ANALYSIS OF GROUND MOTION IN MEXICO CITY DURING THE APRIL 25, 1989 GUERRERO EARTHQUAKE

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ABSTRACT

In this work we analyze instrumental observations of ground motion in Mexico City during the April 25, 1989 Guerrero earthquake. Our aim is to understand various aspects of the seismic response of the valley that are not completely resolved. Such understanding of the basic mechanisms that control the seismic behavior of the valley sediments will be crucial in any modeling attempt. The study of vertical motion for this event, which practically was not affected by site conditions, leads to identify a prominent long period

Rayleigh wave. This and the availability of absolute time for some stations allowed to establish a common time reference for all recordings. On the other hand, horizontal motion is significantly amplified, with large increases in duration, at lake bed sites. In order to interpret the observed complexity of ground motion we studied two simplified models of soft alluvial valleys. One of these is two-dimensional and it is excited by plane S waves with variable polarization and incidence angles. This model allows three-dimensional response. The other is a three-dimensional axisymmetric flat valley with rigid base. Computations are performed in the frequency domain by means of a boundary integral method for the two-dimensional model and using a collocation least-squares technique for the three-dimensional one. Seismograms are obtained through Fourier synthesis. It is found that the irregular soft layer response produces polarization patterns that are similar to the observations, suggesting that the latter are consequence of three-dimensional effects.

INTRODUCTION

The great significance of local site effects is now widely recognized. Being produced by geotechnical conditions and the very surficial geology, they can produce large variations of seismic ground motion and concentrated damage. The last two decades witnessed both theoretical advances in the characterization of such effects and dramatic examples of its reality as well. However, much work is still needed to transform this body of knowledge and evidence into practical rules to mitigate seismic hazard.

The importance of local amplification was evinced by the unprecedented effects observed in Mexico City during the great 1985 Michoacan earthquake.

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The earthquake was generated at a part of the subduction zone of the Mexican coast along the Pacific Ocean. A portion of this region, the so-called Guerrero Gap, has a high seismic potential in the short term [27]. It is uncertain whether the energy that accumulates there will be released in a big event or in many, smaller ones. In any case it is of interest to understand the characteristics of the response of Mexico City Valley for coastal events.

Since 1985 considerable efforts have been devoted to a better understanding of both the valley response (see e. g. [2,12,13,14,15,20,21,22, 23,26,27]) and the effects related to source and path [3,4,27]. In particular, the recently installed accelerometric network, which by now has more than 100 stations, has allowed to extensively record seismic ground motion from coastal events. This has been useful to define general characteristics of the response of the valley [20,26] and regional amplification as well [13]. Such results have been used to establish practical parameters and recommendations for seismic design. However, the large variability of amplitudes, the long duration of recorded seismograms and their peculiar polarization have not been completely understood. These effects cannot be explained in terms of one-dimensional shear model alone. Two- and three-dimensional effects must be invoked in order to account for observations.

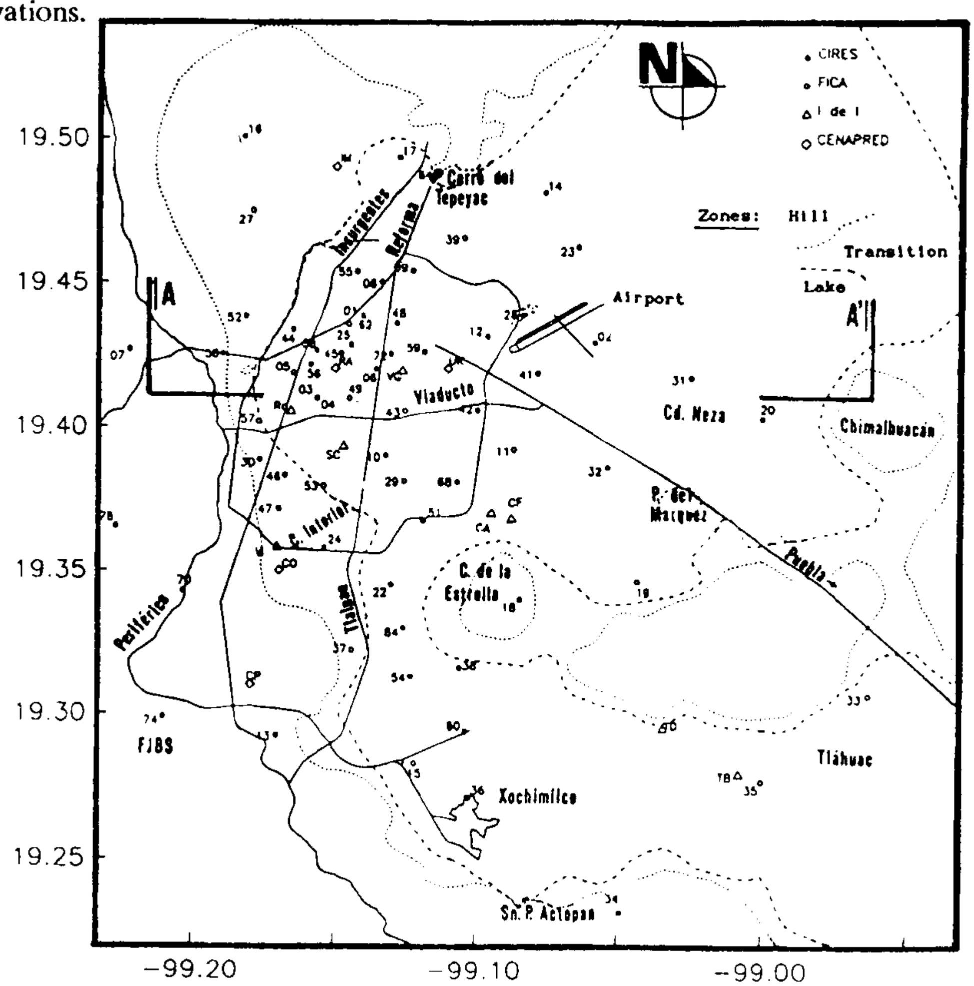

FIGURE 1. Mexico City Accelerometric Array

In this work we study instrumental observations of ground motion in Mexico City during the April 25, 1989 Guerrero earthquake (Ms=6.9). The epicenter was located at about 300 km south of Mexico City with depth of 17 km (i e precisely at the Guerrero Gap). This event was well recorded in the valley at more than 60 sites and is one of the best recorded earthquakes since 1985. Figure 1 displays the location of nearly all the stations of the Mexico City Accelerometric Array (MCAA). Stations belong to various institutions: Centro de Instrumentación y Registro Sísmico CIRES), Fundación de Ingenieros Civiles Asociados (FICA), Instituto de Ingeniería (I de I) and Centro Nacional para la Prevención de Desastres (CENAPRED). Main avenues are given for reference with continuous lines in the figure. The actual geotechnical zoning, based on Marsal and Mazari [9] is also indicated. The boundaries of transition zone with hill and lake-bed zones are given, respectively, with dotted and dashed lines.

VERTICAL MOTION

Vertical displacements in the valley during the 1985 Michoacan

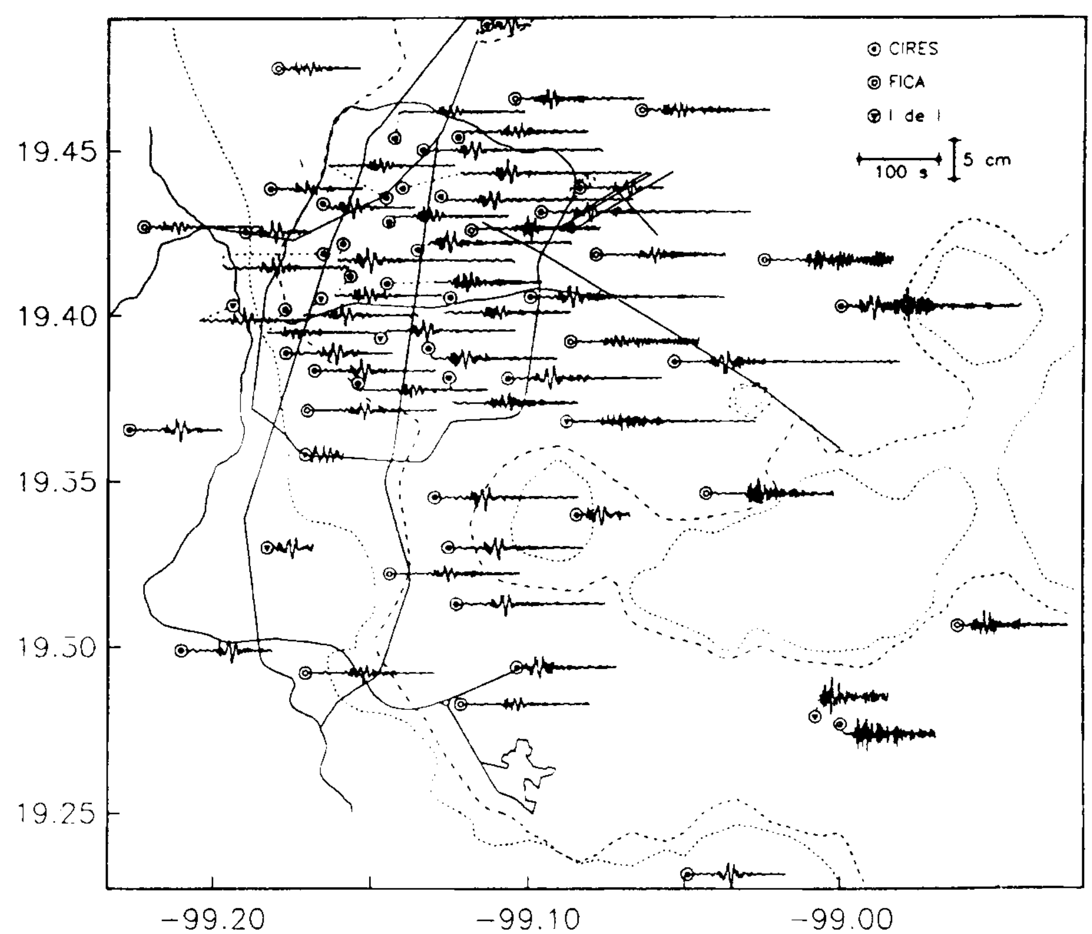

FIGURE 2. Vertical displacements in Mexico City during the April 25, 1989 Guerrero earthquake.

Considering that the distance covered by stations with absolute time is of about 7 km and that the origin time can have a maximum error of .25 sec, our estimate may be with an error of about 0.2 km/sec. In any case, the upper bound of our group velocity is still a very small value for continental paths. Our result has to be verified. If it is true, it may imply that the crust beneath the valley of Mexico is thinner and/or has lower rigidity than other continental regions. In fact, Ewing et al, [6] observed for Rayleigh waves, with period of 10 sec, group velocities of about 3 km/sec for typical continental paths. On the other hand, values as low as 1 km/sec have been measured for oceanic ones (e g [10,16,8]). Certainly, these effects are largely attributable to the water layer, but partly to the slow velocity sediments as well. Regarding continental regions, Oliver and Ewing [11] pointed out that in this frequency range surface wave velocity "may be strongly affected by sediments and sedimentary rocks near the earth's surface". For periods less than about 10 sec they reported velocities as low as 2 km/sec. Perhaps this can serve to explain Ordaz and Singh's [13] observation for regional amplification of horizontal motion of more than 10 at the hill zone and at some locations around the Mexico City's valley, with respect to both theoretical values and observations for similar distances. In addition, these authors suggest that this amplification could be ue to deep (about 1 km) and extended (about 60 km) soft deposits. The subject is a matter of current research.

By assuming our estimate for group velocity of 1.6 km/sec as correct, a common time reference for all recordings can be established from a correlation analysis. Figure 4 displays the vertical seismograms with a common time basis and a vertical offset given by the latitude of the recording station. For some stations the site effects are spectacular with significant amplifications of late phases. For instance, station 20 (see Figs 1 and 2) shows a conspicuous wave train with period of 4-5 sec that can be been with about 30 sec of delay with respect to our reference Rayleigh wave.

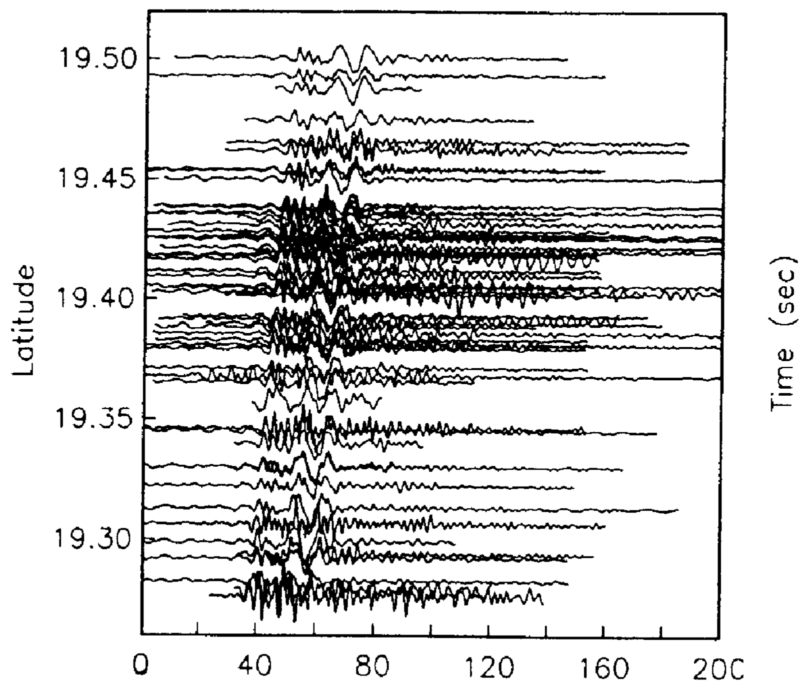

FIGURE 4. Vertical displacements for 60 stations of MCAA with a common time basis

Earthquake showed nearly identical waveforms and amplitudes which were not significantly affected by local site conditions [4,23]. The long period wave was identified as a Rayleigh surface wave, whereas the observed (2-3 sec) ripples were interpreted as higher-mode crust-guided Lg waves. The April 25, 1989 event showed up again similar waveforms. Figure 2 displays vertical displacements for most stations of the array. They were computed from the double integration of recorded accelerations. There is much similarity among seismograms. This confirms that vertical motion is little affected, if any, by the local conditions. On the other hand, the uncoupling from horizontal motion suggests that, in principle, vertical motion contains significant information of the incident wave fields. In fact, the common waveform in the vertical displacements is associated with the incident long period (10 sec) Rayleigh wave. This time with an amplitude of about 1 cm (1/8 of that for the Michoacan earthquake but still well recorded).

Absolute time is available for 5 stations of Instituto de Ingeniería, UNAM (Almora and Mena, personal communication). They are: La Viga (Vg), Tacubaya (Ty), Roma (Ro), Secretarha de Comunicaciones y Transportes (SC), and Viveros (Vi). Their location can be seen in Fig 1. Figure 3 shows the vertical displacements for these stations. This information allowed establishing, through a least-squares fitting of the prominent waveform correlation, a group velocity of 1.6 km/sec, given the incidence is from the south.

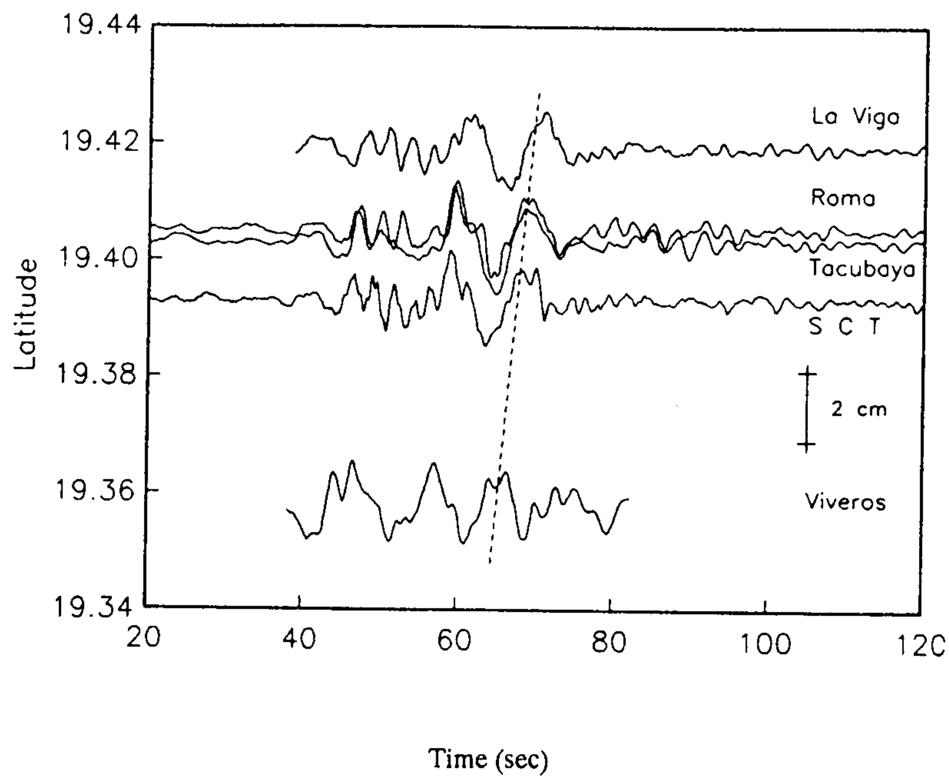

FIGURE 3. Vertical displacements for some stations of Instituto de Ingenieria with absolute time

HORIZONTAL MOTION

The geotechnical zoning in Mexico City is based on the pioneering work of Marsal and Mazari [9]. The data from recent earthquakes show that it is consistent with observed seismic response. Recorded horizontal ground motion

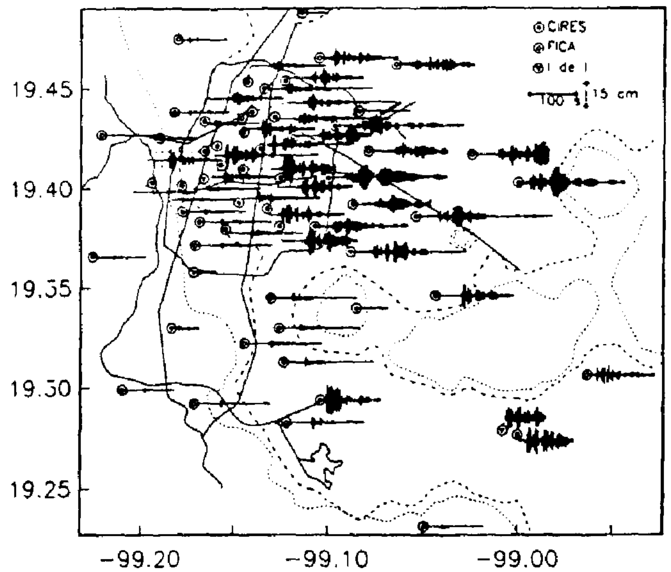

FIGURE 5. NS displacements in Mexico City during the April 25, 1989 Guerrero earthquake

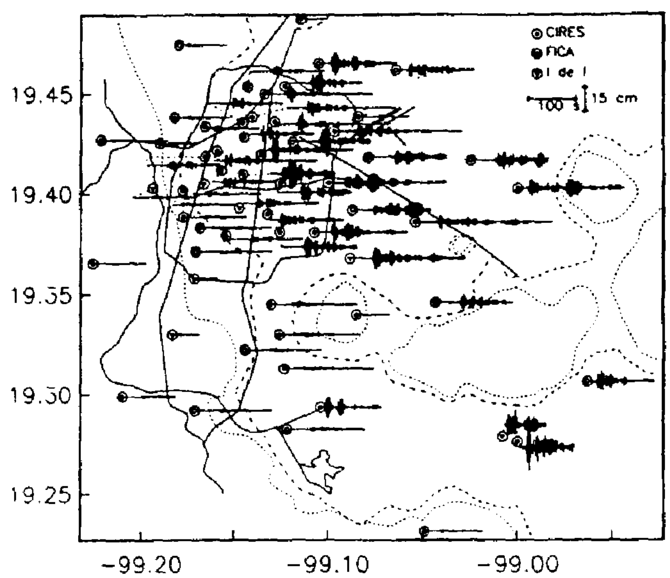

FIGURE 6. EW displacements in Mexico City during the April 25, 1989 Guerrero earthquake

is clearly different whether the site is on the hill, transition or lake bed zones, respectively. In order to illustrate this, we use data from the April 25, 1989 Guerrero earthquake. Figures 5 and 6 show, respectively, the displacements for NS and EW components for most stations of MCAA.

hese plots allow direct comparisons of recorded ground motions, both in amplitude and duration, that take into account the geotechnical conditions. It is then clear that horizontal motion is significantly amplified, with large increases in duration, at lake bed sites. Typically after a portion with a relatively wide frequency content, the records show a nearly monochromatic coda of extraordinary duration. For most locations, the dominant period of this coda is the same as that predicted for the one-dimensional response of each site. However, these effects cannot be explained in terms of one-dimensional shear model alone. Two- and three-dimensional effects must be invoked in order to account for observations. In fact, spectral amplification at lake bed sites reach more than 50 with respect to CU, a hill zone site [18,26]. This could be produced by focusing of the incident waves and to the very efficient generation of local Love and Rayleigh surface waves at the edges of the basin (see e g [1,2,7,19]) and at small scale irregularities (see e g [2,5]).

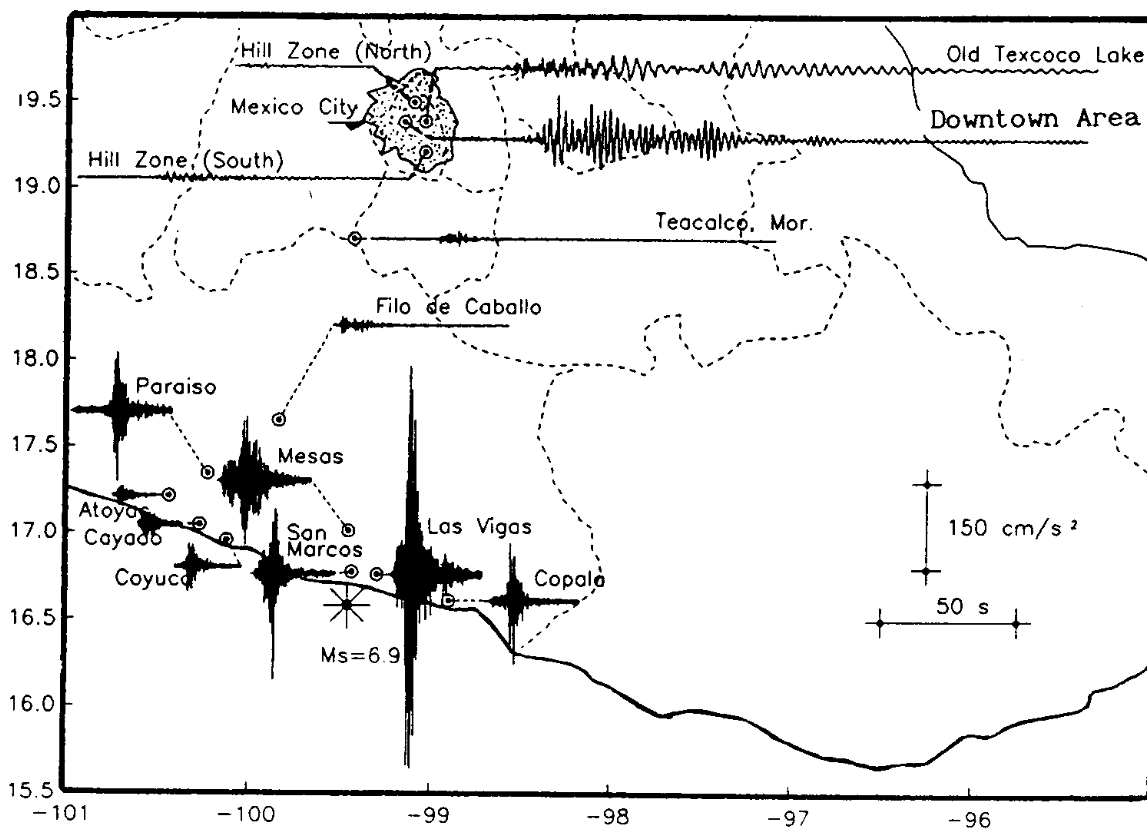

FIGURE 7. Regional view of NS ground acceleration during the April 25, 1989 Guerrero earthquake. Near-source, along-path and Mexico City records are displayed

On the other hand, we have computed Fourier spectral ratios at eleven sites in the hill zone (07, 13, 18, 28, 34, 50, 64, 74, 78, CU and TY, see Fig 1) in Mexico City and the average of three sites (Parahso, Filo de Caballo, and Teacalco, Fig 7) located along the path. Results are presented in Fig 8 for NS and EW components. Computed ratios show a significant amplification for periods between 1 and 5 sec. A remarkable peak can be seen around 3 sec. This is consistent with Ordaz and Singh's [13] observation.

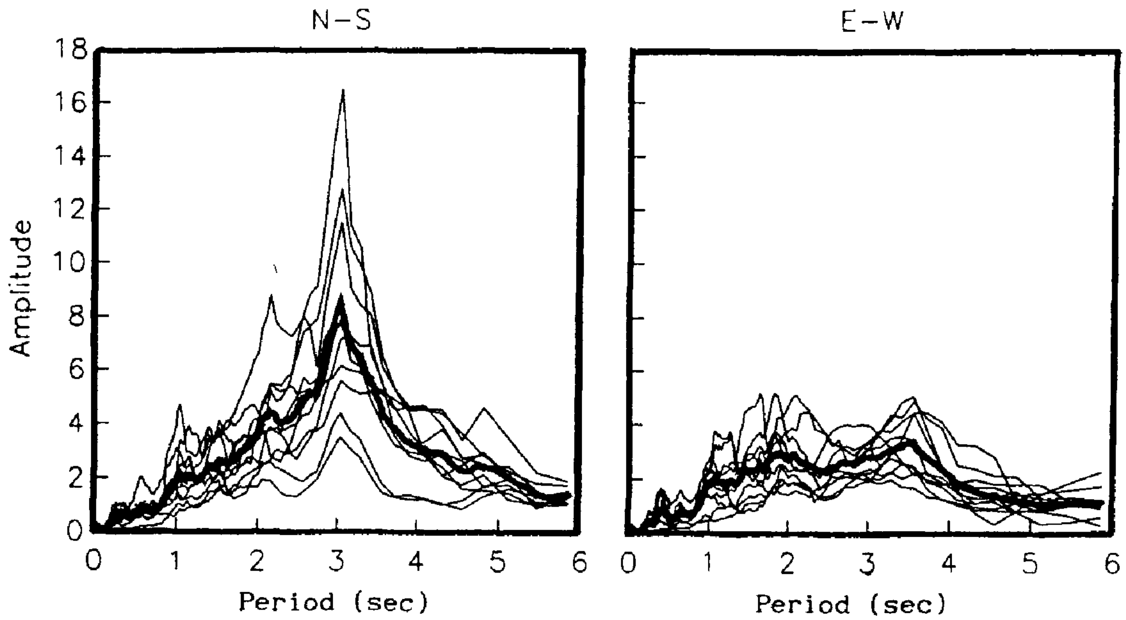

FIGURE 8. Spectral ratios between 11 Mexico City hill-zone spectra and average external ones for the April 25, 1989 Guerrero earthquake. NS and EW components are displayed at the left and right hand-side, respectively. Mean values are indicated with thick lines

To illustrate the complexity of horizontal motion in Fig 9 the particle trajectories are given for each station of the network. These plots are known as polarization diagrams or hodograms. At first look they seem chaotic. In all cases the horizontal polarization patterns show a conspicuous variation

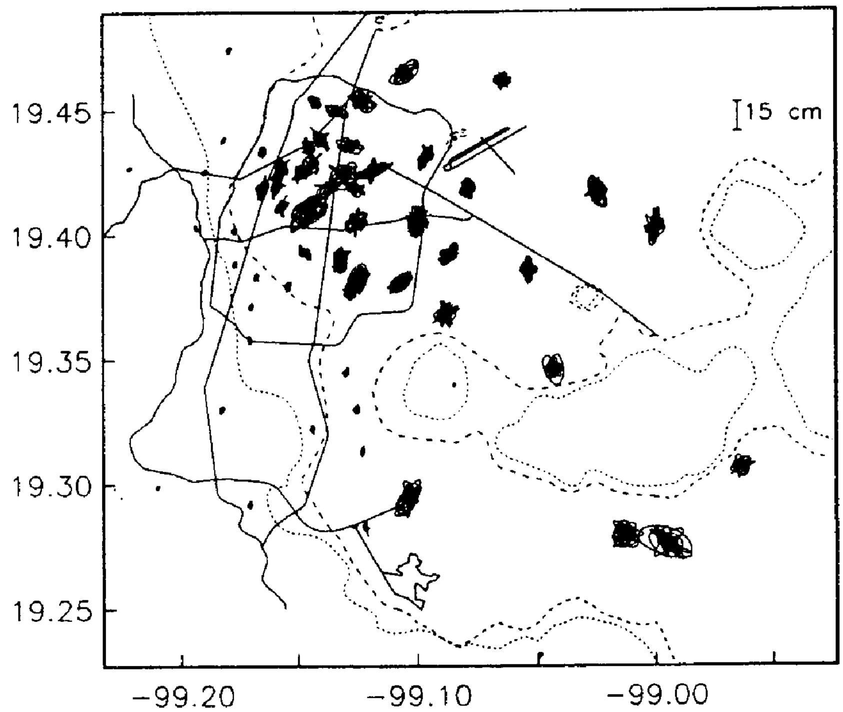

FIGURE 9. Horizontal particle motion in Mexico City during the April 25, 1989 Guerrero earthquake

(they rotate with time) that we interpret as due to the interference of locally generated surface waves. For most stations the NS component is larger than its EW counterpart. It is likely that in addition to the complexity of incoming wave field, significant effects of the response are related to the azimuth of incident waves. For instance, Fig 10 displays the corresponding polarization diagrams for the May 31, 1990 (Ms=6.1) event. This earthquake was generated in direction S35E, some 300 km away from Mexico City. Of course, the azimuth is different but so are the size of the earthquake and the seismic waves' path.

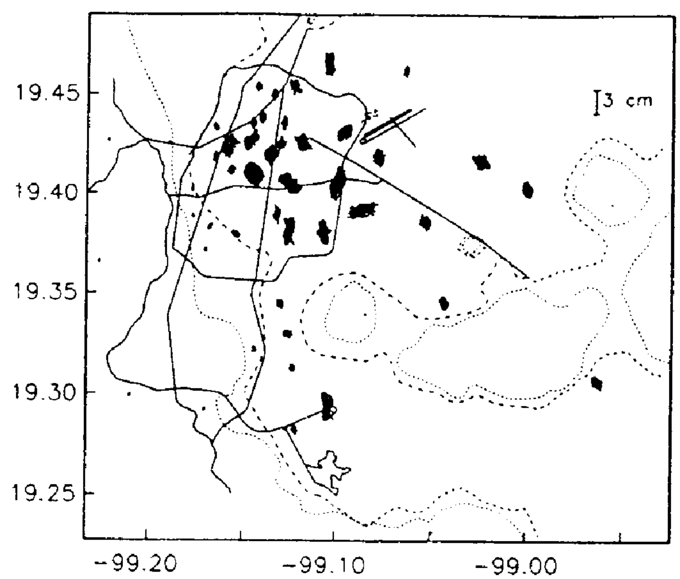

FIGURE 10. Horizontal particle motion in Mexico City during the May 31, 1990 Michoacan earthquake

An interpolation code based on least-squares fitting of polynomial functions was applied in order to see the continuous spatial variations of motion across Mexico City. Use was made of only the coherent part of observed Fourier spectra. Therefore, time histories inferred for sites inside Mexico City are reliable for frequencies between 0.1 and 1.25 Hz [15]. In fact, this frequency range defines the width of the band pass filter. Figures 11 and 12 show, respectively, the NS and EW interpolated components along the section A-A' indicated in Fig 1. Note that the motion looks roughly as produced by one-dimensional response. However, there are various interferences that suggest the presence of Love and Rayleigh waves.

This pattern can be explained by the one-dimensional response of flat soft layers combined with the propagation of local surface waves generated at the edges of the basin.

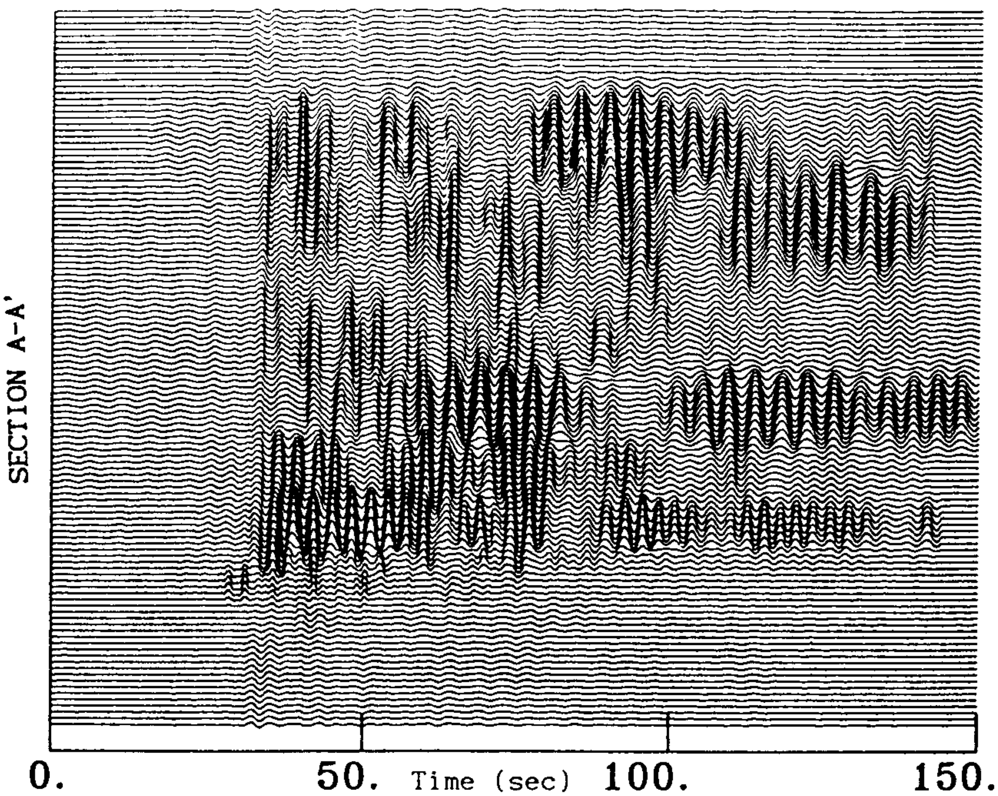

FIGURE 11. Interpolated NS displacements along the section A-A' obtained from recorded data of the April 25, 1989 Guerrero earthquake

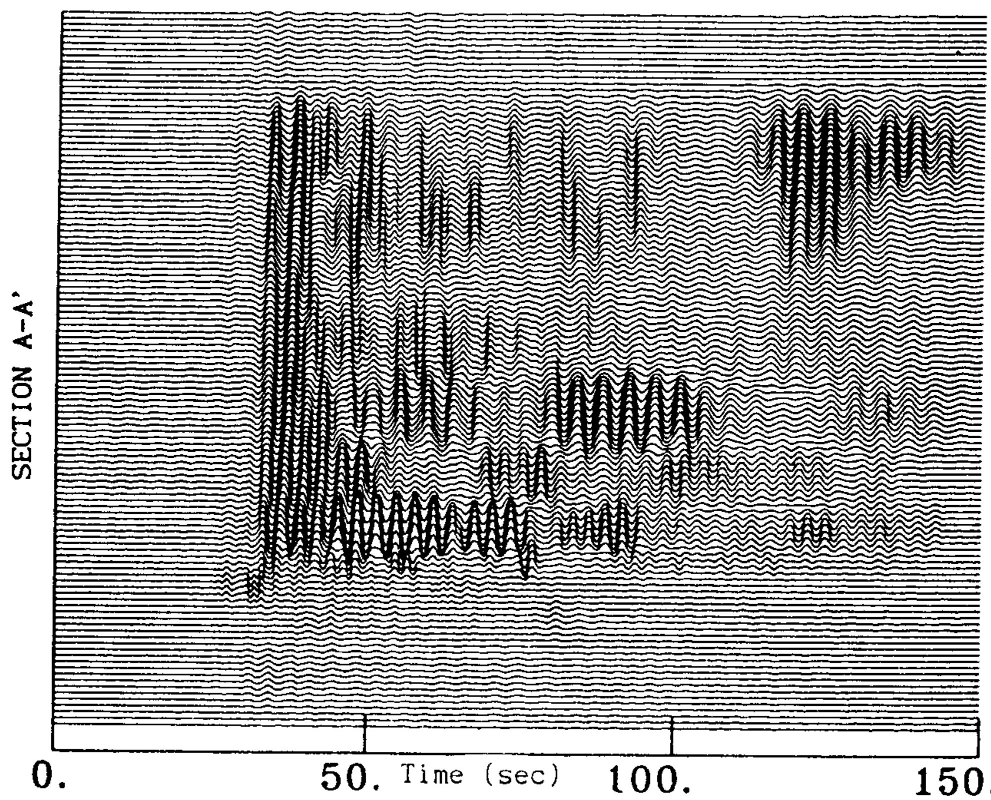

FIGURE 12. Interpolated EW displacements along the section A-A' obtained from recorded data of the April 25, 1989 Guerrero earthquake

SIMPLIFIED MODELS FOR 3D EFFECTS

In order to clarify two- and three-dimensional effects in the response of alluvial valleys, we studied two simplified elastic models. One of these is two-dimensional and is excited by plane S waves with variable polarization and incidence angles. Computations are performed in the frequency domain by means of a boundary integral method based upon the formulation of Sanchez- Sesma and Campillo [25]. The geometry and properties of the valley and half-space model studied are depicted in Fig 13. The shape assumed for the interface is parabolic with a maximum depth of 0.05α, where α = half width of the deposit. Material properties are $\beta_E = 4\beta_R$, where β = shear wave velocity and subscripts E and R correspond to half-space and valley, respectively, Poisson ratios are $\nu_E = 1/3$ and $\nu_R = 0.49$ (compressional wave velocities are $\alpha_E = 2\beta_E$ and $\alpha_R = 7.14\beta_R$), mass densities are $\rho_E = 2\rho_R$, and quality factors $Q_E = 1000$ and $Q_R = 500$. These properties were set to represent a soft alluvial valley with a relatively high Poisson ratio, as it is the case for

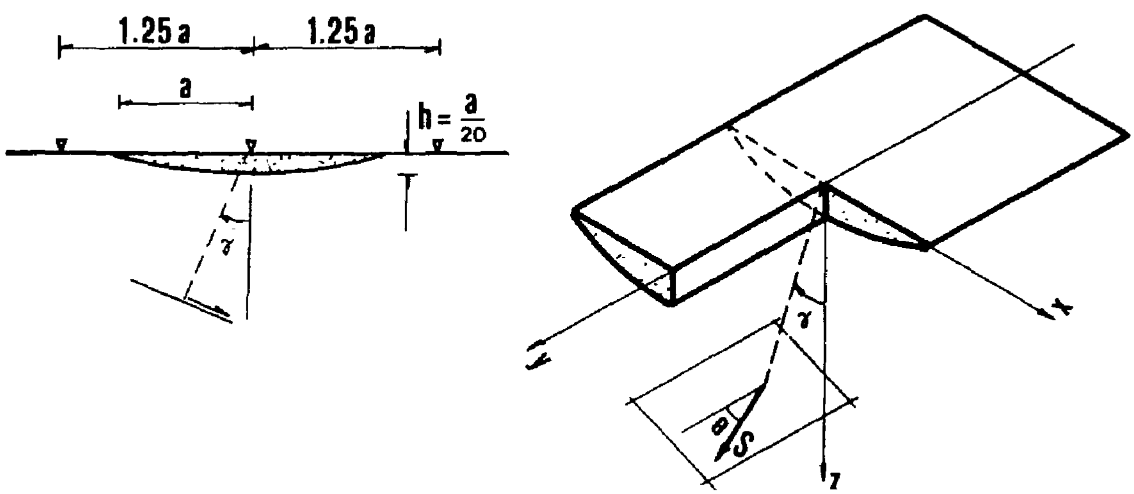

FIGURE 13. Soft alluvial valley with parabolic interface under incidence of plane S waves. Incidence and polarization angles are represented by γ and θ, respectively.

Mexico City's sediments. Even though this model is two-dimensional, we can consider the incidence of a plane S wave with a given incidence angle γ and arbitrary polarization θ (see Fig 13) by the simple combination of SH ($\theta = 0$) and SV ($\theta = \pi/2$) responses. Each one will be modulated by $\sin\theta$ and $\cos\theta$, respectively. This allows to see how the distinct wave propagation properties of Love and Rayleigh surface waves which produce the anti-plane and in-plane components, respectively, interact and control the polarization of horizontal motion. The time variation of incoming wavefield is given by a Ricker wavelet with characteristic period $t_p = 0.5\, t_0$, where $t_0 = 2\alpha/\beta_E$. Seismograms are obtained through Fourier synthesis. For an incidence angle $\gamma = 30°$, Figs 14 and 15 show the synthetics for SH and SV waves, respectively. Figure 16 shows the horizontal particle motion by means of polarigrams (plots of displacement vectors shifted along the time axis) and hodograms for sites across the valley when the polarization angle is $\theta = 45°$. It is found that the model response produce horizontal polarization patterns that remind the rotation with time of observed ones. In our model this effect is due to the different velocities of Love and Rayleigh waves which are present in displacements v and u, respectively. This apparently obvious result has been developed in a formal way and can be the departure for a quantitative explanation of observed response.

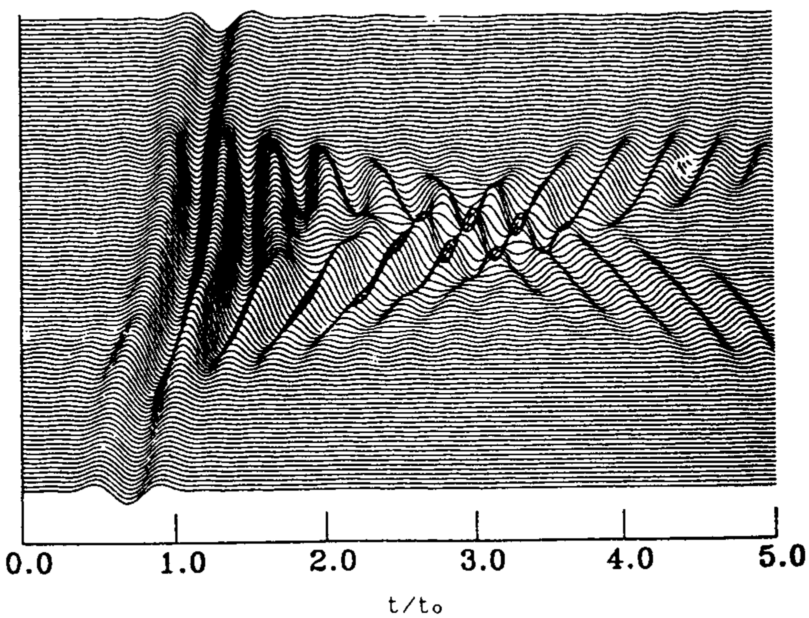

FIGURE 14. Synthetic seismograms for incidence of SH waves in 51 stations (from -1.25a to 1.25a) across the surface of the two-dimensional model

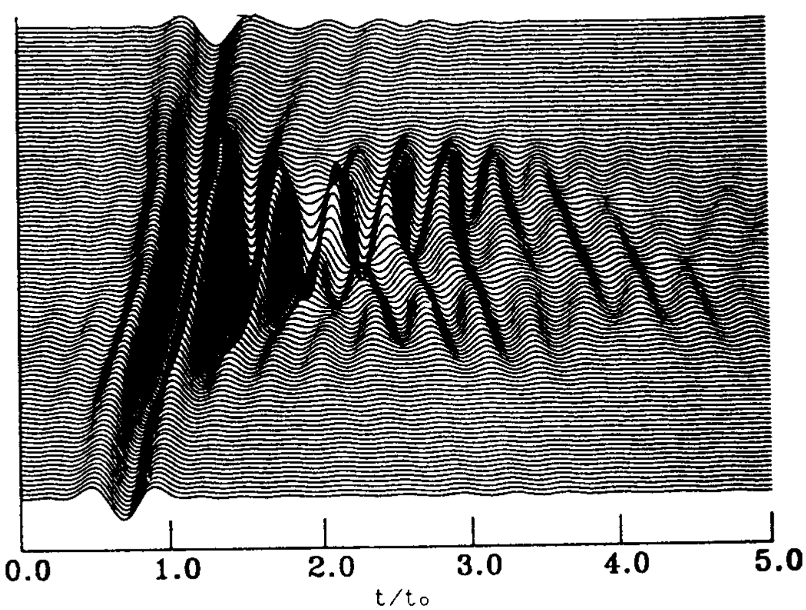

FIGURE 15. Horizontal synthetic seismograms for incidence of SV waves in the stations used in figure 14.

The other model studied is a three-dimensional axisymmetric valley with a rigid base with prescribed motion in the x direction. Poisson ratio is $\nu = 0.45$ (compressional wave velocity is $\alpha = 3.33\beta$ and β = shear wave velocity of the valley) with a quality factor Q = 20. The model is shown in Fig 17. It is a limited flat layer with thickness h = $0.2a$, where a = radius of the valley at the free surface. A diametral cross-section shows the assumed lope of 45° at the basin's edge. Transfer functions were constructed using a superposition of spherical wave functions and a collocation least-squares

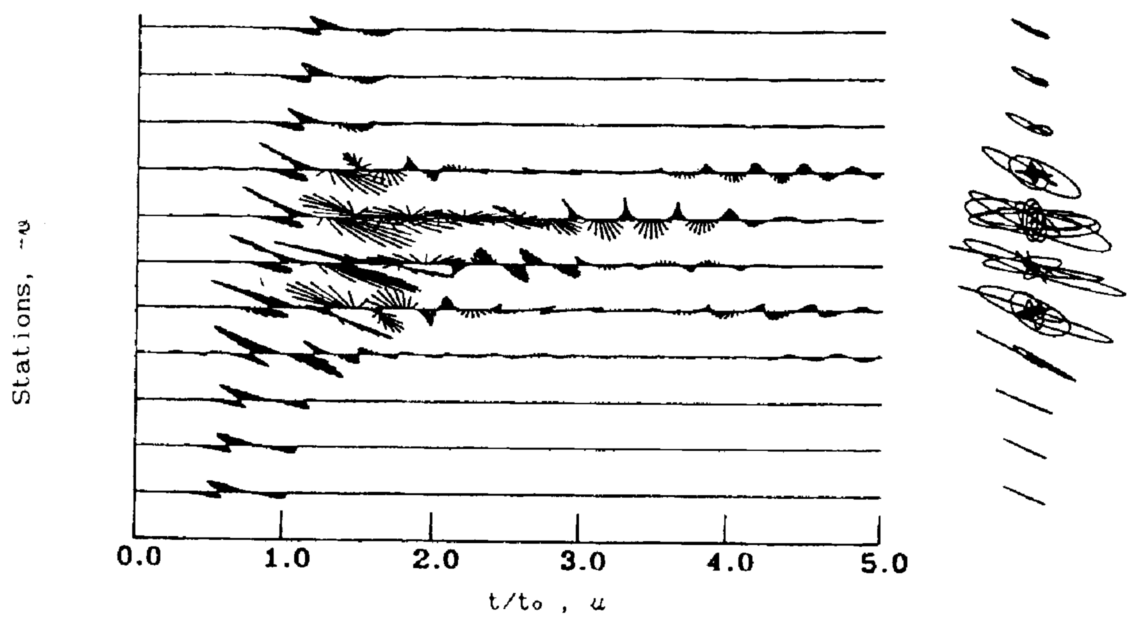

FIGURE 16. Polarigrams and horizontal particle motion for 11 stations (from $-1.25a$ to $1.25a$) across the two-dimensional model when polarization angle θ = 45°

matching of boundary conditions [17,24]. For reasons of symmetry, the total motion of the model's surface, under the assumed excitation, can be described by three radial functions modulated by cos ϕ for radial and vertical motion and by sin ϕ for circumferential motion, where ϕ = azimuthal angle.

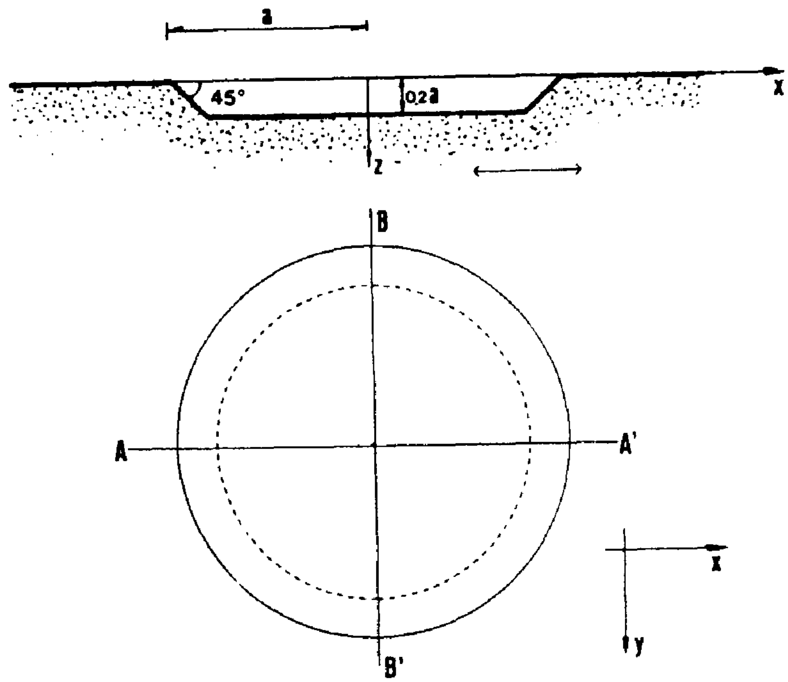

FIGURE 17. Three-dimensional axisymmetric alluvial valley with rigid base and unit slope at the edge. Motion is imposed at the base in the x direction

Therefore, to represent the ground motion at any point of the surface it suffices to know the response for two slices of the model. Figure 18 displays the horizontal ground motion along sections A-A' and B-B', respectively.

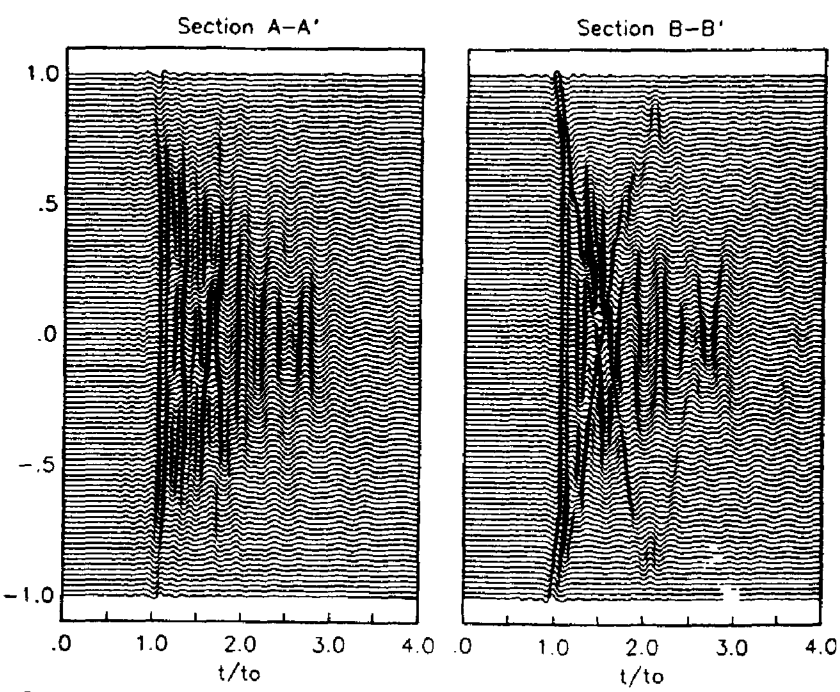

FIGURE 18. Horizontal synthetic seismograms in 101 stations along the sections A-A' and B-B', respectively, of the three-dimensional model.

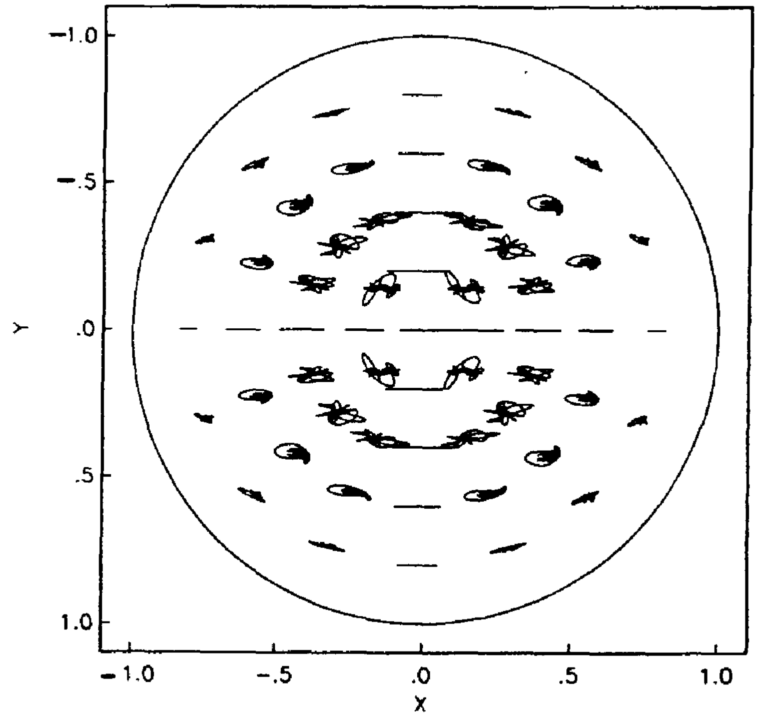

FIGURE 19. Horizontal particle motion at selected sites on the surface of the three-dimensional model. The motion of the base is depicted in the bottom-right corner.

Again, due to symmetry such motion takes place in the x direction. It is radial at section A-A', whereas it is circumferential at B-B'. If our model is considered, alternatively, as two-dimensional for these two sections, then we have in-plane (P-SV-Rayleigh) and anti-plane (SH-Love) responses, respectively. Here, they are mixed due to the three-dimensional nature of our model. Synthetics correspond to a Ricker wavelet input with characteristic period tp = 0.2 to, where to has the same meaning that in the two-dimensional model. These results allow to establish that the response in flat valleys is clearly composed by the one-dimensional response strongly modified by surface waves. This is clear in section B-B' due to the lower velocity of Love modes, even if modified by other wave contributions from the edge. Figure 19 shows the horizontal particle motion in the surface of the valley as well as the prescribed motion. Despite the simplicity of our model, it shows quantitatively that local surface wave generation in three-dimensional valleys strongly modify the characteristics of ground response, such as amplitude, polarization, and duration of motion.

CONCLUSIONS

The MCAA has allowed to observe peculiar characteristics of the strong ground motion in the valley. The April 25, 1989 Guerrero earthquake was well recorded at more than 60 sites. It was possible to identify in vertical displacements a prominent 10 sec Rayleigh wave. Its correlation and the availability of absolute time for five stations lead us to establish a common reference time. The least-squares estimated velocity for (10 sec) Rayleigh waves is lower than the values accepted for typical crustal regions, and perhaps, is related to the regional amplification observed. On the other hand, spectral ratios of horizontal motion between all sites in the hard-zone of Mexico City and sites in the middle of the path from the coast show great amplifications around periods of 3 sec. At lake-bed sites, horizontal ground motion is greatly amplified both in amplitude and duration. In addition, important spatial variations are observed. Mathematical modeling allowed us to understand features of the response of alluvial valleys in terms of locally generated Love and Rayleigh waves. We interpret these as three-dimensional effects. Despite the simplicity of our models, it is possible to point out the substantial role played by local surface waves in the whole response. Qualitative comparisons of data with synthetics show that the understanding of the seismic response of alluvial valleys is feasible with the help of simplified mathematical models. Our results must be regarded as preliminary but they suggest that simpler, more powerful methods can be devised. These must be calibrated with both observations and rigorous solutions in order to properly account for the three-dimensional nature of seismic response.

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REFERENCES

1.- Aki, K, "Local site effects on strong ground motion", Earthquake Engineering and Soil Dynamics II - Recent advances in ground motion evaluation, J L Von Thun (ed), Geotechnical Special Publication No. 20, 103-155, Am Soc Civil Engr, New York, 1988.

2.- Bard, P-Y, M Campillo, F J Chávez-Garcha and F J Sánchez-Sesma, "A theoretical investigation of large- and small-scale amplification effects in the Mexico City valley", Earthquake Spectra, Vol 4, pp 609-633, 1988.

3.- Campillo, M, P-Y Bard, F Nicollin and F J Sánchez-Sesma, "The incident wavefield in Mexico City during the great Michoacan earthquake and its interaction with the deep basin", Earthquake Spectra, Vol 4, pp 591-608, 1988.

4.- Campillo, M, J C Gariel, K Aki and F J Sánchez-Sesma, "Destructive strong ground motion in Mexico City: Source, path and site effects during the great 1985 Michoacan earthquake", Bull Seism Soc Am, Vol 79, pp 1718-1735, 1989.

5.- Campillo, M, F J Sánchez-Sesma and K Aki, "Influence of small lateral variations of a soft surficial layer on seismic ground motion", Soil Dyn Earthq Engrg, Vol 9, pp 284-287, 1990.

6.- Ewing, W M, W S Jardetzky and F Press, Elastic waves in layered media, McGraw-Hill Book Co, New York, 1957.

7.- Kawase, H and K Aki, "A study on the response of a soft basin for incident S, P and Rayleigh waves with special reference to the long duration observed in Mexico City", Bull Seism Soc Am, Vol 79, pp 1361-1382, 1989.

8.- Keilis-Borok, V I, Seismic surface waves in laterally inhomogeneous earth, V I Keilis-Borok editor, Kluwer Academic Publishers, 1989.

9.- Marsal, R J and M Mazari, El subsuelo de la ciudad de Mexico/ The subsoil of Mexico City, Facultad de Ingenieria, UNAM, Mexico, D.F., 1959.

10.- Oliver, J, "A summary of observed seismic surface wave dispersion", Bull Seism Soc Am, Vol 52, pp 81-86, 1962.

11.- Oliver, J and M Ewing, "The effect of surficial sedimentary layers on continental surface waves", Bull Seism Soc Am, Vol 48, pp 339-354, 1958.

12.- Ordaz, M, S K Singh, E Reinoso, J Lermo, J M Espinoza and T Domhnguez, "Estimation of response spectra in the lake bed zone of the Valley of Mexico during the Michoacan earthquake", Earthquake Spectra, Vol 4, pp 815-834, 1988.

13.- Ordaz, M and S K Singh, "Source spectra and spectral attenuation of seismic waves from Mexican earthquakes, and evidence of amplification in the hill zone of Mexico City", Bull Seism Soc Am, submitted, 1991.

14.- Paolucci, R and E Faccioli, "Analysis of spatial variation of earthquake ground motion in the Mexico City area", Proc 4th Int Conf on Seismic Zonation, Standford, California, August 26-29, 1991, in press.

15.- Perez-Rocha, L E, "Analisis del movimiento del terreno del valle de Mexico durante el sismo del 25 de abril de 1989", Centro de Investigacion Sismica AC, Report to Departamento del Distrito Federal, January 1991.

16.- Pomeroy, P and J Oliver, "Seismic waves from high-altitude nuclear explosions", J Geophys Research, Vol 65, No 10, pp 3445-3457, 1960

17.- Sanchez-Sesma, F J, "Diffraction of elastic waves by three-dimensional surface irregularities", Bull Seism Soc Am, Vol 73, pp 1621-1636, 1983.

18.- Sanchez-Sesma, F J and S K Singh, "Grandes temblores y sus efectos en el valle de Mexico: Observaciones y teoria", Los sismos de 1985: Casos de mecanica de suelos, Soc Mex Mec Suelos, pp 1-12, September 1986.

19.- Sanchez-Sesma, F J, "Site effects on strong ground motion", Int J Earthq Eng Struct Dyn, Vol 6, pp 124-132, 1987.

20.- Sanchez-Sesma, F J, S Chavez-Perez, M Suarez, M A Bravo and L E Perez-Rocha, "On the seismic response of the Valley of Mexico", Earthquake Spectra, Vol 4, pp 569-589, 1988.

21.- Sanchez-Sesma, F J, L E Perez-Rocha, M A Bravo and S Chavez-Perez, "Synthetic modeling of strong ground motion on a class of alluvial valleys", Proc 9th World Conf Earthq Engr, Vol 8, pp 31-36, Tokyo-Kyoto, Japan, August 2-9, 1988.

22.- Sanchez-Sesma, F J, M A Bravo, S Chavez-Perez, L E Perez-Rocha and M Suarez, "Modelado de la respuesta sismica del Valle de Mexico: Resultados preliminares", Proc VIII Congreso Nacional de Ingenieria Sismica, Vol 1, pp A177-186, Acapulco, Gro, November 16-19, 1989.

23.- Sanchez-Sesma, F J, M Campillo, P-Y Bard, J C Gariel and K Aki, "The great 1985 Michoacan earthquake: A unified approach considering source, path and site effects", Proc. 4th Int. Conf. Soil Dyn. Earthquake Engr., Mexico, DF, October 23-26, in: Engineering Seismology and Site Response, A S Cakmak and I Herrera (eds), Computational Mechanics Publications, Southampton, pp 53-75, 1989.

24.- Sanchez-Sesma, F J, L E Perez-Rocha and S Chavez-Perez, "Diffraction of elastic waves by three-dimensional surface irregularities. Part II", Bull Seism Soc Am, Vol 79, pp 101-112, 1989.

25.- Sanchez-Sesma, F J and M Campillo, "Diffraction of P, SV and Rayleigh waves by topographic features: a boundary integral formulation", Bull Seism Soc Am, Vol 81, in press.

26.- Singh, S K, E Mena and R Castro, "Some aspects of source characteristics of the 19 September, 1985, Michoacsn earthquake and ground motion amplification in and near Mexico City from strong ground motion data", Bull Seism Soc Am, Vol 78, pp 451-457, 1988.

27.- Singh, S K and M Ordaz, "Sismicidad y movimientos fuertes en Mwxico: Una vision actual", Centro Nacional de Prevencion de Desastres, Mexico, November 1991.