Ground Motion and Building Damage: Caracas 29 July 1967 and Mexico City, 19 September 1985

Lawrence A. Drake
Observatorio San Calixto
Casilla 12656
La Paz, Bolivia

Abstract

The propagation of Love and Rayleigh seismic surface waves from a region of consolidated surface rock to one of partially consolidated sediments can be really modelled by the finite element method. At periods of from 0.5 s to 2 s, there is a large increase in the amplitude of Love waves at the earth's surface. Because Rayleigh waves of a period of a little over 1 s in a region of approximately 100 m of alluvium over shale have predominantly vertical motion at the surface of the earth, and at a period of a little under 2 s have predominantly horizontal motion at the surface of the earth, Rayleigh waves of periods from approximately 1.5 s to approximately 2 s, on passing from a region of consolidated rock to one of alluvium over other sediments with low shear wave velocities, show a large increase in horizontal amplitude. These increases in the horizontal amplitudes of Love and Rayleigh waves in regions of alluvium and other sediments with low shear wave velocities contributed to the catastrophic results of the earthquake of 29 July, 1967 in Caracas and that of 19 September, 1985 in Mexico City.

In the region of Caracas, Love waves of a period of 0.7 s, passing from the region of consolidated surface rock in the mountains to the north of the city to a region of sediments of low shear wave velocities, for example, in the region of Los Palos Grandes, increase their amplitude at the earth's surface by a factor of approximately six. This effect is partially compensated by absorption in the sediments of these short period waves. Love waves of a period of 2 s, and also the horizontal displacements of Rayleigh waves of a period of 2 s, increase their amplitude at the earth's surface by a factor of approximately 1.4. In 1967 in Caracas, tall buildings were designed to be seismically resistant, but many lacked sufficiently rigid connections between the vertical transverse reinforced concrete frames and the horizontal floor slabs joining them. Buildings were insufficiently rigid in the horizontal direction perpendicular to the reinforced concrete frames.

As a result of the earthquake of 29 July, 1967, approximately 250 people lost their lives, mainly in the collapse of four tall buildings built over sediments of low shear wave velocities in the region of Los Palos Grandes. As a result of the earthquake of 19 September 1985 in the former Michoacan gap, off the southwest coast of Mexico, peak accelerations of 19, 34 and 33 cm/s^2, in the vertical, north-south and east-west directions, respectively, were recorded at Tacubaya on hard soil in the Hills zone west of Mexico City. At the Secretaria de Comunicaciones y Transportes on very soft clay in the Lake zone of Mexico City, 4 km further from the epicentre of the earthquake, the corresponding peak accelerations were 38, 98 and 168 cm/s^2. These correspond to an increase of peak horizontal acceleration by a factor of four. About 1000 buildings, mostly of masonry and reinforced concrete, were destroyed, and it has been estimated that 20,000 people lost their lives.

Introduction

The finite difference method is a numerical scheme that propagates complete seismic wave fields through two-dimensional media with arbitrary spatial variations in seismic velocity (Frankel and Wennerberg, 1987). However, because this method is computationally time-consuming for large regions and long time intervals and because incorporation of attenuation varying with wave frequency is difficult in the time domain (Emmerich and Korn, 1987), it is advantageous to use the finite element method in the frequency domain to study the propagation of seismic waves through irregular regions (Lysmer and Drake, 1972; Drake, 1980).

In this paper, the finite element method is used, simply in one dimension, to study the propagation of Love and Rayleigh waves from the mountainous region north of Caracas to the city itself, and, more completely, in two dimensions, to study the propagation of Love and Rayleigh waves from the Hills zone west of Mexico City to the city itself. In the earthquake of 29 July 1967, approximately 250 people lost their lives, mainly in the collapse of four buildings of between 10 and 12 storeys in the region of Los Palos Grandes of Caracas (Esteva, 1968). In the earthquake of 19 September 1985, about 1000 buildings, mostly of masonry and reinforced concrete, were destroyed in Mexico City (Hall and Beck, 1986), and it has been estimated that more than 20,000 people lost their lives (Lomnitz, 1987).

Caracas earthquake, 29 July 1967

The earthquake of 29 July 1967 occurred approximately 55 km NNW or WNW of the city of Caracas (Figure 1). Hypocentral data from three agencies are tabulated in Table 1. Seed et al. (1970) accepted the International Seismological Centre (ISC) location of the earthquake, and estimated its magnitude to be 'about 6.4'.

Love and Rayleigh waves propagated from the mountainous region north of the city to the alluvial valley in which the city is situated. The amplification of these waves at the earth's surface can be estimated approximately by simply looking at the shapes of their fundamental modes in horizontally layered models of the mountainous region and of the alluvial valley. The method of Haskell (1953) could have been used in these simple one-dimensional problems, but the fundamental mode shapes plotted in Figures 2 to 4 were found by the finite element method. The amplitudes are normalised so that the energy carried by the mode is proportional to its frequency and wave number (Lysmer and Drake, 1972). The properties of the model of the alluvial valley are tabulated in Table 2. The first two rows of Table 2 give representative values of strongly compacted sediments. Typical values for a soil depth of 180 m, used by Seed et al. (1970) in their study of the Los Palos Grandes region of Caracas, are lower (Table 3). The third row of Table 2 gives representative values of the uppermost 20 km of the earth's continental crust (Dziewonski et al., 1975). These alone were used for the model of the mountainous region. The model with 100 m of sediment omitted the second row of Table 2.

It can be seen from Figure 2 and Table 4 that there is approximately a six-fold increase of surface amplitude of Love waves of the fundamental mode at a period of 0.7 s on coming from the mountainous region to the alluvial valley with 200 m of surface sediment. Of course, these short period waves will be absorbed, although in the model of strongly compacted sediments given in Table 2, these waves travel 34 km before being reduced to half their amplitude (Los Palos Grandes is only a few kilometres from Pico Oriental; Figure 1). Figure 3 and Table 4 show that there is an increase of surface amplitude of Love waves of the fundamental mode at a period of 2 s of approximately 1.4 on coming from the mountainous region to the alluvial valley with 200 m of sediment. Also, Figure 4 and Table 4 show that, at a period of 2 s, there is an increase by a factor of approximately 1.4 of the horizontal component of Rayleigh waves on coming from the mountainous region to the alluvial valley with 200 m of sediment, and a slight decrease by a factor of 0.99 in the vertical component. This is in agreement with the calculation of Money and Bolt (1966), who found that, in a model of 100 m of alluvium over Pierre Shale, the fundamental Rayleigh mode had purely vertical motion at a period of 1.05 s, and purely horizontal motion at a period of 1.9 s; between these periods the motion of the mode was prograde.

The fundamental period of oscillation of a building of 16 storeys and of width (in its narrow direction) of 10 m is approximately 1.5 s; this period lengthens if the building yields and begins to suffer damage (Robson and Canales, 1968; Hall and Beck, 1986). Esteva (1968) has noted that in 1967 in Caracas many buildings lacked sufficiently rigid connections between their vertical transverse reinforced concrete frames and the horizontal floor slabs joining them. These buildings were insufficiently rigid in the horizontal direction perpendicular to the reinforced concrete frames and the horizontal floor slabs

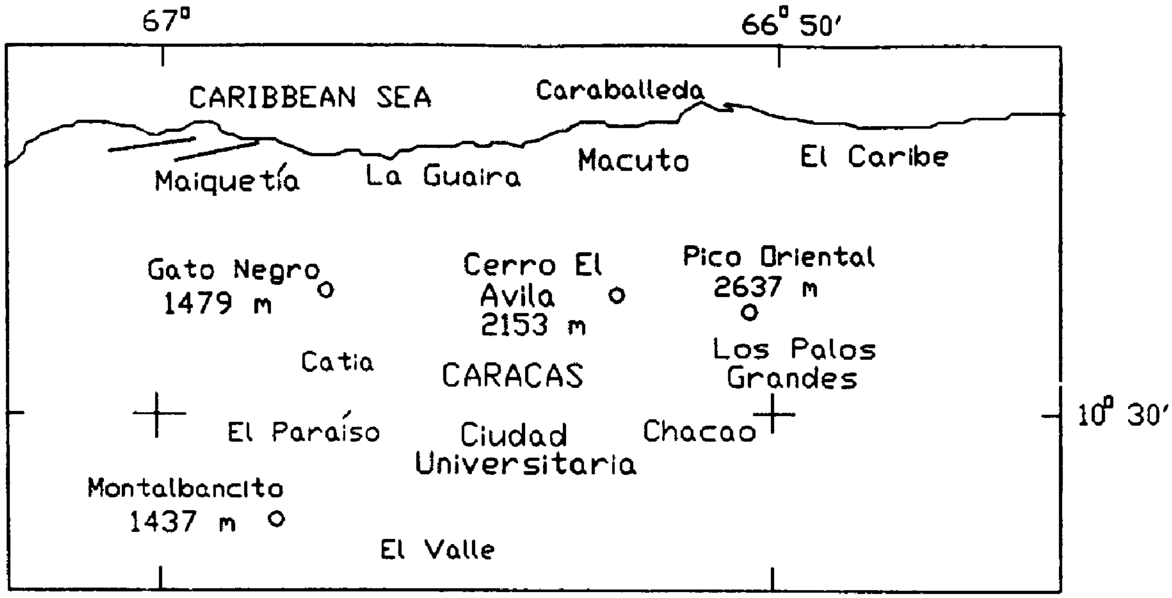

Figure 1: **Caracas: The earthquake of 29 July 1967 was approximately 55km NNW or WNW of Caracas (111.2 km/deg.).**

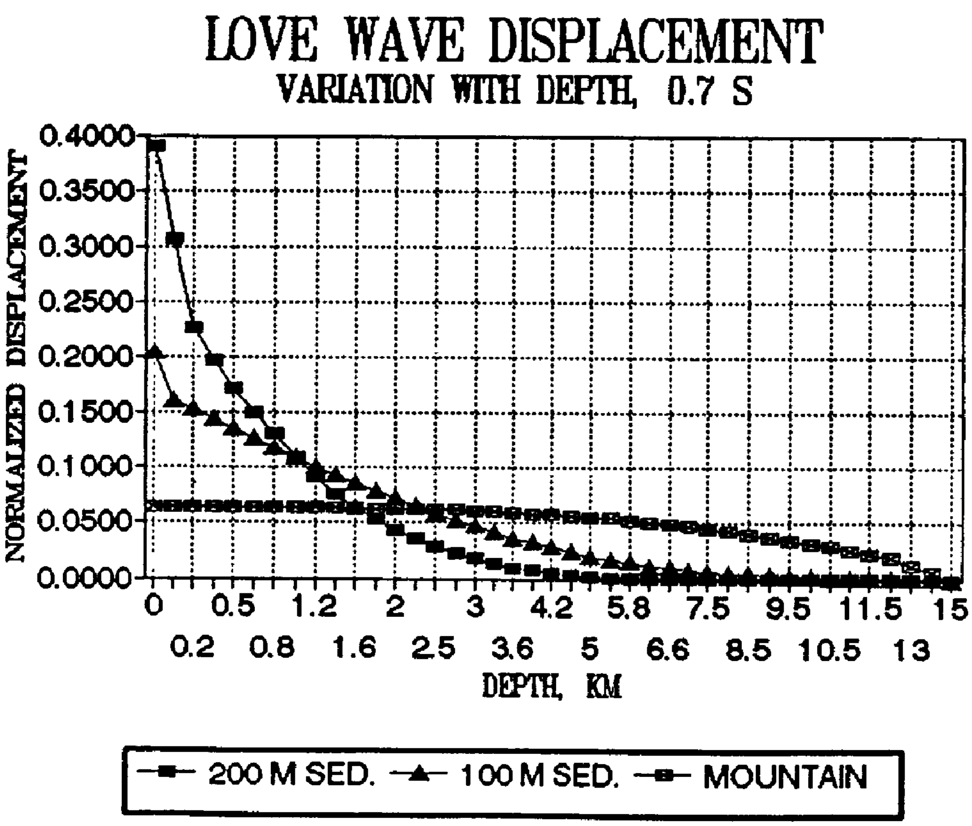

Figure 2 Variation of love wave displacement with depth for 200m of sediment, 100m of sediment and for a mountainous region (0.7 s).

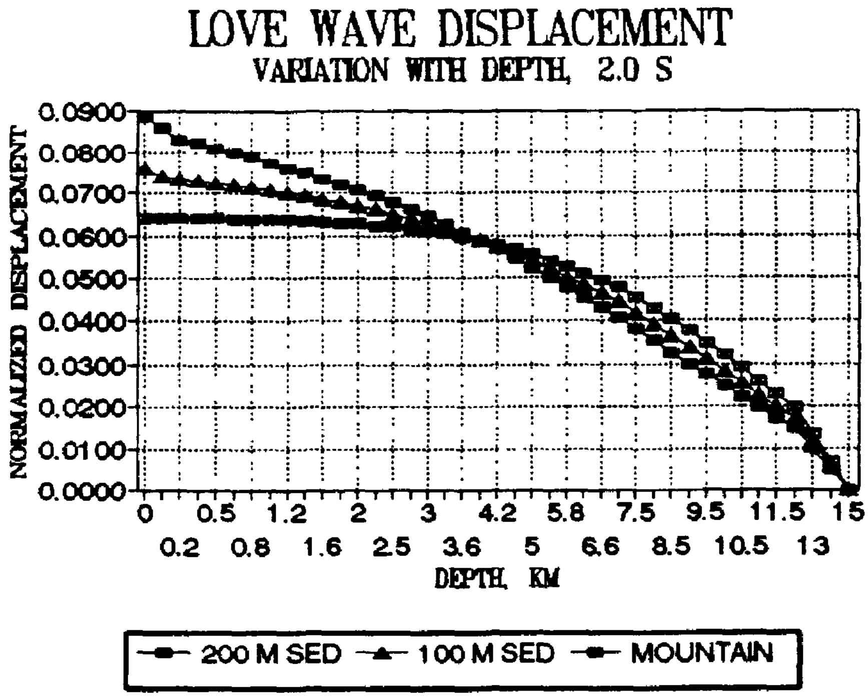

Figure 3: Variation of love wave displacement with depth for 200m of sediment, 100m of sediment and for a mountainous region (2.0 s).

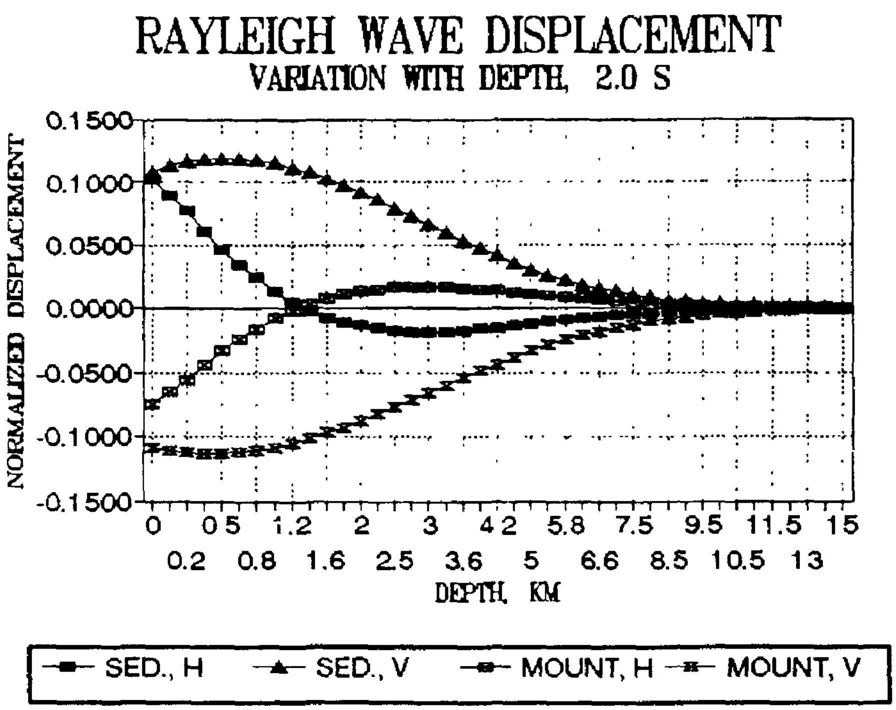

Figure 4: Variation of Rayleigh wave horizontal and vertical displacement with depth for 200m of sediment and for a mountainous region (2.0 s).

Table 1: Hypocentral Data for Caracas Earthquake, 29 July 1967

Origin time h	m	s	Latitude (deg. N)	Longitude (deg. W)	Depth (km)	Magnitude (m_b)	Agency
23	59	58.7	10.56	67.26	10	5.60	USCGS
24	00	02.7	10.68	67.40	26	5.70	ISC
24	00	07.2	11.03	67.00	88	6.25	Trinidad

USCGS: United States Coast and Geodetic Survey

Table 2: Properties of Model of Alluvial Valley of Caracas

Layer	Thickness (km)	Compress. velocity (km/s)	Shear velocity (km/s)	Density (g/cm^3)	Quality factor	Poisson's ratio
1	0.1	3.0	1.2274	1.70	17	0.40
2	0.1	4.0	1.9215	1.80	17	0.35
3	14.8	5.8	3.4500	2.72	200	0.23

Table 3: Properties of soil of 180 m depth (from Seed et al., 1970)

Thickness (m)	Compress. velocity (km/s)	Shear velocity (km/s)	Density (g/cm^3)	Quality factor	Poisson's ratio
20	0.5227	0.2134	1.7	10	0.40
50	0.9517	0.4572	1.8	10	0.35
40	1.2055	0.5791	1.9	10	0.35
30	1.2546	0.6706	2.0	10	0.30
40	1.3401	0.7163	2.1	10	0.30

Table 4: Amplification of surface amplitude, rock to sediments

Period	Love waves Sediment thickness		Rayleigh Sediment	(horizontal) thickness	(Rayleigh) Sediment	(vertical) thickness
(s)	100 m	200 m	100 m	200 m	100 m	200m
0.7	3.18	6.08	1.65	2.14	0.98	0.90
2.0	1.19	1.38	1.20	1.36	1.00	0.99

joining them. These buildings were insufficiently rigid in the horizontal direction perpendicular to the reinforced concrete frames. Paradoxically, many tall buildings were weak in their long directions. In addition, there were many torsional failures at the ground level of tall buildings (Esteva, 1968). Simple one-dimensional modelling shows that Love and Rayleigh wave horizontal ground displacement will build up at the resonant periods of tall buildings at the surface of sediments of low shear wave velocities.

Michoacan earthquake, 19 September 1985

The earthquake of 19 September 1985 occurred in the former Michoacan gap, off the southwest coast of Mexico. Hypocentral data from three agencies are tabulated in Table 5 and the third location is also plotted in Figure 5 (UNAM Seismology Group, 1986). The earthquake was multiple; the first event was followed by a second almost identical event, approximately 90 km southeast and 25 s later (Eissler et al., 1986; Singh et al., 1988; Kanamori et al., 1993). Mexico City is approximately 400 km from the first event and 300 km from the nearest point of the rupture between the events.

Figure 6, which is taken from Anderson et al. (1986) and Singh et al. (1988), shows the three zones of Mexico City, the Hills zone, the Transition zone and the Lake zone, together with, respectively, the peak vertical, north-south and east-west accelerations in cm/s^2 recorded from the earthquake at stations Tacubaya (TACY), Secretaria de Comunicaciones y Vibradora (CUMV), University City (CUIP), Centro de Abastos, Oficina (CDAO) and Centro de Abastos, Frigorifico (CDA).

Figure 7 shows a length of 250 m of the uppermost part of a two-dimensional finite element model of the Transition zone of Mexico City. Shear wave velocities and densities of the regions are marked. The total length of the sloping section of the model was 775 m (155 columns of elements). The model was analyzed for the propagation of Love and Rayleigh waves of periods of from 0.5 s up to 2 s. At periods above 1s, the length of the model was extended to 2.5025 km (15.5 m elements). Table 6 shows values of the properties of the uppermost 5 km of the Hills zone of the model and Table 7 shows values of the properties of the uppermost 5 km of the Lake zone (after Zeevaert, 1964; the surface is 45 m below the surface of the Hills zone). Because of suggestions of liquefaction of the Lake zone as a result of the earthquake (Lomnitz, 1987), a high value of Poisson's ratio (0.488) was used. Values of the rock properties below the depth of 5 km are representative values of the earth's continental crust (Dziewonski et al., 1975).

Some results of the finite element analysis of the model are shown in Table 8. There is a good deal of fluctuation of surface amplitude across the model from interference of different propagating modes (cf. Lysmer and Drake, 1972). The values shown in Table 8 are ratios of the final and incident amplitudes across the model. It can be seen that, at a period of 1.25 s, the amplification of vertical Rayleigh wave motion (2.09) is greater than the amplification of horizontal Rayleigh wave motion (1.79), while, at a period of 2 s, the amplification of horizontal Rayleigh wave motion (5.72) is greater than the amplification of vertical Rayleigh wave motion (1.34). These results are in accordance with those of Mooney and Bolt (1966). The observed amplification of horizontal peak acceleration from Tacubaya to the Secretaria de Comunicaciones y Transportes was approximately 4, but accompanied by a move to longer periods (Anderson et al., 1986). The amplifications of Love wave motion at periods of 1.75 s and 2 s across the finite element model are 4.26 and 6.96. These amplifications of horizontal Rayleigh wave and of Love wave motion at these longer periods, together with the long durations of Rayleigh and of Love wave motion, were important factors in the destruction of buildings and loss of life in Mexico City.

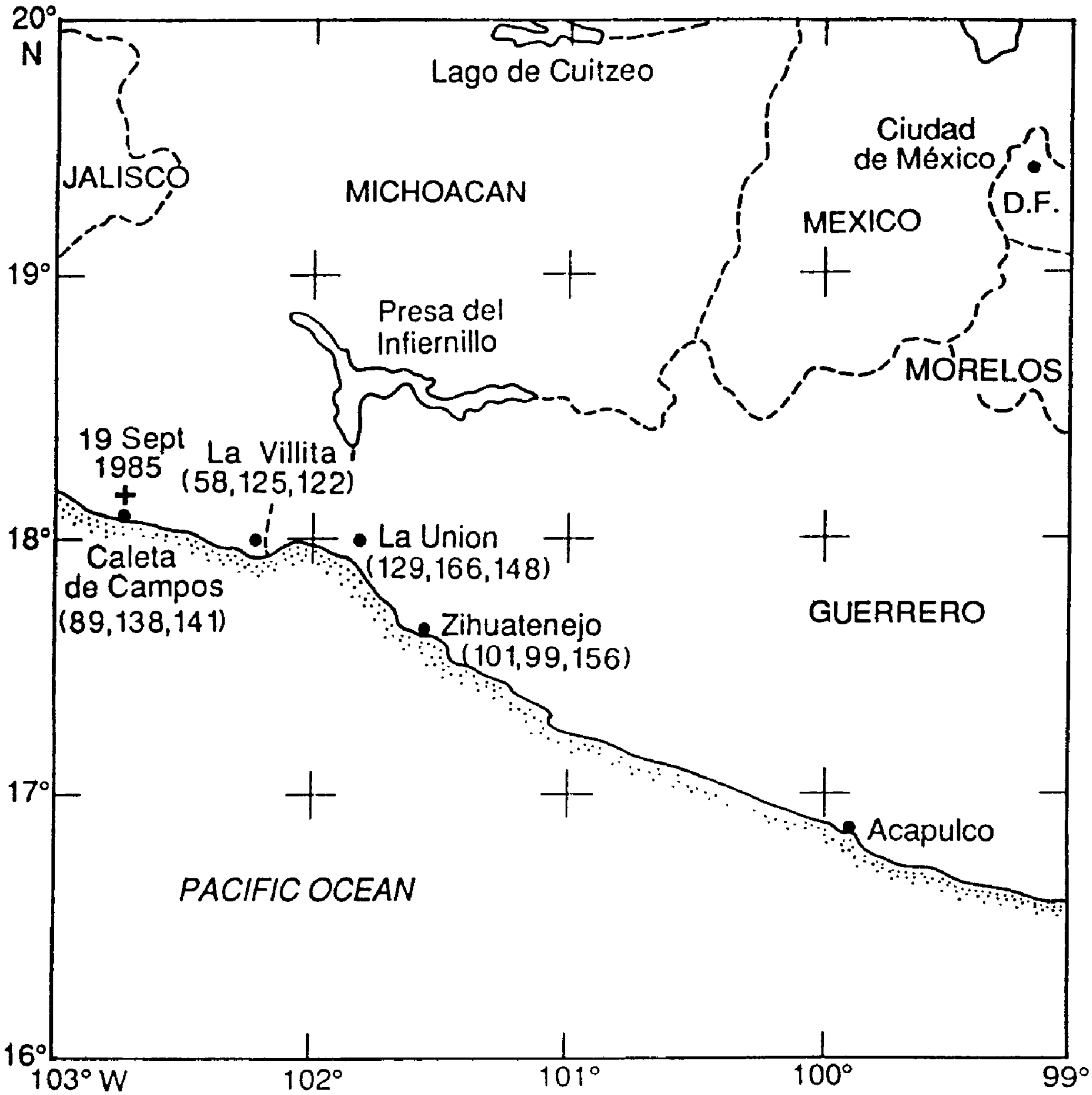

Figure 5. Michoacán earthquake of 19 September 1985, with recorded peak vertical, north-south and east-west accelerations (after Anderson et al., 1986).

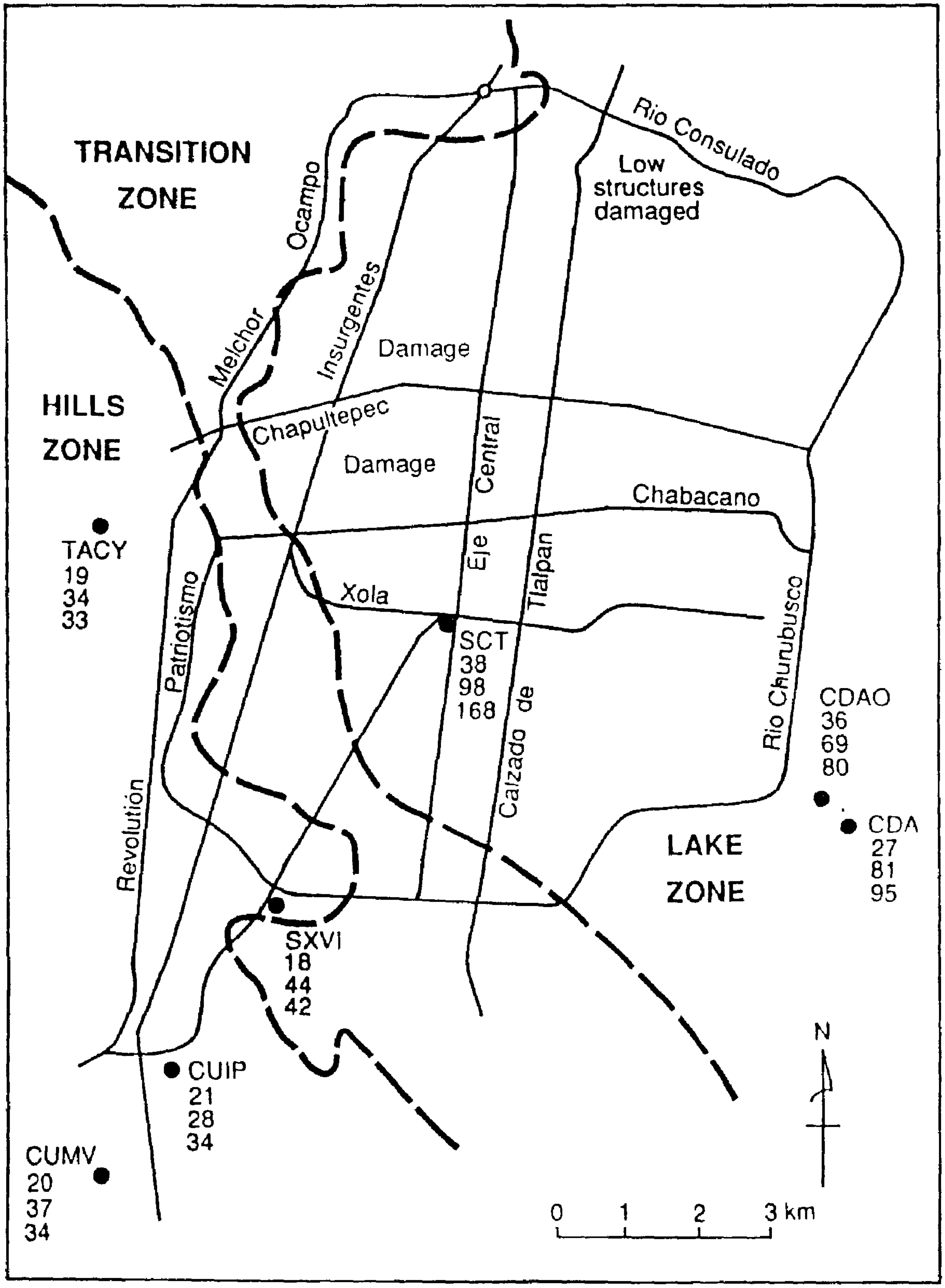

Figure 6:. Zones of Mexico City with recorded peak vertical, north-south and east-west accelerations, 19 September 1985 (after Anderson et al., 1986).

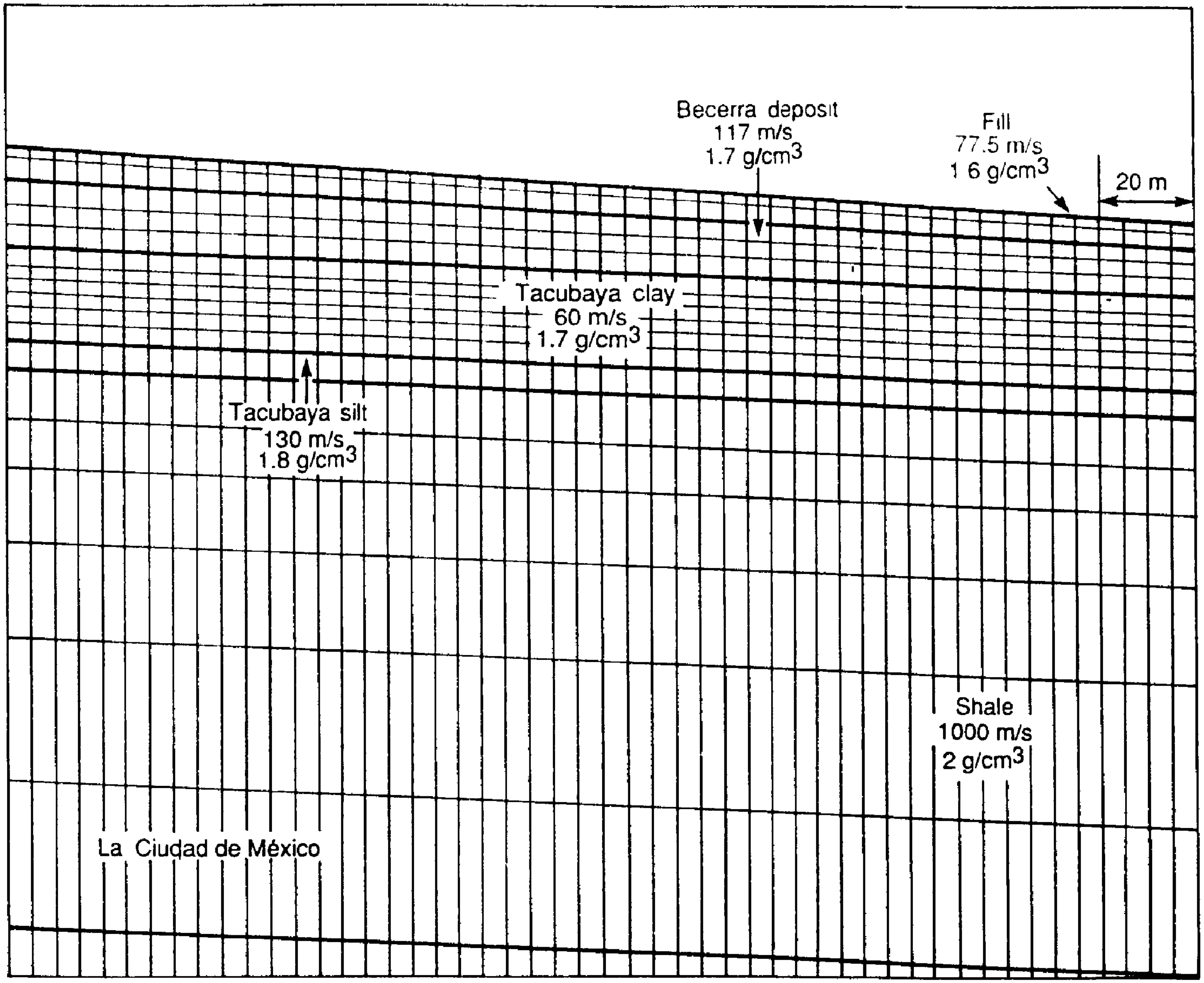

Figure 7: Part (250m width) of the uppermost section of a finite element model of the Transition Zone, Mexico City.

Table 5: Michoacan Earthquake, 19 September 1985

Origin time h	m	s	Latitude (deg. N)	Longitude (deg. W)	Depth (km)	Magnitude m_b	M_s	Agency
13	17	47.3	18.20	102.50	28	6.8	8.1	NEIC
13	17	50.1	18.54	102.32	29	6.4	7.9	ISC
			18.14	102.71	16		8.1	UNAM

NEIC: National Earthquake Information Center
UNAM: Universidad Nacional Autónoma de México

Table 6: Properties of the Hills zone of Mexico City (After Zeevaert, 1964)

Thickness (km)	Compress. velocity (km/s)	Shear velocity (km/s)	Density (g/cm^3)	Quality factor	Poisson's ratio
0.0066	2.0	1.00	2.000	25	0.33
0.1024	4.0	2.00	2.682	50	0.33
1.8910	4.2	2.10	2.750	50	0.33
3.0000	5.8	3.45	2.800	200	0.23

Table 7: Properties of the Lake zone of Mexico City (After Zeevaert, 1964)

Thickness (km)	Compress. velocity (km/s)	Shear velocity (km/s)	Density (g/cm^3)	Quality factor	Poisson's ratio
0.005	0.50	0.0775	1.600	17	0.488
0.010	0.75	0.1170	1.700	17	0.488
0.019	0.40	0.0600	1.700	17	0.488
0.006	0.86	0.1300	1.800	17	0.488
0.115	2.00	1.0000	2.000	25	0.330
0.290	2.40	1.2000	2.136	25	0.330
0 400	3.30	1.6500	2.443	50	0.330
0.110	4.00	2.0000	2.682	50	0.330
1.000	4.20	2.1000	2.750	50	0.330
3.000	5.80	3.4500	2.800	200	0.230

Table 8: Amplification of surface motion, Mexico city

Transition width (km)	Period (s)	Love waves	Rayleigh waves horizontal	Rayleigh waves vertical
0.7750	1.25	1.34	1.79	2.09
2.4025	1.75	4.26	3.79	1.51
2.4025	2.00	6.96	5.72	1.34

Conclusions

Finite element analysis in one dimension of the mountainous region north of Caracas and of the alluvial valley of Caracas itself has shown that Love and Rayleigh wave horizontal ground motion will build up at resonant periods of tall buildings, and can contribute to destruction of buildings and loss of life. More complete finite element analysis in two dimensions of the Transition zone of Mexico City, with the use of much lower sediment shear wave velocities, has confirmed that Love and Rayleigh wave horizontal ground motion builds up at periods approaching 2 s.

Acknowledgement
Research sponsored by US Air Force Office of Scientific Research, Air Force Material Command, under Grant No. F49620-93-1-0433. The US Government is authorized to reproduce and distribute reprints for Governmental purposes notwithstanding any copyright notation thereon. The views and conclusions contained in this document are those of the author and should not be interpreted as necessarily representing the official policies or endorsements, either express or implied, of the Air Force Office of Scientific Research or the US Government.

References

Anderson, J.G., Bodin, P., Brune, J.N., Prince, J., Singh, S.K., Quaas, R. and Onate, M. (1986). Strong ground motion from the Michoacan, Mexico, earthquake. Science, 233: 1043-1049.
Drake, L.A. (1980). Love and Rayleigh waves in an irregular soil layer. Bull. Seism. Soc. Am., 70: 571-582.
Dziewonski, A.M., Hales, A.L. and Lapwood, E.R. (1975). Parametrically simple earth models consistent with geophysical data. Phys. Earth Planet. Inter., 10: 12-48.
Eissler, H., Astiz, L. and Kanamori, H. (1986). Tectonic setting and source parameters of the September 19, 1985 Michoacan, Mexico earthquake. Geophys. Res. Lett., 13: 569-572.
Emmerich, H. and Korn, M. (1987). Incorporation of attenuation into time-domain computations of seismic wavefields. Geophysics, 52: 1252-1264.
Esteva, L. (1968). Venezuela: el sismo de Caracas de 29 de julio de 1967: ingenieria estructural. UNESCO, No. 571 BMS-RD/AVS, Paris.
Frankel, A. and Wennerberg, L. (1987). Energy-flux model of seismic coda: separation of scattering and intrinsic attenuation. Bull. Seism. Soc. Am., 77: 1223-1251.
Hall, J.F. and Beck, J.L. (1986). Structural damage in Mexico City. Geophys. Res. Lett., 13: 589-592.
Haskell, N.A. (1953). The dispersion of surface waves on multilayered media. Bull. Seism. Soc. Am., 43: 17-34.
Kanamori, H., Jennings, P.C., Singh, S.K. and Astiz, L. (1993). Estimation of strong ground motions in Mexico City expected for large earthquakes in the Guerrero seismic gap. Bull. Seism. Soc. Am., 83: 811-829.
Lomnitz, C. (1986). Lecciones del terremoto de 1985. Vuelta, 125: 64-67.
Lysmer, J.and Drake, L.A. (1972). A finite element method for seismology. In Bolt, B.A. (ed). Methods in Computational Physics, 11. Academic Press, New York, pp. 181-216.
Moohey, H.M. and Bolt, B.A. (1966). Dispersive characteristics of the first three Rayleigh modes for a single surface layer. Bull. Seism. Soc. Am., 56: 43-67.
Robson, G.R. and Canales, L. (1968). Venezuela: el sismo de 29 de julio de 1967: description general. UNESCO, No. 571 BMS-RD/AVS, Paris.
Seed, H.B., Idriss, I.M. and Dezfulian, H. (1970). Relationships between soil conditions and building damage in the Caracas earthquake of July 29, 1967. Earthquake Engineering Research Centre, Report No. EERC 70-2, Berkeley.

Singh, S.K., Mena, E. and Castro, R. (1988). Some aspects of source characteristics of the 19 September 1985 Michoacan earthquake and ground motion amplification in and near Mexico City from strong ground motion data. Bull. Seism. Soc. Am., 78: 451-477.
UNAM Seismology Group (1986). The September 1985 Michoacan earthquakes: aftershock distribution and history of rupture. Geophys. Res. Lett., 13: 573-576.
Zeevaert, L. (1964). Strong ground motions recorded during earthquakes of May 11th and 19th, 1962 in Mexico City. Bull. Seism. Soc. Am., 54: 209-231.

New Concepts in Earthquake Hazard Mapping

S.T. Algermissen
U.S. Geological Survey,
Reston, Virginia 22092, USA

Abstract

Expanded data bases and improved ground motion modelling have made it possible to develop better estimates of the severity of future earthquake related ground motion. These improved ground motion estimates have, in turn, led to better seismic design provisions of building codes. Progress in these fields is reviewed and efforts to develop worldwide estimates of expected earthquake ground motion in given periods of time of interest are reviewed. One improvement of interest is the development of techniques for the estimation of equal probability hazard spectra as a useful parameter in earthquake resistant design. Progress in the USGS-OFDA Worldwide Earthquake Risk Management Programme (WWERM), a programme of the IDNDR aimed at providing a better understanding of the global aspects of earthquake hazard and risk, is discussed.