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The Mexico Earthquake of September 19, 1985—The Incident Wavefield in Mexico City during the Great Michoacán Earthquake and Its Interaction with the Deep Basin

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Abstract : We used the vertical displacement records of the ground motion in Mexico City during the great 1985 Michoacan earthquake to identify the nature of the waves responsible for the heavy damage suffered by the town. The records at the different stations exhibit very similar waveshapes. A multichannel phase analysis shows the arrival, from the source zone, of a strong coherent wavetrain which represent the most of the energy incident at periods around 3 sec. We interpreted this arrival as the regional continental phase Lg. The study of other instrumental data in the period range relevant to the present investigation shows the efficiency of Lg propagation between the subduction zone and Mexico City.

We have computed the response to Lg waves of a sedimentary basin whose characteristics correspond to the deep basin beneath Mexico City. The amplification reaches a value of about 5. The results obtained are in good agreement with the response of the basin to a single obliquely incident plane wave. The durations of the theoretical signals are similar to those of actual observations at sites in the hills zone and in the intermediate zone.

Introduction

On September 19, 1985 occured an earthquake of magnitude 8.1, the the rupture zone of which stretched over 170 km along the Pacific coast of Mexico in the states of Guerrero and Michoacan (UNAM Seismology Group, 1986). That earthquake caused very heavy damage in Mexico City, although this city lies at a distance of about 300 km from the epicentre. The intensity of the ground shaking was higher than predicted by the building code of Mexico City in the lake bed zone.

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Different hypothesis have been proposed to explain this feature. Because the damage appears to be related to a spectral peak at about 0.3 Hz, the resonance of the sedimentary basin may be invoked (Beck and Hall, 1986). The effect of the presence of a soft surficial layer is an increase in the amplitude and the duration of the signal in series of limited bands. So, one may conclude that the principal phenomenon to be considered to the exceptional importance of the damage, is the response of the basin beneath Mexico City. Singh et al. (1988) and Mendoza and Hartzell (1988) point out the possible existence of an anomalous radiation in a frequency band around 0.5 Hz. These observations come from teleseismic P-waves and therefore concern only a possible source effect. On the other hand, one must note after Houston and Kanamori (1986) that the average moment rate spectrum of this earthquake is not abnormally high in the frequency band critical for the ground motion in Mexico City (0.3-0.5 Hz). On the contrary, Houston and Kanamori showed that the source spectrum of the Michoacan earthquake is depleted between periods of 1 and 10 sec in comparison with the average spectrum of large earthquakes occuring along different subduction zones (several other earthquakes

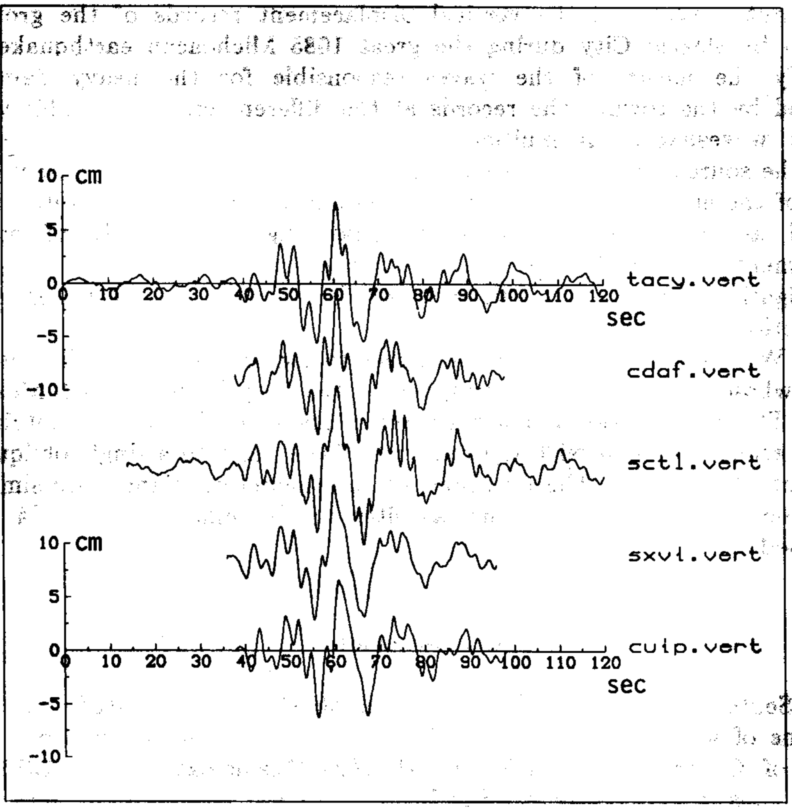

Figure 1: Examples of vertical displacement records obtained at different sites in Mexico City (after Mena et al., 1986).

along the Mexican trench follow the same trend). Thus, the presence of ripples with a period of about 3 sec on most of the Michoacan earthquake records can not be explained simply by the effect of a source characteristic such as an extremely short rise-time, but implies that a complex faulting be considered (Aki et al., 1988). These ripples can be seen on teleseismic signals but also on displacement records obtained from integration of accelerograms recorded in Mexico City. We shall use these strong motion records to study the nature of the seismic phases incident on the basin of Mexico City. Our aim is to give a realistic interpretation of these waves and thus to investigate the characteristics of the response of a sedimentary basin to such waves.

The displacement records in Mexico City

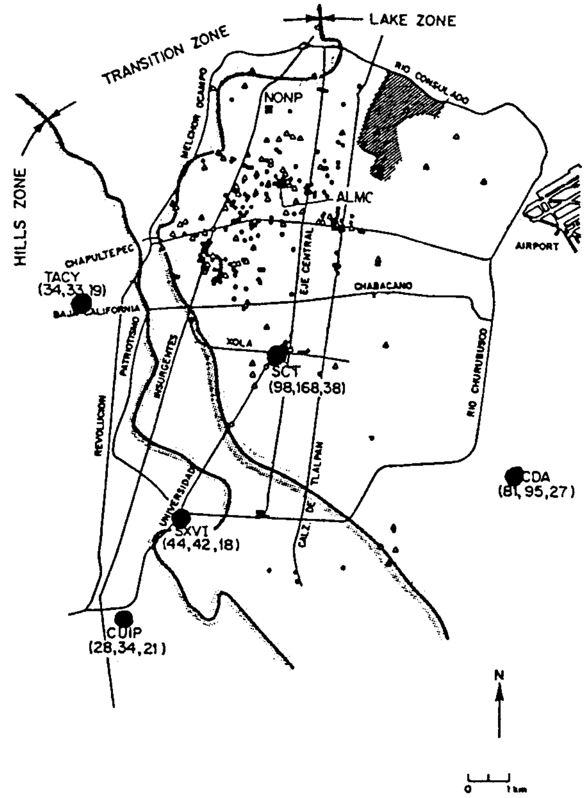

Figure 2: Locations of the stations whose records are presented on Figure 1. The heavy lines indicate the limits between the different structural zones (after Anderson et al., 1986).

Five free-field accelerometers located in Mexico City and its immediate suburbs have been considered. An important observation is the similarity of the wave shape and of the amplitude of the vertical displacement records at the different sites (Figure 1). These signals have been shifted arbitrarily in order to line up the waveshapes. These signals have been recorded at sites located on different types of ground (Figure 2). Stations TACY and CUIP are located on the hills zone where the soil consists of firm materials of the pre-Chichinautzin sedimentary layer. According to Suarez et al. (1987) the depth of the substratum is about 100 m at TACY and 250 m at CUIP. Station SXVI is located in the so-called transition zone which separates the area with soft lacustrine clay and the hills zone. At this site a thin layer of soft material (about 10 m) covers the deep sediments which are 450 m thick. Stations SCT and CDAF are in the lake zone. The thickness of clay overlying the deep sediments is about 35 m in SCT and 45 m in CDAF while the sedimentary layer itself is about 450 m and 600m thick at the two stations respectively. The very different structure beneath the stations and the great similarity of the vertical records indicate that the main characteristics of the signals, i.e. a long period pulse superposed with 3 sec ripples, are not simply associated with the response of the basin. Because of the limited band width of the spectral response of the recording system and of the accelerogram processing, the longer period content of the ground motion is almost absent from the records which have been convolved with a Ormsby filter whose low frequency limit is 0.07 Hz (Mena et al., 1985).

Such a similarity of the ground displacement in the different locations in Mexico City can be observed on the vertical component for raw displacement data and also on low-pass (<0.2 Hz) filtered horizontal data. On the other hand the waveshapes and amplitudes of unfiltered horizontal motion are strongly sensitive to the presence of clay.

The identification of the nature of the seismic phase associated with the 3 sec ripples is of crucial importance in understanding the damaging nature of this earthquake in the specific site of Mexico City because, according to Romo and Seed (1986) and Suarez et al. (1987) the maximum response of the surficial layer occurs in the same frequency band. The type of building destroyed during the earthquake confirms the instrumental observations that the frequency band relevant to the damage is between 0.25 and 0.5 Hz. In order to identify the incident wavefield, we take advantage of the similarity of the vertical displacement records and of the spacial distribution of the stations which is favorable to a phase analysis of the signals. However, because of the absence of a precise absolute time reference, only relative phase measurements will be possible.

Phase analysis

The study of the relative phase of the signals allows the verification of the different hypotheses on the nature of the ripples appearing on the records and tentatively of the long period pulse. If these arrivals consist of direct body waves, as is usually assumed in site response studies, we may expect that there is no variation of the relative phase between 12 s and 3 s at the different sites. If the two prominant arrivals are associated with two different modes of propagation, the difference in phase will vary with the apparent distance from the source, at least if the waves propagate in the same direction. An important point is to test whether the ripples are associated, at least partially, with the local response of a deep structure on a pluri- kilometric scale or not.

A way to test if these hypotheses are acceptable or not is to perform a multichannel phase analysis. We apply a method using the spectral matrix and its eigenvalues and eigenvectors (Glangeaud and Latombe, 1983) which has been proposed to perform wave separation in seismic data (Glangeaud and Lacoume, 1985; Nicollin et al., 1988). In our case, the spectral matrix is a 5x5 matrix for each frequency. This technique is based on the projection of the signals, in the frequency domain, on the eigenvectors of the spectral matrix. The relative importance of the eigenvalues allows to separate the signals between a coherent part, which may consists in the contribution of different waves,and the noise whose energy is equally distributed on the different eigenvalues. Considering the 5 stations whose locations are shown on Figure 2, we computed the eigenvalues of the spectral matrix. The results are presented on Figure 3 where the eigenvalues are shown as a function of frequency with the total spectral amplitude. In the two frequency bands in which energy is concentrated the signal is strongly dominated by the contribution of a single eigenvalue. Therefore the contribution associated with the four other eigenvalues is considered as irrelevant noise in the following. Because we analyse two separate frequency bands we can not conclude at this point that the entire signal consists of a unique type of wave (as direct body wave for example). Nevertheless, this result shows that in each of the frequency bands a single mode of propagation is represented. Because the records consists mainly of

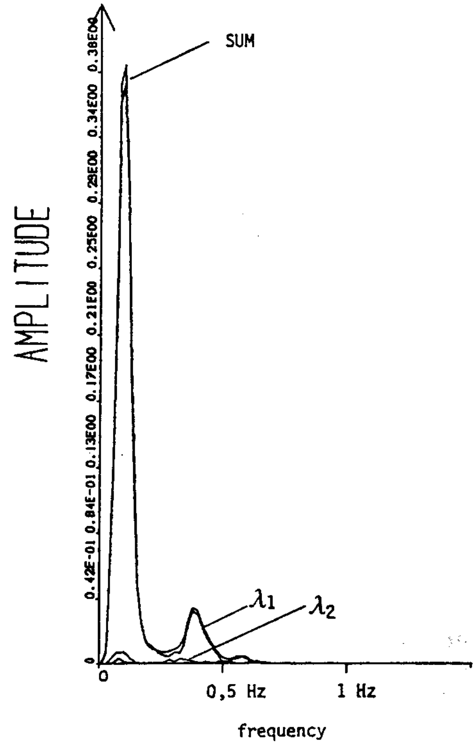

Figure 3: Spectral amplitude of the signals (SUM) and contribution of the eigenvalues. The contributions of the two first eigenvalues are indicated.

the superposition of two quasi monochromatic signals, the study of the phase difference between them gives indications on their propagation characteristics. We computed the phase of the cross spectrum of each record with the signal obtained observed at SXVI, which is chosen as the reference station because of its central position in the set of stations used. In order to improve the quality of the phase measurement, we use the data projected following the vector associated with the first eigenvalue, that is after reducing the level of the incoherent noise. The results obtained are presented on Figure 4. One must remember that the original signals have been shifted arbitrarily to line up the pulses. The phase difference between SXVI and the other stations is smaller for the 3 sec spectral component than for the long period component (except for station CUIP). This is due to the fact that the visual alignment is made essentially on the highest frequency. The phase difference between the two prominent spectral components clearly changes from one station to the next. This suggests that these two components are associated with two different modes of propagation, or that they are associated with a mode displaying a strong dispersion. In any case, this result indicates that the model of the single body wave is not consistent with the data. The next point consists of checking the

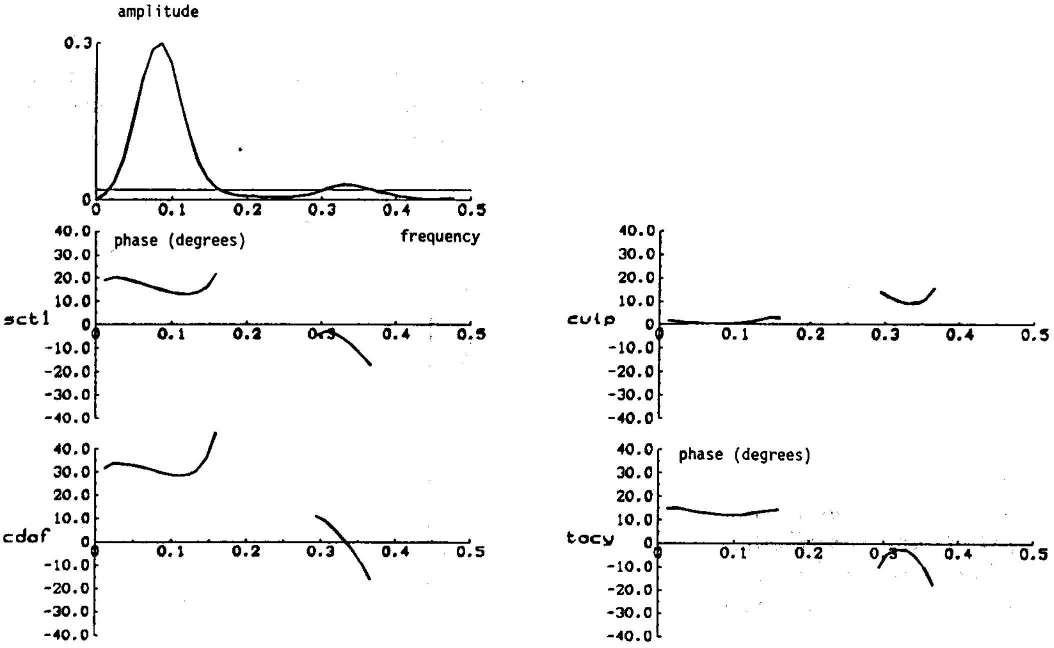

Figure 4: Phase shift between the reference station SXVI and each of the others stations as a function of frequency. The total amplitude is shown in order to define the frequency bands in which a reliable measurement can be made.

hypothesis of the complete wavetrain coming directly from the source, versus the hypothesis of the ripples associated with the presence of the deep basin. The simplest approach is to compute the relative delay of the two spectral components with respect to the reference station and then to display this delay as a function of the distance from the source. The delay is evaluated by considering the mean values of the phase around the maxima of amplitude. Figure 5 presents the results obtained when the relative distances are computed in the direction of the rupture zone (W30S). In spite of the scattering of the points, this figure shows clearly that the delay varies with the epicentral distance and thus invalidates the hypothesis that the ripples are waves diffracted in the deep basin. The delay measured between the 3 sec component and the 12 sec component increases with distance indicating that the ripples are associated with the higher phase velocity.

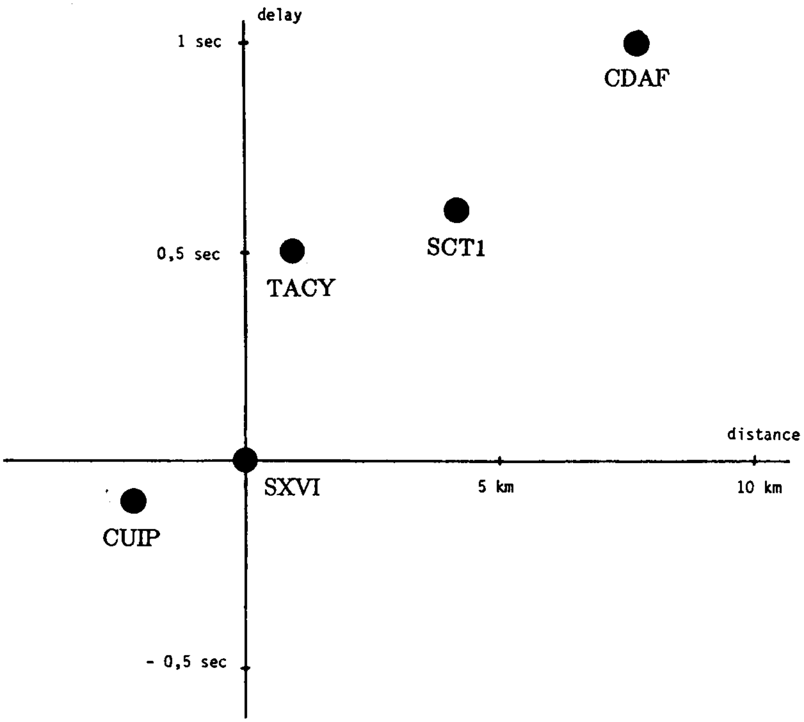

Figure 5: Delays deduced from the phase measurements as a function of the apparent distance from the fault zone.

The nature of the incident wavefield around the 3 sec period

The interpretation of these two arrivals in term of classical seismic wave type is difficult and perhaps non-unique because of the limited information available. Nevertheless, one can draw some conclusions from our analysis. We have seen that each of the two prominent contributions at 3 and 12 sec are associated with a single mode of propagation which is probably different in the two cases (because of the different phase velocities). This element excludes the hypothesis of direct body waves which are not dispersive. For the 3 sec ripples, the most likely interpretation is that they consist of Lg wave, because this arrival is well known to be the prominent phase at regional distance in continental areas. Lg wave consists of S-waves multiply reflected at post critical angles in the crust and therefore trapped in. This mode of propagation results in complex wavetrains whose amplitude varies slowly with distance and that therefore dominate the short period seismograms between 150 and several hundred kilometers. Lg, as a guided wave is not very sensitive to smooth lateral heterogeneities of the crust (Campillo, 1987). Herrmann and Kijko (1983) have computed the spectrum of the Lg wavetrain in the elastic response of a flat layered crustal model to an impulsive double-couple. They found that this spectral response is almost flat over the frequency range 0.15 to 10 Hz and strongly decreases for periods greater then 7 sec. This property explains why, after our eigenvalue decomposition, there is no contamination of Lg in the spectral peak around the 12 sec period.

Nevertheless, if in nearly all cases, Lg produces the prominent wavetrain of records at regional distance along continental paths, several examples have been reported where anomalous propagation results in strong attenuation and even complete vanishing of the phase (e.g. Ruzaikin et al.,1977; Chinn et al.,1980 and Kennett et al.,1985). In order to verify this possibility, we have considered the records obtained at Tacubaya Observatory in Mexico City for two moderate earthquakes (obviously, the seismograph was clipped during the great 1985 earthquake). We use records from a vertical component seismometer with a natural period of 4 sec, thus the records are directly relevant to the frequency band of interest for the damaging effect in Mexico City. We consider two earthquakes with magnitudes of 5.5 and 5.6 at epicentral distances of 470 and 275 km. They are located respectively North-West and South-East of the rupture zone. The seismograms are presented in Figure 6. The arrival times of the energetic wavetrains indicate that they could consist of Lg waves. We have computed synthetic seismograms to check the validity of this interpretation. We have considered a flat layered model derived from the results of deep seismic soundings (Steinhard and Meyer, 1961; Valdes et al., 1986). Because these two events occured in the subduction zone, we assumed that their focal mechanisms are identical to the one of the great 1985 earthquake. The source time function used in the computation is a ramp function with a duration of 3 sec. The synthetics are compared with the observed seismograms in Figure 6. In spite of the very sparse informations and constraints on the source characteristics and crustal structure, the agreement between computed and actual seismograms is rather good, showing the efficiency of Lg propagation between the subduction zone and Mexico City. As a consequence one can expect that the amplitude decay of strong ground motion with distance is considerably less than in the case of body waves. According to Nuttli (1973) and Campillo et al. (1984) the decay of peak amplitude for Lg in the time domain is of the form: $r^{-0.83}$ while in the spectral domain the amplitude decay is of the form: $r^{-0.50}$.

In the most likely hypothesis that the 3 sec period ripples correspond to the Lg wavetrain, the problem of the nature of the long period pulse remains puzzling.

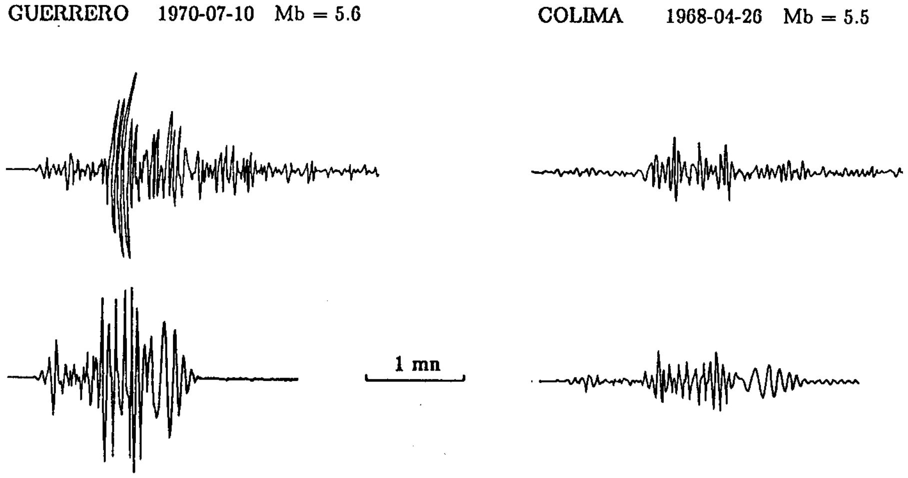

Figure 6: Comparison between records obtained at Tacubaya Observatory and theoretical waveshapes for two earthquakes along the subduction. The synthetics are convolved by the instrumental response.

Considering its large amplitude and the results of our measurement of phase velocity, one may identify this arrival to be the fundamental mode of Rayleigh wave. Nevertheless, this interpretation requires to include in the discussion some hypotheses on the source process. Indeed, if the source is considered as punctual, the arrival of the 12 sec pulse is too early for a Rayleigh wave. Houston and Kanamori (1986) and Mendoza and Hartzell (1988) have proposed to interpret the rupture by complex faulting, involving 3 subevents of probably different dynamic characteristics. As a consequence, the energetic radiation found in different frequency ranges is emitted at different times and locations on the fault. This fault complexity cannot be resolved with the only data used in the present study.

Response of the sedimentary basin to a complex wavefield

The usual way to evaluate the strong ground motion at a given site consists of convolving a reference motion recorded at a close hard rock site with the plane wave response of the structure beneath the site, computed taking into account the values of known parameters such as sediment thickness, velocities and attenuation. This plane wave response can be a 1D or 2D response (theoretical methods to compute 3D response still need development), depending upon the problem considered. Different examples of successfull comparisons between observations and 2D simulations have been presented (e.g. Aki, 1988, Horike, 1988). The effects of the basin characteristics (such as its geometry for example) have been investigated in detail (Bard and Bouchon, 1985), as well as the influence of the incidence angle for plane waves of different types (P or SV). Nevertheless, in the 2D case the studies are almost limited to incident plane waves.

The important differences expected between the plane wave model and the actual configurations depend on the source -receiver distance. Considering a site within a short epicentral distance, the main factor is the curvature of the wavefront which interferes with the structure. At greater distances, the ground motion becomes more and more complex because of the contributions of the different types of waves such as reflections on crustal heterogeneities and surface waves. In the case of Mexico City we are interested in modelling a complete configuration including a distant source, crustal propagation and a sedimentary basin. Eventually we shall compare our results with those obtained by using the incident plane wave assumption. The geometry of the problem is depicted on Figure 7a. The characteristics of the basin were chosen to represent the deep sediments beneath Mexico City. The parameters of the media are given in Table 1. The source depth considered is 10 km. The basin is limited by a branch of parabola. Its width is 11 km and its depth is 500 m. We have limited our investigations to the case of SH-waves. Because at this distance range the wavefield is dominated by guided propagation (higher modes), the characteristics of SH waves (Love waves) and SV (Rayleigh waves) are very similar.

Crustal Model				
	thickness	velocity (km/s)	density	quality factor
1	5.00	2.53	2.67	300
2	10.00	3.30	2.77	300
3	15.00	4.03	3.09	300
4	15.00	4.10	3.10	300
5	00.00	4.82	3.30	300
Basin structure				
1	0.50	1.0	2.0	50

Table 1.

We have computed in a flat layered model the displacement due to a source at a depth of 10 km and at epicentral distances from the first receiver of 100, 200 and 300 km (Figure 7a). The source consists of a simple transverse force. The simulation includes frequencies between 0 and 1 Hz and the source excitation spectrum has its maximum value at 3 sec. The source function used is given by:

$$S(\omega) = \frac{\omega^2 t_0}{\sinh(\omega \pi \frac{t_0}{4})}$$

where ω denotes the angular frequency. The seismograms shows clearly the prominance of multiply reflected waves in this distance range. We have then included the sedimentary basin in the model. The computation relies on the boundary equation-discrete wavenumber method, a technique which allows to compute the field diffracted by an irregular free-surface (Bouchon, 1985) or by irregular interfaces between media that can be stratified (Campillo and Bouchon, 1985; Campillo, 1987). The results obtained either in a flat layered medium or considering the presence of the basin are presented in Figures 7b and 7c respectively. The effect of amplification is clear whatever the epicentral distance range considered. For a source at a distance of 100 km, one can identify the diffracted surface wave in the basin as the latest arrival associated with a low group

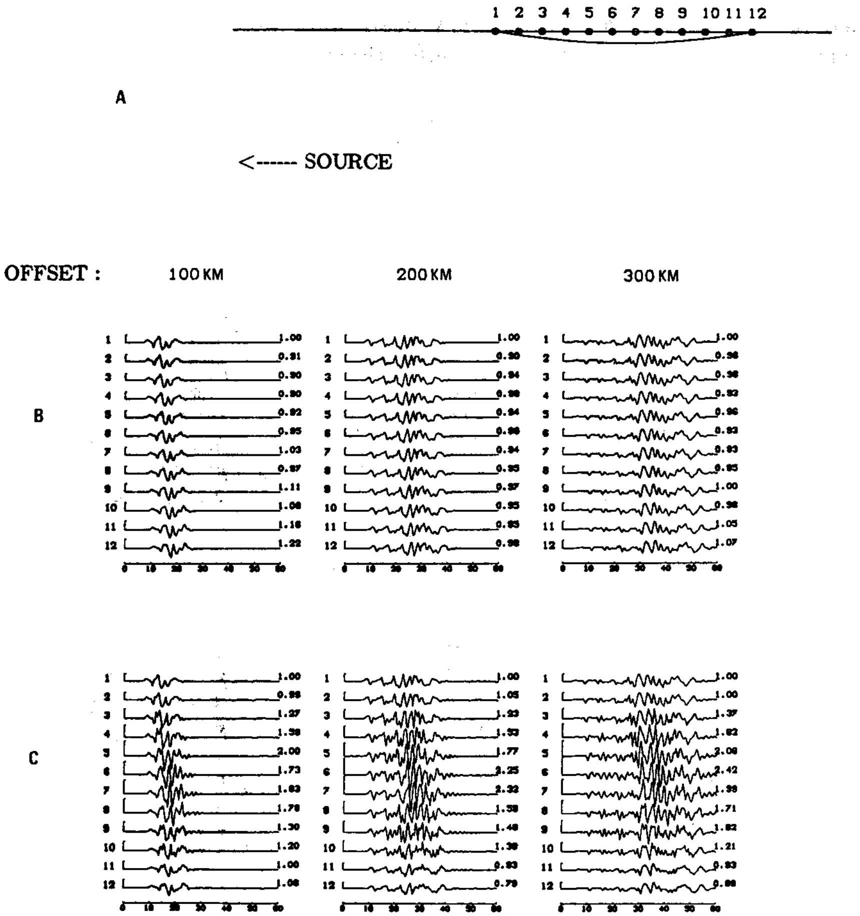

Figure 7: a)Source receiver configuration. b)Synthetic seismograms obtained in a flat layered crust. c)Synthetic seismograms in presence of the basin.

velocity. For receivers 6 to 10 this wave strongly contributes to increase the duration of the signals. This phenomenon is more difficult to figure out for source offsets of 200 and 300 km because of the presence of the fundamental mode of Love wave. Nevertheless a careful inspection of the seismograms shows the existence of waves travelling at low group velocities in every case. The maximum amplification of the peak amplitude occurs near the center of the basin (receivers 6 and 7). The longer durations of the signals are obtained at receivers 6 to 8, i.e. shifted with respect to the center of the basin on the side the farther from the source.

We present on Figure 8 the spectral ratios between the seismograms obtained in the case of the sedimentary basin and the seismograms computed in a flat layered medium. The larger amplifications occur in the central part of the

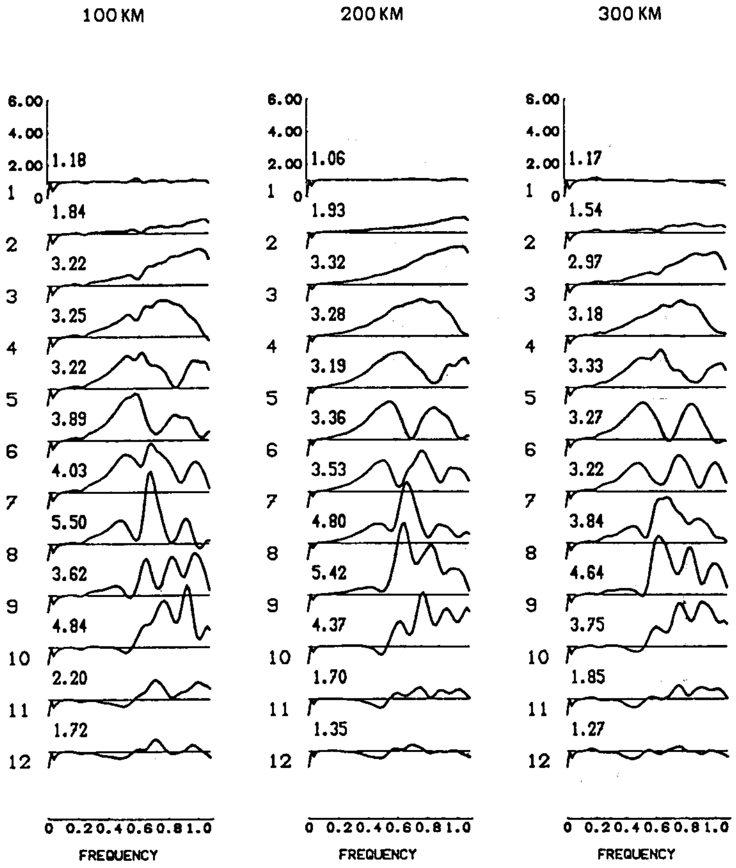
100 KM 200 KM 300 KM

Figure 8: Spectral ratios computed between the synthetics in presence of a sedimentary basin and in a flat layered medium.

basin and reach a value of about 5. One can note the shift of the maxima to the farther side of the basin. Some features of these curves are very similar for the 3

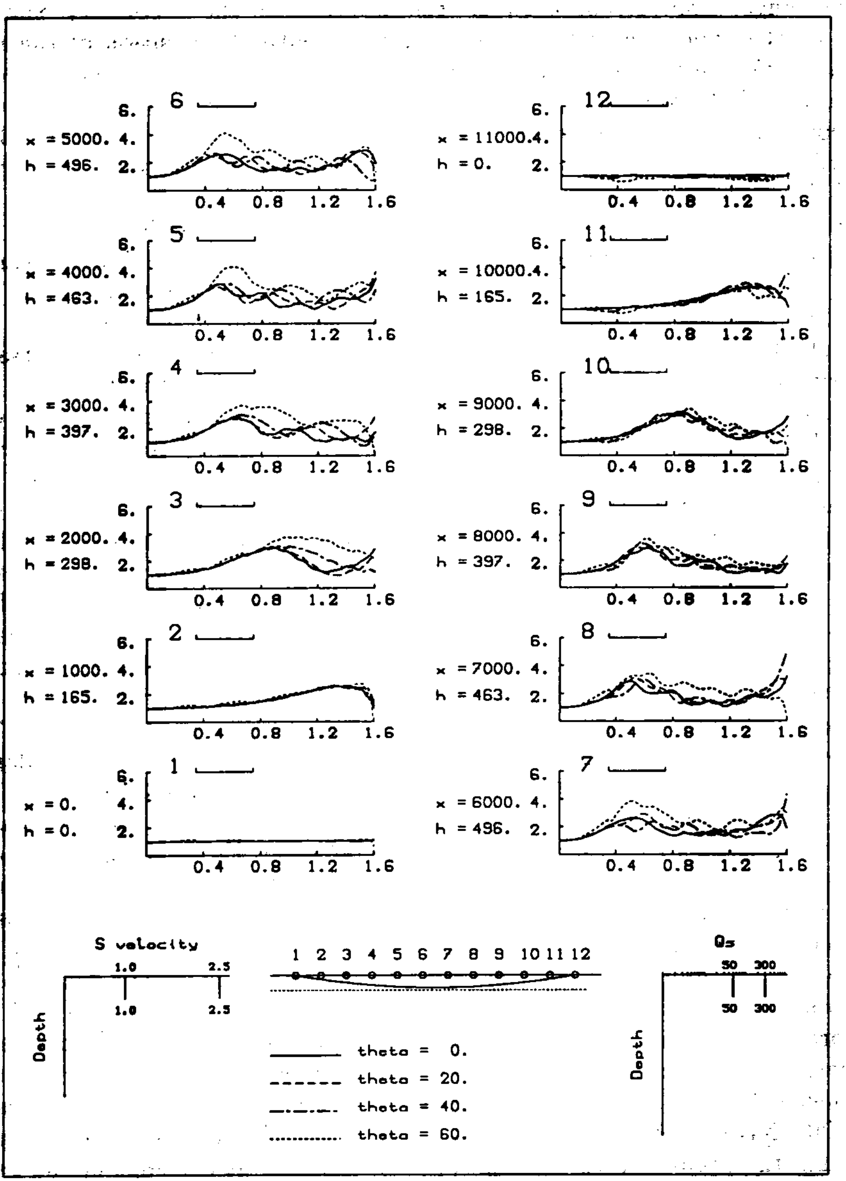

Figure 9: Spectral responses of the sedimentary basin to obliquely incident plane waves at different angles. The geometry of the basin, the locations of the receivers and the characteristics of the media are similar to those used previously.

distance ranges considered, such as the position of the secondary maxima and minima or the evolution of the mean amplitude with the position of the receivers. Only the peak values reached at the resonance frequency of the basin appear to be sensitive to the distance range. This is due to the very nature of the Lg wavetrain which consists of a superposition of arrivals incident at different angles, that leads to interference phenomena which are very sensitive to distance and frequency. Nevertheless, the agreement between these different results suggests that the site effect is almost independant from the epicentral distance, at least in this distance range. For the source at an epicentral distance of 300 km, which is relevant to the Mexico City problem, we compared our results with the spectral ratios obtained under the plane wave assumption and using the method developed by Aki and Larner (1970). The geometry of the basin and the impedance contrast at its boundary are kept unchanged. The spectral responses obtained at the different sites considered previously are presented on Figure 9 for different incidence angles. The results obtained for angles of 0°, 20° and 40° are very similar. Nevertheless, a clear discrepancy appears with the case of the incidence angle of 60°. If one compares these responses with those presented in Figure 8 for incident Lg waves, the agreement between the two approaches seems satisfactory, despite the fact that the plane wave response is stronger for the receivers located on the basin half closer to the source for an incidence angle of 60°. This can be explained by the fact that the Lg can be regarded locally as a superposition of plane waves incident with different angles and therefore that the response of the basin to Lg represent a mean value with respect to angle. In the crustal model considered, a plane wave incident on the Moho at the critical angle reaches the surface at an angle of 31.7°. Thus we can expect to overestimate the response by identifying the Lg as a plane wave incident at angles as large as 60°. The most significant characteristics of the basin response are correctly predicted by the plane wave response at small angles of incidence, at least with respect to the few informations available on the actual structure of the crust. Because of the weak sensitivity of the response to incidence angles less than 40°, the vertical incidence can be effectively regarded as a good indication of the actual response of the basin to incident Lg.

In these computations we have considered the source to be a point force with a short rise-time. Seismograms durations are due only to path effects and possibly to the presence of the deep sediments. At a distance of 300 km from the source, the duration of the complete SH wavetrain is about 50 sec at the center of the basin (neglecting the long period arrivals). Assuming that the accelerometers in Mexico City have not been triggered by Sn waves or direct S but more likely by the onset of Lg, the predicted duration is reduced to 20 sec at the edge of the basin and 30 sec at its center. These values are in good agreement with the observations at sites in the hills zone and in the intermediate lake zone. Of course this does not agree with actual accelerograms recorded in the lake zone, such as for CDAO records, for which the effect of the clay layer and its geometry has to be taken into account. A detailed study of these effects is presented in a companion paper (Bard et al., 1988).

Conclusions

1) We have shown that the vertical displacement records of the great Michoacan earthquake in Mexico City are almost unsensitive to the locations of the stations. Whichever is the station considered, the 3 sec period ripples which are associated with the damage, are present on the observed seismograms even for the station on the hills zone. The presence of these arrivals can not be attributed simply to the presence of the clay in the lake zone.

2) The similarity between the vertical displacement records has allowed us to perform a multichannel phase analysis. The eigenvalue decomposition indicates that each of the spectral peak is associated with a single mode of propagation. The phase analysis shows that the waves associated with the two prominant frequencies are of different types. The apparent phase velocities observed are coherent with a propagation in the direction of the source. These results are an additional indication that this earthquake has a peaked source spectrum.

3) We propose to interprete the 3 sec ripples as the contribution of the regional phase Lg which is the prominant arrival in the frequency range considered in most of the continental areas. In order to test the validity of this assumption we have perform a simple simulation of moderate magnitude events in the subduction zone. The observations, in the frequency range relevant to the problem of Mexico City, confirm the efficiency of Lg propagation between the Pacific Coast and Mexico City and the absence of anomalous structures within the crust in this area.

4) We have computed the response of the deep basin beneath Mexico City to incident Lg waves. Our computations were limited to the SH case. The presence of the basin results in a clear amplification and increase of the duration in the center of the structure. The durations of the theoretical signals are in good agreement with the observations at sites in the hills zone or in the intermediate zone. We have computed the spectral ratios between the signals with and without the presence of the sedimentary basin. The amplification reaches a value of 5. A comparison of these spectral ratios with the response to an obliquely incident plane wave indicates that the response to Lg may be roughly represented by the mean response to plane waves incident at angles corresponding to critically reflected rays. In absence of a detailed knowledge of the structure of the crust and of the local geology, a plane wave response is a reliable indication of the effect of the presence of a sedimentary basin.

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