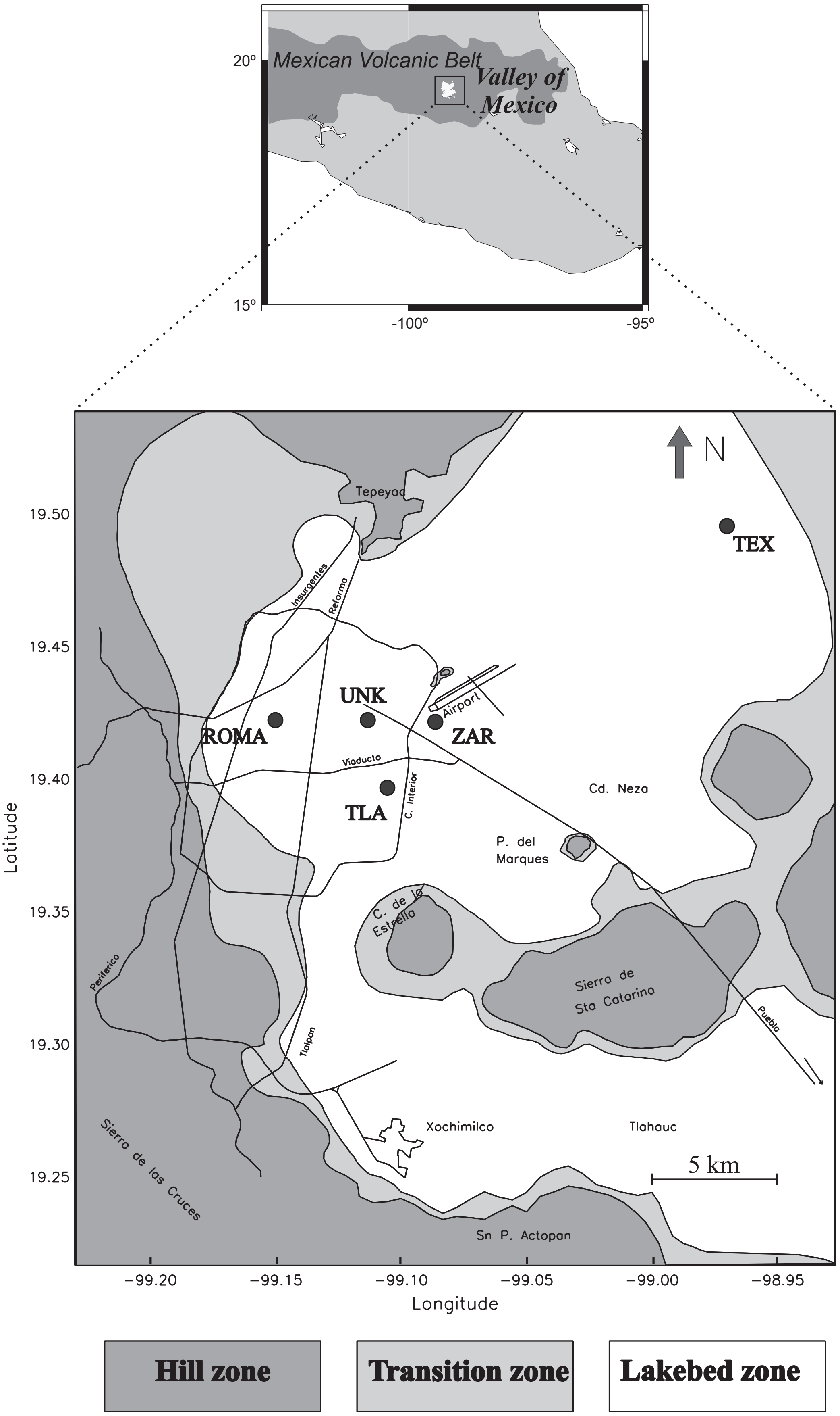

Figure 1. Top: location of the Valley of Mexico. Bottom: map of the Valley of Mexico showing the three principal geotechnical zones. Locations of station used in this study are indicated with black circles.

the underlying layers and, as a consequence, provokes dramatic amplification of incident seismic waves in the lake-bed zone. Early studies showed that simple 1-D model profiles reproduce well the observed fundamental frequency of the lake-bed zone sites and their spectral amplification with respect to the hill zone but fail to generate the long duration that manifests itself as a succession of roughly harmonic beats (e.g. Seed *et al.* 1988; Sánchez-Sesma *et al.* 1988; Kawase & Aki 1989). To explain the observed long coda, several other models have been explored, among them (1) a 2-D valley (e.g. Sánchez-Sesma *et al.* 1988), (2) a large-scale 2-D valley within which a small-scale lake-bed zone is located (e.g. Bard *et al.* 1988; Kawase & Aki 1989), (3) local small-scale variations in the subsoil near the recording sites (Faccioli *et al.* 1989), (4) resonance of horizontally propagating *P* waves in a laterally confined clay layer of the lake-bed zone (Seligman *et al.* 1989), and (5) coupling between evanescent *SP* waves and Rayleigh waves (Lomnitz *et al.* 1999). Models of types (1)–(3) provide a viable explanation of long coda only if shear wave Q in the lake-bed sediments is high (200–300). However, both laboratory (Romo & Ovando-Shelley 1996) and field (Jongmans *et al.* 1996) measurements yield a very low value of Q (10–50) in the lake-bed zone clays.

Examining the recordings of a broad-band seismograph in the valley, Singh & Ordaz (1993) found the presence of long coda even in the hill zone. They hypothesized that this long coda is caused by multipathing between the source and the site (separated by more than 250 km for coastal earthquakes) and/or within the large basin of the Valley of Mexico. From the analysis of earthquake recordings obtained by an array deployed in the hill zone, Barker *et al.* (1996) found strong evidence of multipathing during several earthquakes. However, no clear evidence of off-azimuth arrivals was found for earthquakes with epicentres along the Guerrero subduction zone, which is located more than 250 km to the south of the valley. A recent 2-D, finite difference simulation of wave propagation from sources located on the plate interface of the Mexican subduction zone shows that the low-velocity layers near the trench (i.e. accretionary prism and water) significantly enhance the signal duration in the Valley of Mexico (Shapiro *et al.*, in preparation). These low-velocity layers trap the seismic waves and backscatter them towards Mexico City. This numerical study provides an explanation of the on-azimuth arrival of long coda observed during the Guerrero earthquakes at the hill-zone array. Furumura & Kennett (1998) show that the presence of low-velocity oceanic crust in the upper part of the subducted slab increases the duration of the *Sn* arrival in the Valley of Mexico. Furthermore, the low-velocity, 2-km-thick volcanic rocks, which overlie Cretaceous limestones in the Valley of Mexico (Havskov & Singh 1977–1978; Shapiro *et al.* 1997), also play a role in increasing the signal duration and in the amplification of the seismic waves in the hill zone (Singh *et al.* 1995; Shapiro *et al.* 1997, 2001; Furumura & Kennett 1998).

As we have noted above, the presence of long coda in the hill-zone recordings of the Valley of Mexico is now accepted. Also, recent studies have begun to provide quantitative physical mechanisms that explain this lengthening of the coda. However, it is not clear just how the lake-bed zone responds to this input motion. A definitive answer to this question can only come from an analysis of the characteristics of the wavefield in the lake-bed zone. Towards this goal, in this paper we study some properties of surface waves recorded in the Valley of Mexico. We then calculate dispersion curves and eigenfunctions of Rayleigh waves in an appropriate layered crustal structure below the lake-bed zone of the valley. Finally, we compare the results of our calculations with *in situ* observations. Our main conclusion is that the measured phase velocity and distribution of amplitudes with depth correspond to the higher mode rather than to the fundamental mode of the Rayleigh wave. A major part of the seismic energy, corresponding to higher modes, is not concentrated in the clay layer but in the underlying rocks. Thus, the uppermost clay layer has little effect on the signal duration (although it dramatically amplifies the ground motion). We conclude that the reasons for the long coda observed in the lake-bed zone are the same as those for the long coda present in the hill zone.

2 DESCRIPTION OF THE CRUSTAL MODEL

In many studies of the site effects in the Valley of Mexico, only the very superficial clay layer has been taken into account. This approach successfully reproduces the observed fundamental frequencies of many sites. However, a relatively low-velocity structure extends below the superficial clay layer to depths of a few kilometres (that is, a deep sedimentary basin and Quaternary volcanic rocks), further amplifying the seismic waves. Moreover, the resonance frequency of this structure is relatively close to the fundamental frequency of the clay layer. As a consequence of this coincidence, the dispersion curves and eigenfunctions of surface waves are expected to be strongly affected by the relatively low-velocity structure below the clay layer. For this reason, we have constructed a crustal model of the lake-bed zone based on all available information (Table 1). The model is based on the gross crustal structure determined by Campillo *et al.* (1996). This crust model is overlain by a low-velocity, 2-km-thick volcanic layer reported by Havskov & Singh (1978) and Shapiro *et al.* (1997). Above the volcanic rocks lies a 0.5-km-thick sedimentary basin (Suárez *et al.* 1987; Pérez-Cruz 1988; F. Mooser, personal communication, 1999). The uppermost part of the model consists of lake sediments. The distribution of velocities in this superficial layer, which corresponds approximately to the Roma site in Mexico City, has been obtained from borehole logs (Singh *et al.* 1997). We calculate group and phase velocity dispersion curves as well as eigenfunctions for fundamental and first higher modes of the Rayleigh wave, using programs by Herrmann (1987). We compare the results of these calculations with observations made in the lake-bed zone of the Valley of Mexico.

Table 1. Average velocity model below the lake-bed zone of the Valley of Mexico.

Thickness H (km)	V_P (km s^{-1})	V_S (km s^{-1})	ρ (g cm^{-3})
0.03	0.8	0.05	2.0
0.02	1.2	0.1	2.0
0.3	2.0	0.4	2.05
0.2	2.5	0.8	2.05
2.0	3.0	1.70	2.2
5.0	5.28	3.05	2.4
12.0	5.71	3.3	2.4
28.0	6.4	3.7	2.7
∞	8.13	4.7	3.3

3 OBSERVATIONS

3.1 Horizontal-to-vertical spectral ratio

Our analysis is based on the records of nine earthquakes (Table 2) obtained at five sites in the lake-bed zone (Fig. 1). We begin the analysis with the ground motion recorded by one of the stations of the microarray located at the ROMA site in Mexico City. One of the stations of the array is equipped with borehole sensors located at depths of 30 and 102 m. In Fig. 2(a), we show three-component ground displacement recorded by the sensor located at the surface during event 3. It illustrates the main characteristics of the lake-bed zone records well, that is, the long duration and almost monochromatic behaviour of the signal on the horizontal components. The displacement spectrum is shown in Fig. 2(b). It can be seen that the dominant frequency of the ROMA site is close to 0.4 Hz. We have also calculated a horizontal-to-vertical displacement ratio at ROMA using the following steps. First, amplitude spectra for three displacement components for events 2, 3, 4, 5, 6 and 7 were calculated. Then, these spectra were smoothed in a 0.37-Hz-width window. For each event, we calculated average spectral amplitudes from two horizontal components. The average horizontal amplitudes obtained were divided by the vertical spectral amplitudes. The average horizontal-to-vertical spectral ratio and its standard deviation calculated for all six events is shown in Fig. 3(a). This ratio also shows a maximum at 0.4 Hz. Moreover, an additional maximum appears near 0.2 Hz. This observed horizontal-to-vertical displacement ratio can be compared with the theoretical radial-to-vertical ratio calculated for Rayleigh waves corresponding to our model (Table 1). In Fig. 3(b), we show the theoretical ratios for the fundamental and the first higher Rayleigh wave modes. It can be seen that each Rayleigh wave mode has a narrow maximum in the horizontal-to-radial ratio. These maxima are produced by the resonance response of the structure. More precisely, at these resonance frequencies the Rayleigh waves are essentially composed of almost horizontally propagating *S* waves. Comparing Figs 3(a) and (b), we conclude that the maxima at 0.2 and 0.4 Hz correspond to the fundamental and the first higher mode of the Rayleigh wave, respectively. From Fig. 2(b), it can be seen that most of the energy is concentrated at frequencies

Table 2. Parameters of earthquakes used in the study.

N	yy/mm/dd	hh:mm:ss	Lat (°N)	Lon (°E)	Depth (km)	M_w
1	93/05/15	03:09:34	16.2	−98.4	6	5.7
2	93/05/15	03:11:56	16.5	−98.7	20	6.0
3	93/10/24	07:52:16	16.5	−99.0	22	6.6
4	94/05/23	01:41:44	18.0	−100.6	45	6.2
5	94/12/10	16:17:41	18.0	−101.6	54	6.4
6	95/09/14	14:04:36	17.0	−99.0	22	7.3
7	95/10/09	15:35:54	18.8	−104.5	10	8.0
8	98/02/03	03:02:05	15.9	−96.2	24	6.3
9	98/04/20	22:59:22	18.8	−100.9	60	5.9

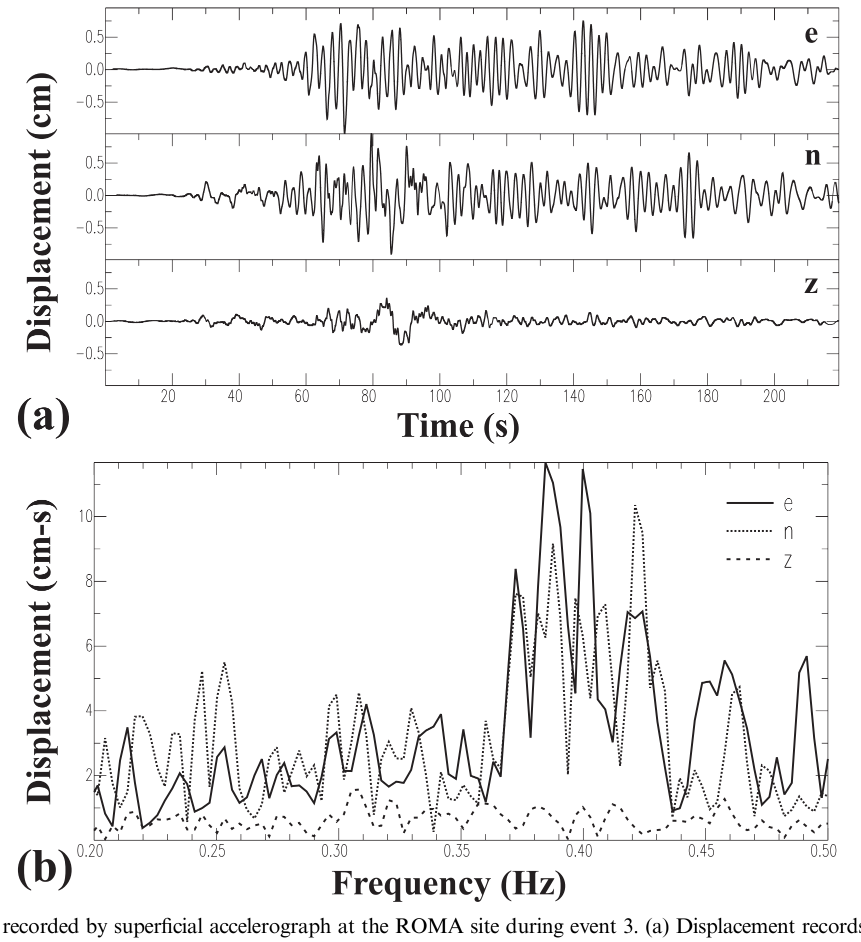

Figure 2. Ground motion recorded by superficial accelerograph at the ROMA site during event 3. (a) Displacement records; (b) displacement spectra.

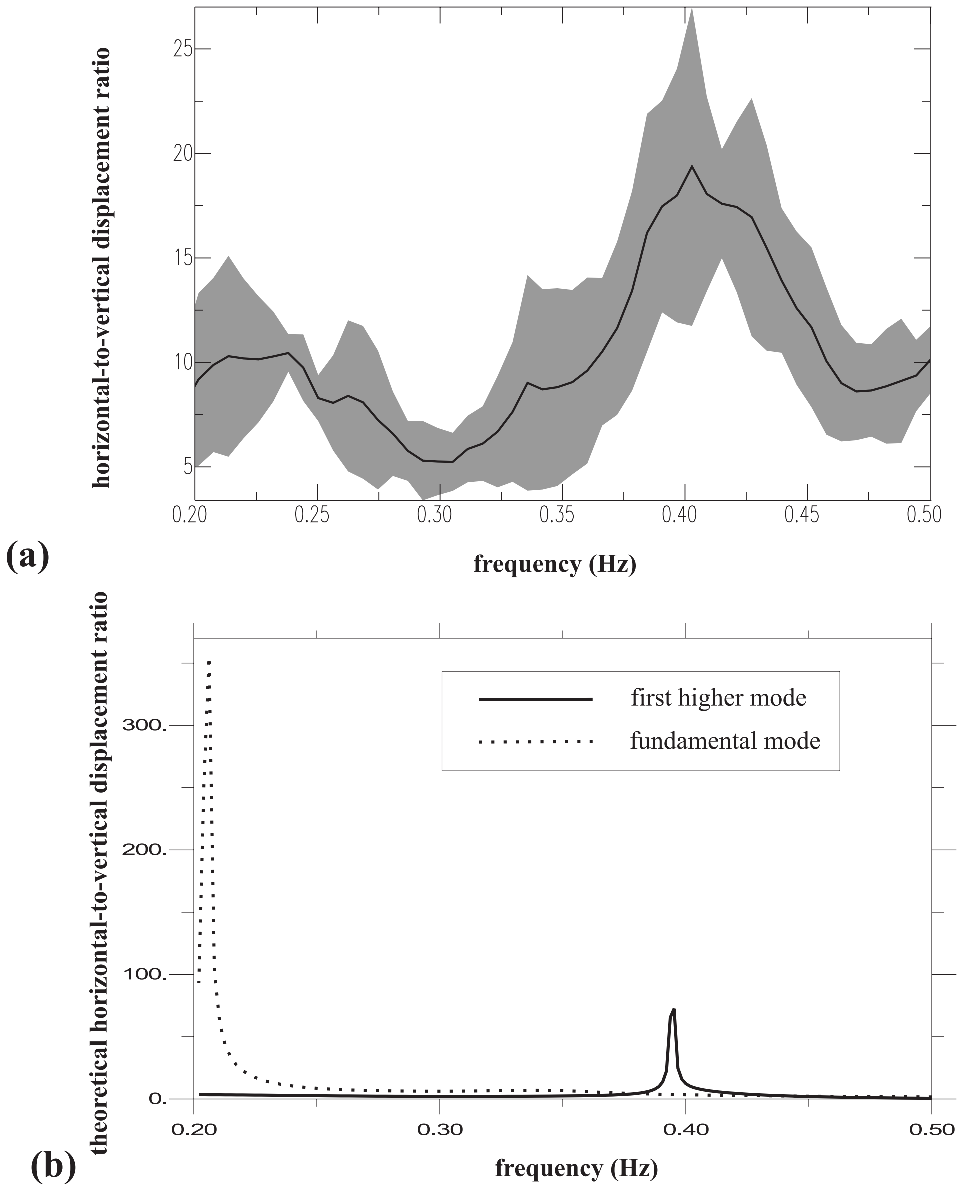

Figure 3. (a) Horizontal-to-vertical spectral ratio measured at the free surface at ROMA. The solid line shows the average value while the shaded area shows the standard deviation. (b) Horizontal-to-vertical spectral ratio calculated for the model given in Table 1 for the fundamental (dotted line) and the first higher (solid line) Rayleigh wave modes.

around 0.4 Hz, that is, in the first higher mode. Unlike in the calculations (Fig. 3b), the observed amplitude of the peak near 0.2 Hz is significantly smaller than that at 0.4 Hz (Fig. 3a). This is due to the fact that in the observed signal the fundamental mode is masked by the higher mode.

3.2 Distribution of the displacement with depth

The distribution of the displacement with depth provides another possibility to discriminate between the fundamental and the first higher modes. In Fig. 4, we show eigenfunctions calculated for the fundamental and the first higher modes of Rayleigh and Love waves. All eigenfunctions are normalized so that they have a unit value at the surface. Since our crustal model represents approximately the structure below the ROMA array, we consider the eigenfunctions calculated at periods close to the observed resonance period of the site (2.5 s). These eigenfunctions give theoretical distributions of displacement with depth for each individual mode. It can be seen that the displacement decreases more rapidly for the fundamental modes than for the higher modes. Using records of accelerographs installed in boreholes, Singh *et al.* (1997) studied the distribution of the horizontal displacement with depth at different sites inside the lake-bed zone. They found that the horizontal displacement at a depth of about 100 m is approximately one-third of its value at the surface. At this depth, the horizontal eigenfunctions for the fundamental modes of both Rayleigh and Love waves become very small, while the higher-mode eigenfunctions have values close to the observed ones. This indicates that higher modes dominate the signal. The difference is more pronounced if we consider the vertical displacement, which remains nearly constant between 0 and 100 m for the higher mode but vanishes below 50 m for the fundamental mode. In Fig. 5, we show vertical-component seismograms recorded

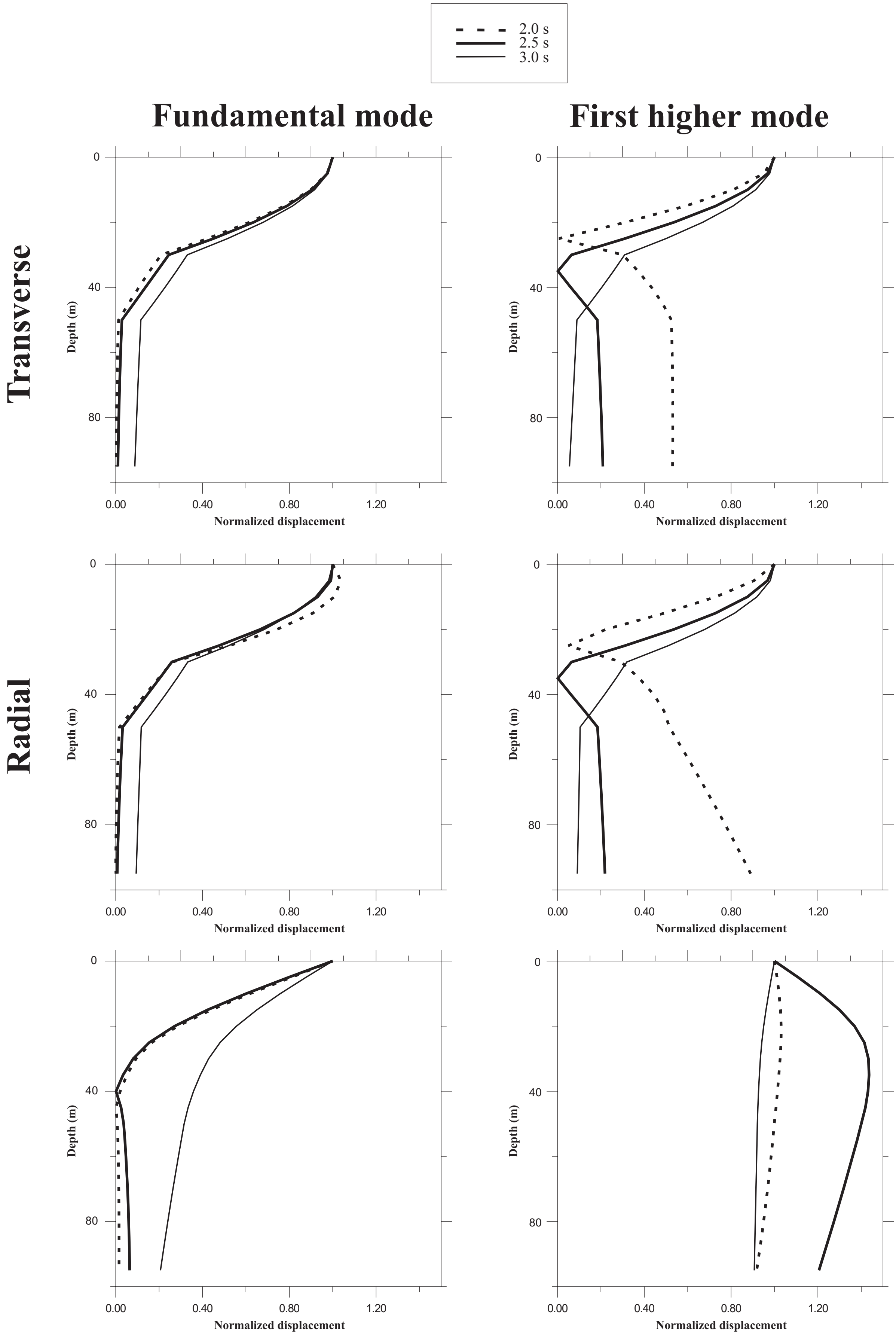

Figure 4. Eigenfunctions of the fundamental and the first higher modes of Rayleigh and Love waves for the model given in Table 1.

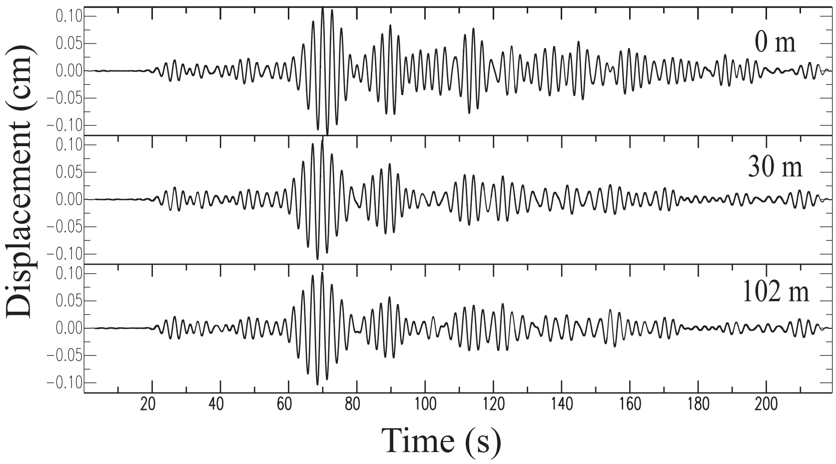

Figure 5. Vertical displacements recorded at 0, 30 and 102 m depth at the ROMA site during event 3. Seismograms have been bandpass filtered between 0.3 and 0.5 Hz.

by borehole accelerographs at the ROMA array during event 3. The accelerograms were integrated twice to obtain displacements and bandpassed between 0.3 and 0.5 Hz. It can be seen that the amplitude of the displacement and the form of the signal do not change significantly with depth. We have analysed the earthquakes listed in Table 2 and recorded by borehole accelerographs at four locations in the lake-bed zone (ROMA, TLA, UNK and ZAR in Fig. 1). In each case, the vertical-component record was integrated to displacement and narrowly bandpassed around the fundamental frequency of the site. Then, the maximum absolute displacement for each seismogram was measured and normalized with respect to the value measured at the surface. Finally, for each station the average normalized displacements and standard deviations were calculated. In Fig. 6, we compare our measurements with the computed eigenfunctions. This comparison and the observation of the horizontal displacements by Singh *et al.* (1997) clearly indicate that the distribution of displacement with depth in the lake-bed zone corresponds to the higher modes and not to the fundamental mode.

3.3 Phase velocity

Our last test consists of the measurement of the phase velocity of surface waves propagating in the lake-bed zone. For this purpose, we have used a small-aperture network installed in Texcoco Lake (TEX in Fig. 1). The network consists of three Kinemetric K2 18-bit accelerographs installed in the form of a triangle (Fig. 7) with its side roughly about 400 m (see Lomnitz *et al.* 1999 for a description of an element of the array). The absolute time is provided by GPS. So far the array has recorded only one earthquake, with a good signal-to-noise ratio, on all three stations (events 8 in Table 1). Because of Love wave contamination and enhanced mode coupling on the horizontal components (Stange & Friederich 1992), we have used only the vertical-component records of this earthquake to measure the phase velocity of the Rayleigh wave. Vertical displacements at the three stations of the array during event 8 are shown in Fig. 8(a). The corresponding displacement spectra are presented in Fig. 8(b). It can be seen that the resonance frequency of the site where the array was deployed is very close to the resonance frequency of the Roma site (ROMA in Fig. 2). In order to eliminate the high-frequency noise, we low-pass filtered the records at 0.7 Hz. The filtered seismograms are shown in Fig. 8(c). A strong coherent wave arrives at ~ 35 s. Spectral analysis shows that this wave corresponds to the resonant frequency of the site (0.3–0.5 Hz). This coherent arrival has been used to measure the phase velocity.

For a given slowness vector **s**, we can calculate theoretical time delays between stations of the array as follows:

$$\delta t_{12} = r_{12}\mathbf{s}\,, \qquad \delta t_{13} = r_{13}\mathbf{s}\,, \tag{1}$$

where δt_{12} and δt_{13} are time delays at stations 2 and 3 with respect to station 1. Vectors r_{12} and r_{13} are shown in Fig. 7. The semblance value between each pair of stations is given by

$$C_{12}(\mathbf{s}) = \frac{\sum_{i=1}^{N} x_1(t_i)x_2(t_i - \delta t_{12})}{\sum_{i=1}^{N} x_1^2(t_i) \sum_{i=1}^{N} x_2^2(t_i)}\,,$$

$$C_{13}(\mathbf{s}) = \frac{\sum_{i=1}^{N} x_1(t_i)x_3(t_i - \delta t_{13})}{\sum_{i=1}^{N} x_1^2(t_i) \sum_{i=1}^{N} x_3^2(t_i)}\,, \tag{2}$$

$$C_{23}(\mathbf{s}) = \frac{\sum_{i=1}^{N} x_2(t_i - \delta t_{12})x_3(t_i - \delta t_{13})}{\sum_{i=1}^{N} x_2^2(t_i) \sum_{i=1}^{N} x_3^2(t_i)}\,,$$

where x_1, x_2 and x_3 are the displacements recorded by stations of the array and N is the length of the window corresponding to the coherent arrival (indicated by the shaded area in Fig. 8c). The total semblance is obtained as the product

$$C(\mathbf{s}) = C_{12}(\mathbf{s})C_{13}(\mathbf{s})C_{23}(\mathbf{s})\,. \tag{3}$$

The result of the semblance calculations is shown in Fig. 8(d). The shaded area corresponds to $C(\mathbf{s}) > 0.95$ and the resulting estimation of the phase velocity lies between 1.5 and 2.5 km s^{-1}. Tests showed that the phase velocities for the later arrivals

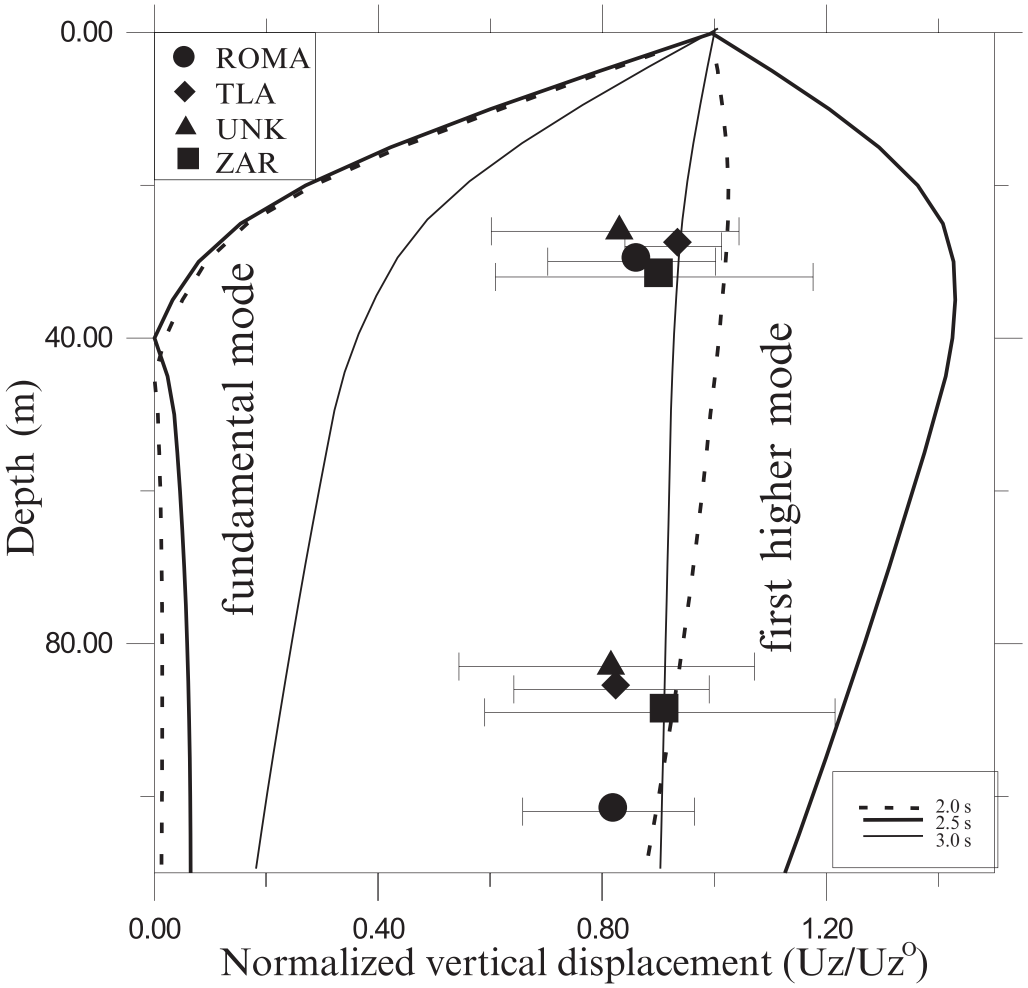

Figure 6. Normalized vertical-component displacement measured at different depths in four locations: ROMA, TLA, UNK and ZAR (Fig. 1). Horizontal bars indicate standard deviations. Also shown are theoretical curves for fundamental and first higher-mode Rayleigh waves corresponding to the crustal structure given in Table 1.

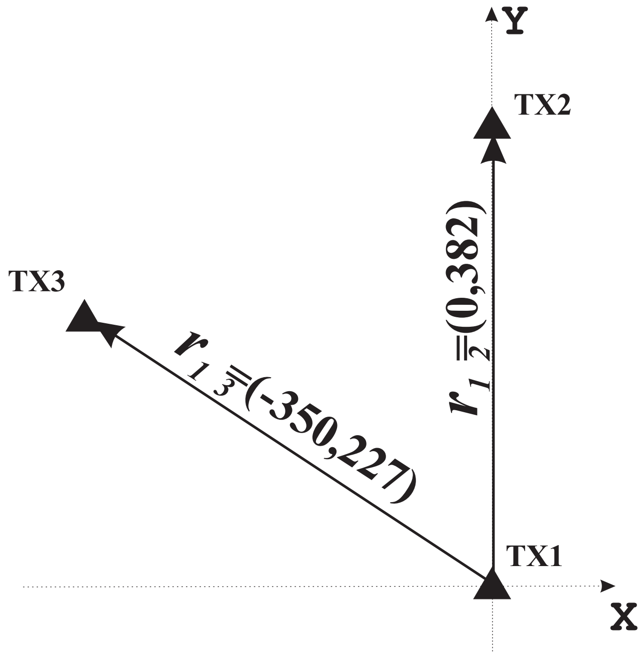

Figure 7. Plan of the Texcoco array. Distances are indicated in metres.

cannot be measured reliably because the results depend strongly on the length of the analysed time window.

In Fig. 9, we show dispersion curves for the fundamental and first higher Rayleigh wave modes for the model in Table 1. The shaded rectangle gives the region of possible values of the phase velocity obtained from the measurements. The comparison of theoretical and measured values clearly shows that the largest surface wave observed on the seismogram is not the fundamental mode. We note that the dispersion curves shown in Fig. 9 differ from those calculated by Bodin *et al.* (1997) for the Roma site. In particular, the phase velocity of the fundamental mode is lower than that computed by Bodin *et al.* (1997). This difference arises from the fact that Bodin *et al.* (1997) used a model with a very thin layer of 'deep sediments' (about 60 m). In this study, we have taken the thickness of the sedimentary basin as 500 m. This thickness is more appropriate for the Valley of Mexico considering the available data (Suárez *et al.* 1987; Pérez-Cruz 1988; F. Mooser, personal communication, 1999). In spite of the difference in the dispersion curves, our principal physical interpretation of the phase velocity measurement is the same as that of Bodin *et al.* (1997): the surface waves do not propagate in the clay layer but in the deep structure. The velocity of propagation of these waves (2 ± 0.5 km s^{-1}) is controlled by *S*-wave velocities in the volcanic layer.

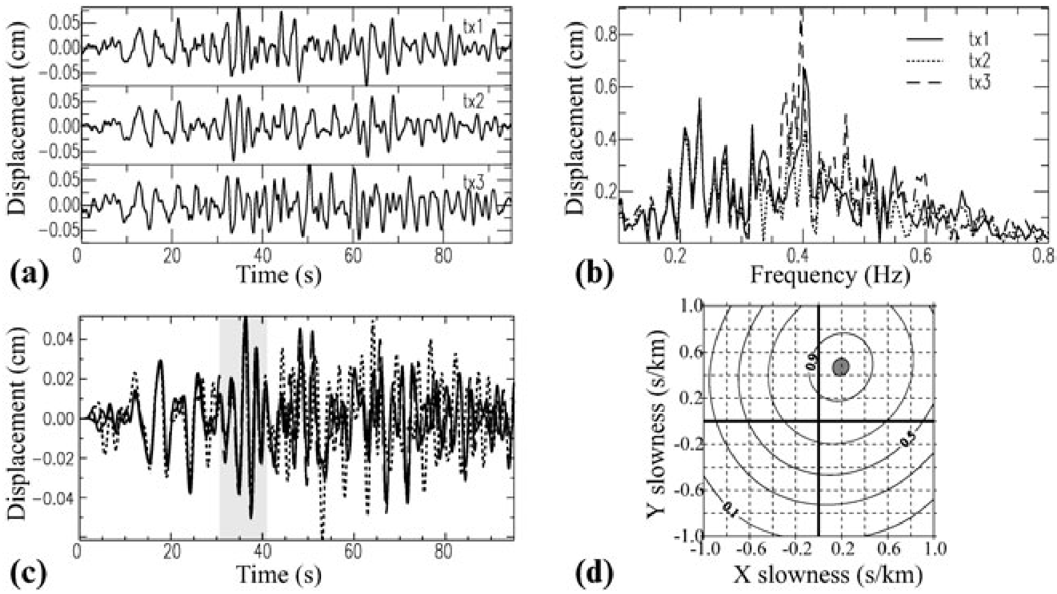

Figure 8. (a) Vertical-component seismograms recorded by the Texcoco array during event 8. (b) Vertical-component displacement spectra. (c) Seismograms, low-pass filtered at 0.7 Hz. Shaded region shows the coherent arrival used for the phase velocity measurement. (d) Results of the array-semblance analysis (see text). Shaded area (semblance >0.95) has been used for the phase velocity determination.

4 DISCUSSION AND CONCLUSIONS

Numerous recent studies of the ground motion in the Valley of Mexico accept the existence of long coda in the hill-zone records. Based on the simulation of wave propagation in reasonable 2-D models of the Mexican subduction zone, a few of these studies provide quantitative explanations for this observation (Furumura & Kennett 1998; Shapiro *et al.*, in preparation). These explanations generally support the hypothesis of Singh & Ordaz (1993). In our view a satisfactory explanation of how the lake-bed zone responds to the long-duration hill-zone wavefield, however, is still lacking. Towards this goal, we have studied the observed wavefield at different locations of the lake-bed zone of the Valley of Mexico. These observations permit measurements of the horizontal-to-vertical displacement ratio, the distribution of the displacement as a function of depth, and the phase velocity. Our results suggest that the surface waves propagating in the lake-bed zone are composed of higher modes and not the fundamental modes of surface waves. A very important difference between fundamental and higher modes is that the energy of the fundamental mode is almost completely concentrated in the superficial layers of the lake sediments, while the higher modes propagate in deeper layers and are thus less affected by the low Q of the clay.

The role of the superficial low-velocity layer is essentially a passive one of amplifying the seismic waves at the fundamental period of the site, which gives a monochromatic appearance to lake-bed records. This narrow-band amplification is explained well by the theoretical vertical-to-radial component ratio of the higher-mode Rayleigh waves. This conclusion contradicts that of Iida (1999), who finds that these signals are principally composed on fundamental-mode waves. In Iida's analysis, the effects of the shallower lake sediments and deeper volcanic layer are treated separately, while our study considers a model including all layers. Thus, we believe that our analysis is more appropriate for the lake-bed zone. Also, another conclusion by Iida (1999), that the signal is essentially composed of Love waves, is not justified. There are some very strong indications that the signals observed in the Valley of Mexico and at different sites inside the Mexican Volcanic Belt are composed of Rayleigh-type waves. For example, it is difficult to explain the very narrow maxima in the horizontal-to-vertical displacement ratio observed in the lake-bed zone (Fig. 3a) assuming Love-wave propagation. On the other hand, this behaviour is in good agreement with the theoretical ratio for Rayleigh waves (Fig. 3). Other evidence of the dominance of Rayleigh waves comes from the observation by Shapiro *et al.* (1997), who

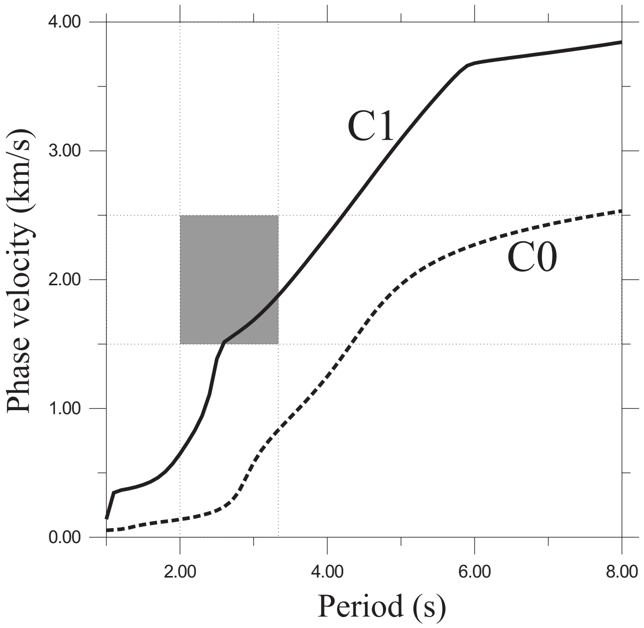

Figure 9. Comparison of theoretical Rayleigh wave phase velocities of the fundamental mode (C0, dashed line) and the first higher mode (C1, solid line) with the measured phase velocity (shaded area).

analysed signals from various coastal earthquakes at volcanic sites in the Valley of Mexico outside the lake-bed zone. Their observations clearly show that the radial component is significantly larger than the transverse component at all sites located in the southern part of the Mexican Volcanic Belt (see e.g. Fig. 3 of Shapiro *et al*. 1997). Barker *et al*. (1996) analysed the same seismic events using the data of a small-aperture array installed in the hill zone in the Valley of Mexico. As mentioned before, they find that later arrivals in the coda come from the epicentral area. Thus, for both the direct arrival and the coda, the radial component corresponds to the Rayleigh waves and the transverse component corresponds to the Love waves. Combining both observations, we conclude that, at volcanic sites, signals are dominated by Rayleigh-type waves.

The recognition that the wavefield in the lake-bed zone is dominated by higher surface wave modes also has some practical implications. For example, the estimation of strains in the lake-bed zone during large earthquakes is of critical importance in adequate designing of pipelines and tunnels (see e.g. Bodin *et al*. 1997; Singh *et al*. 1997). Since the wavelength of the higher mode is significantly larger than that of the fundamental mode, the spatial derivatives of the displacement and, hence, the amplitude of the strain and its distribution for the higher mode differs from those of the fundamental mode. Thus, the recognition of the dominance of the higher mode is important in the correct estimation of the strain. Another implication concerns the possible modelling of the surface waves propagating in the lake-bed zone. The fundamental mode, which is completely trapped in the first 50 m or so, is essentially excited at the edges of the lake zone and is controlled by the geometry of the superficial clay layer. Thus, if the motions were dominated by the fundamental mode then a detailed knowledge of the structure of the superficial layer and its velocity contrast with respect to the deep sediments would be sufficient for the understanding and the possible modelling of main features of the ground motion. The higher modes, on the other hand, propagate in structures underlying the lake sediments. In this case, the goal of modelling the ground motion becomes more difficult since it requires a detailed knowledge of the deeper structure of the Valley of Mexico and the Mexican Volcanic Belt.

ACKNOWLEDGMENTS

We appreciate a careful review of the manuscript by J. Gomberg. We are grateful to C. Lomnitz for providing us with seismograms. Thanks are due to M. Torres, R. Vasquéz and J.M. Velasco for their help in the operation of the Texcoco array. This research was partly funded by the Comisión Nacional de Agua, DGAPA (UNAM) IN109598, and CONACYT (México) J32308-T projects.

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