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Ground Movements in Mexico City During Recent Earthquakes

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SYNOPSIS: Acceleration records were obtained with a rather dense accelerographic array during three recent earthquakes in Mexico City. Following a purely observational approach, useful information about the nature and characteristics of seismic motions was derived from the analysis of these records. Broad regional studies indicate that the distribution of seismic motions in the city may be affected by directivity effects. From local site studies it is concluded that seismic movements at the base of the compressible clay deposits are fairly uniform and accelerograms recorded in vertical arrays suggest that soil strata in Mexico City respond to seismic movements according to established knowledge.

INTRODUCTION

Earthquakes originating mainly in the subduction zone off the Mexican Pacific Coast, have damaged Mexico City time and again. During this century at least three large events have caused extensive human and material losses. The last one took place in September 1985 and still haunts the minds of governmental authorities, planners, engineers and common citizens. This earthquake or rather, its traumatic effects, prompted the initiation of extensive research in which most aspects of Earthquake Engineering in connection to the specific case of Mexico City were revised. It became apparent from the onset of these studies that an idispensable part of such an effort would necessarily be the availability of instrumental data of actual ground movements recorded in and around the city.

Accelerographic records in Mexico City were first obtained during the early sixties when a few stations were installed in its central part. At the time of the 1985 Earthquake there were eleven operational accelerographic stations which yielded some accelerograms that are well known to many seismologists and earthquake engineers. Only one of these can be taken to be representative of the ground movements in the most severely damaged part of the city. In the years that followed, the Mexico City accelerographic network has expanded. By the end of 1987 there were 40 new accelerographic stations and in 1988, anout the same amount was added. Other stations were also installed along the Pacific Coast, near the subduction zone, and in intermediate locations, between it and Mexico City (Quaas *et al*, 1990a). Recent additions to the network include stations installed inside buildings as well as within boreholes, at different depths. Apart from the stations managed by the Institute of Engineering, UNAM, two private foundations and a governmental agency share the responsibility of operating the network (Espinoza *et al*, 1988; Quaas *et al*, 1990b, etc). The map in fig 1 shows the location of some of the accelerographic stations in and around Mexico City as well as the geotechnical zones for seismic design of structures.

With such a network, each recorded event can be built into a case history, provided researchers are not smothered by the enormous amount of information they have to deal with. Analyses at a regional or at a local basis can be performed. In what follows, we illustrate some of the regionally based analyses that have been performed and look at the records obtained from deep seated boreholes, i.e. under the soft clay strata, as well as those obtained at different depths in two sites in the Lake Zone (Zone III, in fig 1). Using a purely observational approach we derive conclusions about the nature and characteristics of seismic movements in Mexico City. Studies are presently under way in order to calibrate models to predict ground motions, on the basis of some of the data shown here.

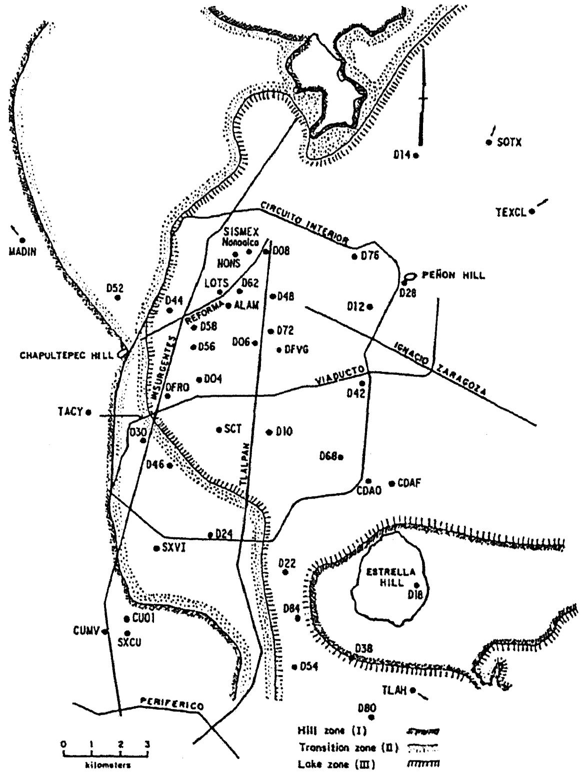


Fig 1 Geotechnical zones and accelerographic network in Mexico City.

REGIONAL ANALYSES

Arias' intensity measure is a tensonrial quantity from which eigen values and eigen directions can be derived from it (Arias, 1973). On February 8, 1988 and in 25 April 1989, two earthquakes having

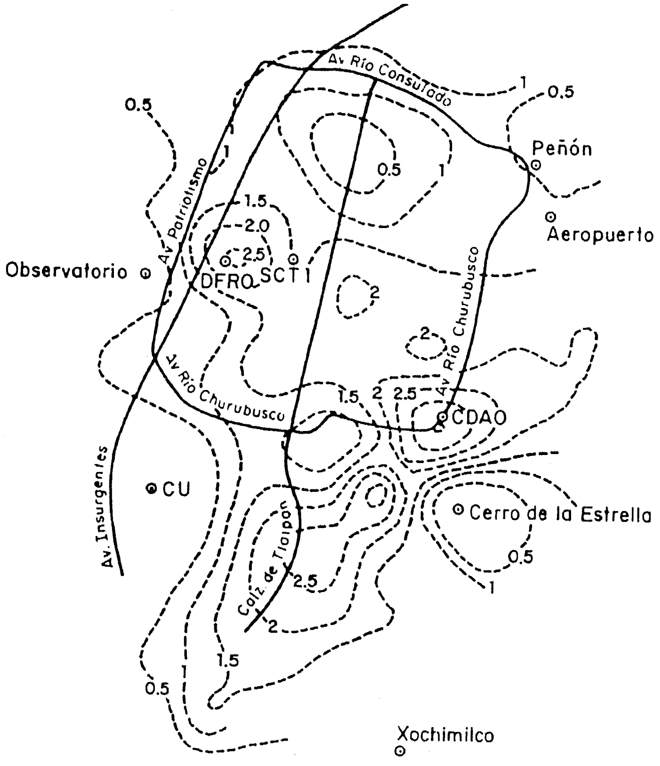


Fig 2 Maximum normalized energy contours, Feb 8, 1988.

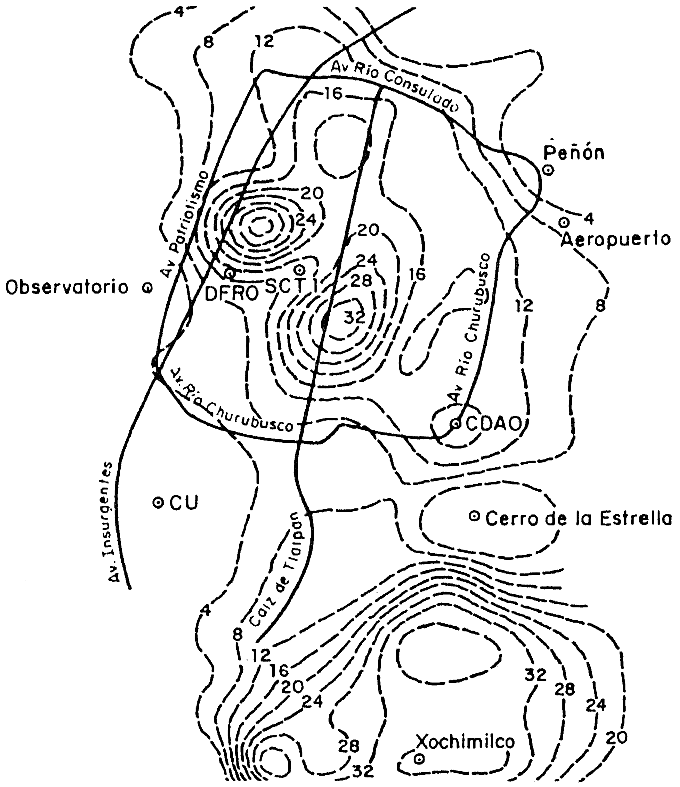


Fig 3 Maximum normalized energy contours, March 25, 1989

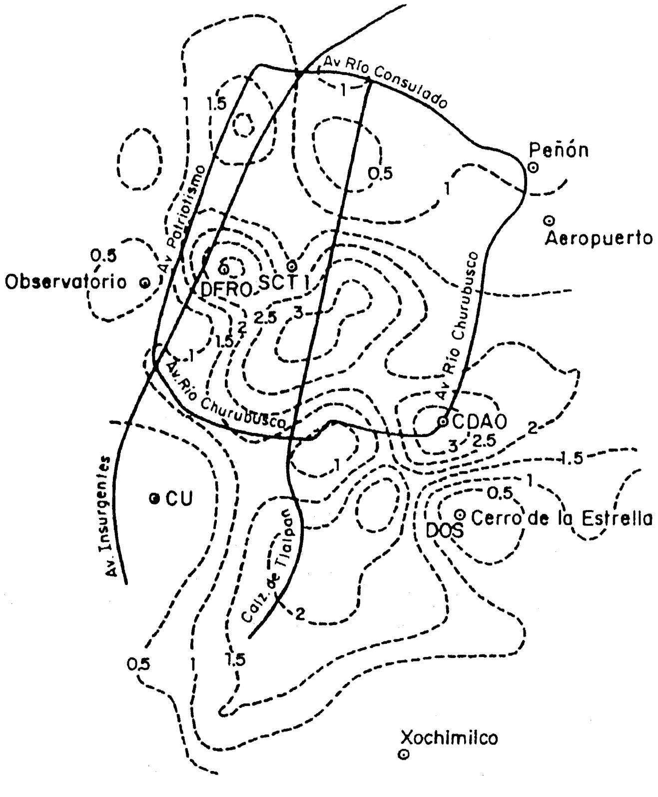


Fig 4 Normalized mean power contours, Feb 8, 1988

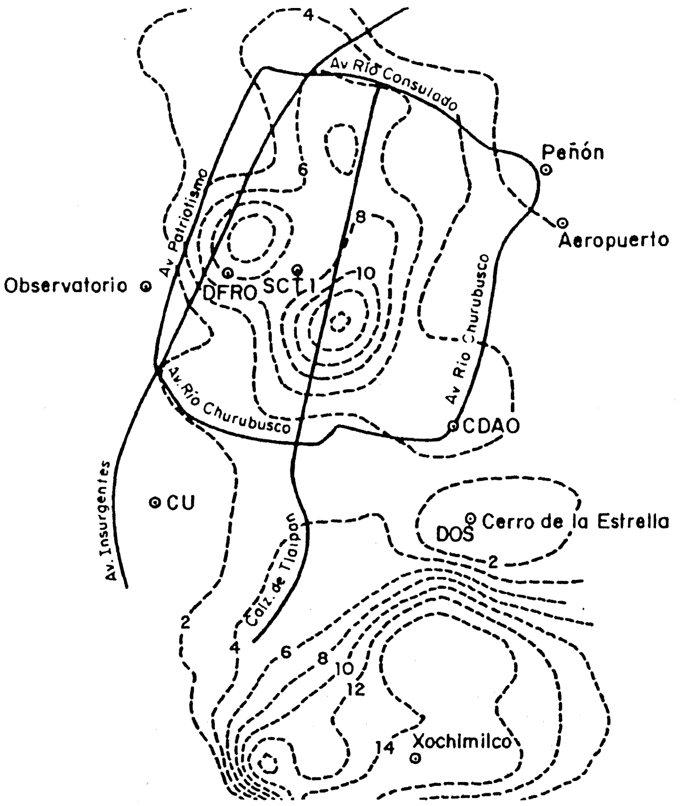


Fig 5 Normalized mean power contours, March 25, 1989

surface wave magnitudes of 5.4 and 6.8, respectively, were recorded by the network. With the records available after these two events we calculated the maximum energy at each of the stations and represented Arias intensity spatial distribution in the city by means of contour maps such as those shown in figs 2 and 3 (Ovando and Romo, 1990). For producing these maps, the horizontal acceleration records were projected along the maximum energy directions and the intensity along this direction, I_{max}, was evaluated with the integral

$$I_{max}=\int_{T_1}^{T_2} a^2(t)dt \tag{1}$$

which is a measure of the energy contained in the acceleration record and, hence, of its potential destructiveness.

The limits of integration in the former expression span over the significant duration of each record which was taken to be equal to the time interval over which 90 % of the energy is concentrated, in each acceleration record, $T_{90}(= T_2-T_1)$. The intensities shown in the map were normalized by the maximum intensity at station CU, located on a basalt outcrop in the southern part of the city .

Since the duration of earthquake motions in Mexico City bears a clear influence on structural damage, a better parameter for correlating intensity and potential damage is the mean power, π, which includes the duration of movement. π is the mean slope of the cumulative distribution of $a(t)^2$, over the significant duration and, accordingly, it directly measures the average energy yield per unit of time:

$$\pi = \frac{I_{max}}{T_{90}} \tag{2}$$

Figs 4 and 5 give the maps of equal mean power contours obtained for the same events, also normalized by the mean power at CU.

Relationships between I_{max} and π and maximum ground acceleration, a_{max}, were also obtained, including data from the 1985 earthquake. These can be expressed as

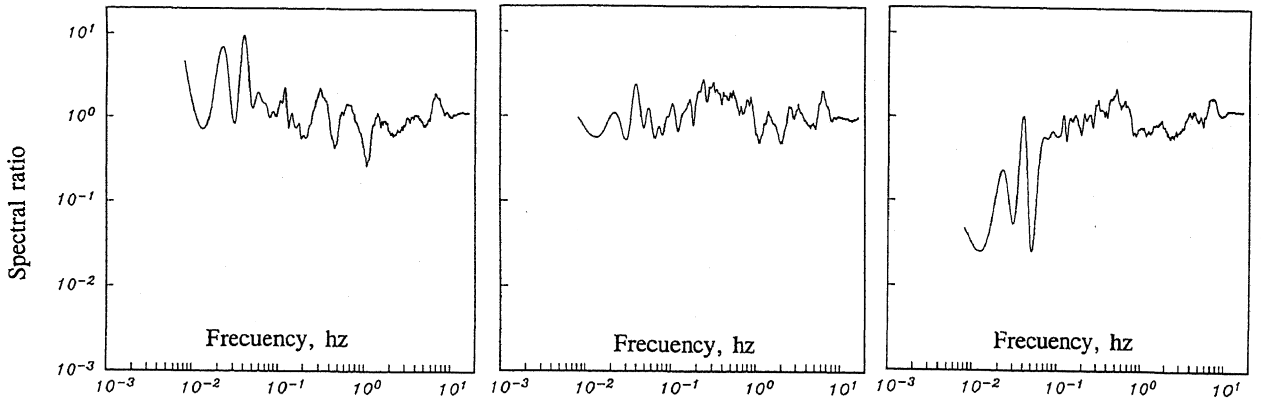
$$I_{max} = \exp\ [c_1 \ln(a_{max}) + c_2] \tag{3}$$

$$\pi = \exp\ [c_3 \ln(a_{max}) + c_4] \tag{4}$$

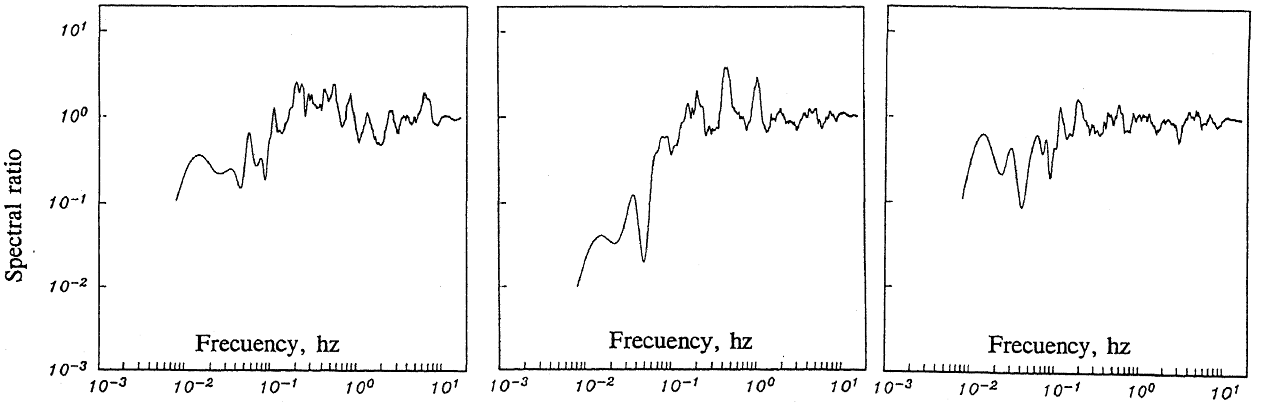
where $c_1= 2.25$, $c_2= 1.52$, $c_3= 1.94$, $c_4= -2.43$.

These expressions are similar to those derived theoretically by Rice (1954).

Despite the fact that the highest intensities and mean powers concentrate, as expected, within the lake zone, i. e. the zone containing highly compressible lacustrine clays, their distributions differ ostensibly for both events, thus exhibiting a dependence of damage potential and, posssibly, of ground movement history, on the location of epicentres: in the 8 February, 1988, event, the epicentre was located 290 km south west of Mexico City whereas in 25 April,



a) Roma/Coyoacán, E-W component b) Roma/Coyoacán, N-S component c) Tlacotal/Coyoacán, E-W component



d) Tlacotal/Coyoacán, N-S component e) Tlacotal/Roma, E-W component f) Tlacotal/Roma, E-W component

Fig 6 Spectral ratios from bedrock motions, 31 May, 1990

1989, the epicentre was sited some 400 km south of it. Topographical irregularities along the boundaries of the Valley of Mexico and the presence of the Santa Catarina Mountain Range, dividing the Texcoco and Xochimilco-Chalco basins towards the southern part of the city, will account for some of these directivity effects. Others arise from source and path effects, which also influence the frequency content and distribution of incoming motions. Still, the data furnished by the maps of figs 2 to 5 consistently mark the zones which have recurrently been more severely damaged during past earthquakes.

BEDROCK AND OUTCROP MOVEMENTS

In early 1990 the first subset of the accelerographic network comprising instruments installed within boreholes became operational (Quaas *et al*, 1990b). It includes three component accelerographs located at different depths. On 31 May that year, a $M_c = 5.5$ subduction earthquake that originated some 300 km south from Mexico City triggered the network. Not all the stations were in working order at the time of this event but for the first time ever, accelerograms representative of seismic movements within the soft clay deposits and of the movements of the strata underlying them, were available. We analyze data obtained from three of them, installed below the soft clay deposits which, for practical purposes, may be considered to lie on firm ground, i. e. bedrock for site response anlyses.

Some of the characteristics of the movement at the base of the clay deposits can be disclosed by looking at their Fourier spectra. However, herein we only wish to determine the degree of uniformity of bedrock movements below the soft clay deposits. This question is important in site or global response analyses in which, for the sake of simplicity, movements at the base of the soft soil deposits are usuallly assumed to be uniform. Further, one dimensional wave propagation models to predict surface movements implicitly require the uniform bedrock movement assumption.

In order to verify this assumption, we resort to the use of Fourier amplitude spectral ratios. For the May 1990 event, we analize the movements recorded at the base of deformable soils at three stations, Coyoacán, Roma and Tlacotal, having instruments at 70, 102 and 86 m, respectively. The first one is located in the Transition Zone towards the south of the city and the latter two within the Lake Zone, according to the geotechnical zoning map included in fig 1. The Roma station lies within one of the zones in the city that has recurrentlye been more damaged and Tlacotal is situated in its eastern sector, in a less densely populated area.

Spectral quotients obtained from the horizontal components of the accelerograms recorded at successive stations are shown in fig 6. These quotients were calculated by dividing the smoothed Fourier amplitude spectra of each pair of signals. The ratios involving the Tlacotal station show the largest departures from unity, especially in the range 0.01 to 0.10 hz but thereon, say, between 0.1 and 10 hz, there are no drastic departures from unity. This latter range is precisely the one of most interest for earthquake engineering applications, as the period of most structures will lie within it. Also, over the short frequency range, numerical errors involved in the digitization of the acceleration signals and in the calculation of Fourier transforms may also contribute to the observed dispersion. Overall, however, it can be concluded that the movements at the base of the three stations are fairly uniform, i. e. that the uniform motion assumption at the base of the compressible strata is not far fetched for mot practical applications. This assertion must be verified in future events and with the analysis of the data rendered by other deep seated accelerographic stations, as they become available.

In site response analyses it is also necessary to specify the input motion, usually by translating outcrop movements to the base of the soil strata under consideration. Many such analyses performed in Mexico City have been carried out using the movements recorded either in the hills west of the city or in basaltic outcrops in the south. For example, the movements at the university, station Cu in fig 1, have been used extensively as input motions in these studies (e. g., Romo *et al*, 1987). In fig 7 we present the spectral quotients of the horizontal components of the movements at Cu with respect to the movements recorded at the three deep seated stations (Roma, Tlacotal, Coyoacán). The spectra shown there give additional proof of the uniformity of movements at the base of the deformable soils. They can also be interpreted as empirically developed transfer functions between outcrop and bedrock movements. It is evident that an average transfer function can be readily obtained from fig 7. Hence, given the movements at CU and the average outcrop-bedrock transfer function, the movements at the base of the compressible clays can be estimated.

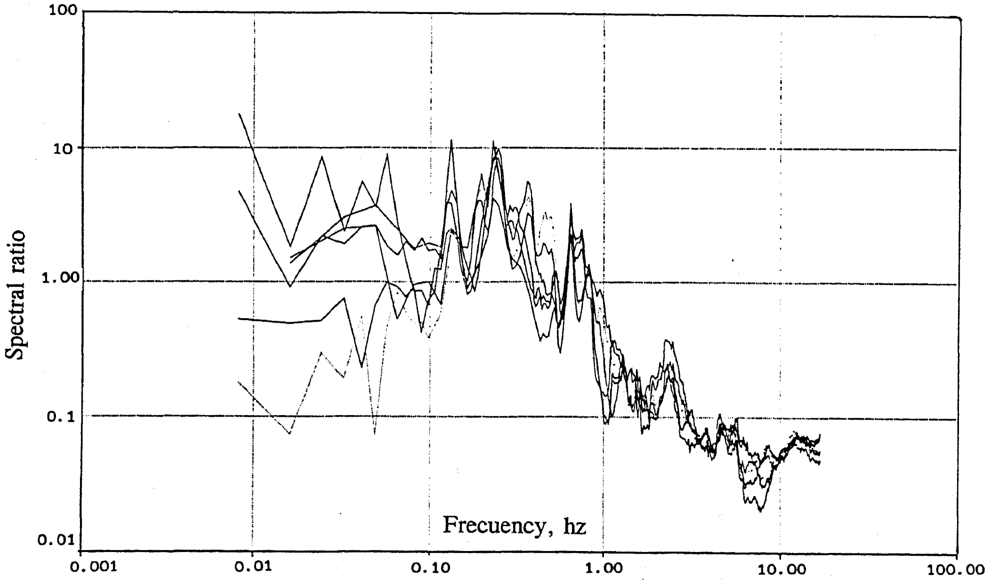


Fig 7 Empirical transfer functions between outcrop site (CU) and the bedrock sites (Roma, Coyoacán, Tlacotal)

MOVEMENTS WITHIN BOREHOLES

We take the 31 May, 1990, horizontal acceleration records along the north-south components from the two stations located in the lake zone and analyze them to gain insight into the manner in which seismic motions are modified in passing through the soft clay strata. Stratigraphical conditions in both sites qualitatively similar.

In the Roma station, a surficial crust, some 5.0 m thick is underlain by a sequence of silty clays (the upper clay formation) down to about 31.0 m. Water contents in these clays, range between 200 and nearly 400%, although they have reduced steadily over the last thirty years as a consequence of water extraction from deep wells. A hard layer constituted by sands, silts and silty sands is found between 31.0 and nearly 36.0 m. The second clay formation follows from this depth to about 41.0 m; water contents in it do not exceed 200%. There on, the so called "deep deposits" follow, down to a few hundred meters. Soils in them are formed by well compacted sands and silty sands within which other clay formations, a few meters thick, appear, typically between 60 and 80 m.

The same strata can be identified in the Tlacotal station but their dimesions differ. The surficial crust in Tlacotal is around 3.0 m thick; the first clay formation is thicker as it extends down to 45.0 m. These clays are softer than in the Roma station (water contents generally exceed 400%) and have been less affected by deep well pumping. The first hard layer in this site is typically not more than one meter thick. The second clay formation reaches a depth of nearly 60.0 m and the deep deposits follow there on.

In both sites, the accelerographs located 30m below the surface lie, roughly, at the base of the first clay formation whereas the deeper instruments are embedded within the deep deposits. Different geometries, i.e. thicknesses and depths of the significant strata, as well as differences in soil properties result in different seismic movements in both sites, as can be judged from the acceleration records given in figs 8 and 9. Surficial accelerations in the Roma station were considerably larger but at the 30 m level, acceleration was somewhat larger in Tlacotal. In the deep deposits acceleration wave forms are also different but maximum values do not differ drastically (2.8 gals in Roma and 2.04 gals in Tlacotal); as was discussed previously, movements in the deep deposits are fairly uniform over a wide range of frequencies.

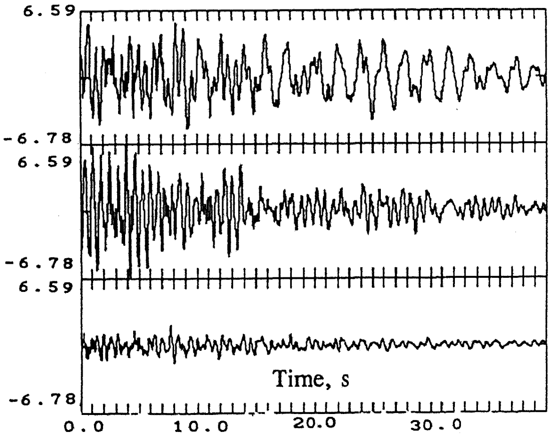


Fig 8 Acceleration records from the vertical array at Tlacotal (accelerations in gals), N-S components, 31 May, 1990

Following the procedure stated earlier empirical transfer functions were obtained for the acceleration traces recorded at the same site but at different levels. In the Roma station, we calculated the empirical transfer function between the surface and the deep deposits (0.0-102 m), between the surface and the base of the first clay formation (0.0-30 m) and finally, between the latter and the deep deposits (30-102 m). Similarly, in the Tlacotal stations the transfer functions were calculated between 0.0 and 86.0 m, 0.0 and 30.0 m, 30.0 and 86.0 m. The resulting graphs are given in figs 10 and 11.

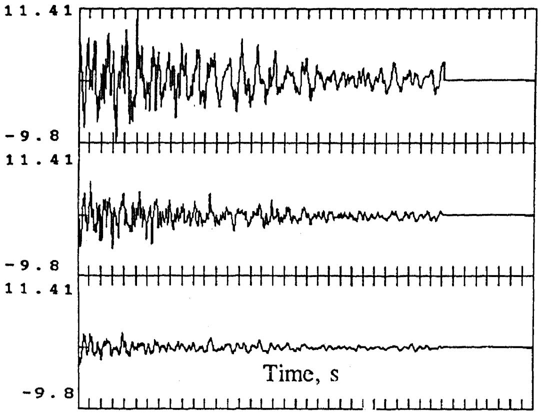


Fig 9 Acceleration records from the vertical array at Roma (accelerations in gals), N-S components, 31 May, 1990

Looking first at the empirical transfer function between the surface and 102 m in the Roma station, it displays a first peak, which is also the largest in magnitude at 0.41 hz (a period of 2.4 s) that matches values found out previously for the dominant frecuency at nearby sites (Romo et al 1987); it is also in accordance with data obtained from ambient vibration measurements. Amplifications at this peak exceeds 14. Other peaks at higher frequencies are less well defined, within the 1.0 to 4.0 hz range. However, identifiable peaks seem to follow the sequence predicted by elastic theory for higher armonies (i.e. 1, 3, 5,...). The other two transfer functions exhibit a better defined sequence of peaks. The highest amplifications between 0.0 and 30.0 m show up at 1.2 and 2.4 hz. In the 30.0 to 102 m transfer function, the same peaks can also be observed. The filtering effect of the soil strata is evinced when comparing the latter two transfer functions. In the deeper strata (30.0 to 102 m) higher frequencies exhibit the largest amplifications and, as expected, in the upper strata (00 to 30 m), they have a lesser influence.

At the Tlacotal station a similar pattern can be established the overall transfer function bears a greater resenblance with ideal elastic transfer functions. Notice that the dominant frequency is close to 0.25 hz (around 4.0 s) which may seem an extremely low value but it is quite in agreement with measured values in the zone.

The outstanding thing to consider in regard to the empirical transfer functions of figs 10 and 11 is that there are no surprises about them. Indeed, these transfer functions indicate that the soil at both sites is responding to seismic excitations as one would expect from established knowledge. Further, it is also very encouraging that, at least in the case of the Tlacotal station, the shape of the overall empirical transfer function closely resembles that of an elastic system that can be modelled rather straightforwardly. Transfer functions at the Roma station turned out to be less clean; surely in part, due to a stratigraphy that includes thicker hard strata which may introduce higher frequency noise due to reflection and refraction of waves passing through them.

Cross-correlation functions can be used to determine the time lag between signals, i.e. the difference in arrival times of incoming

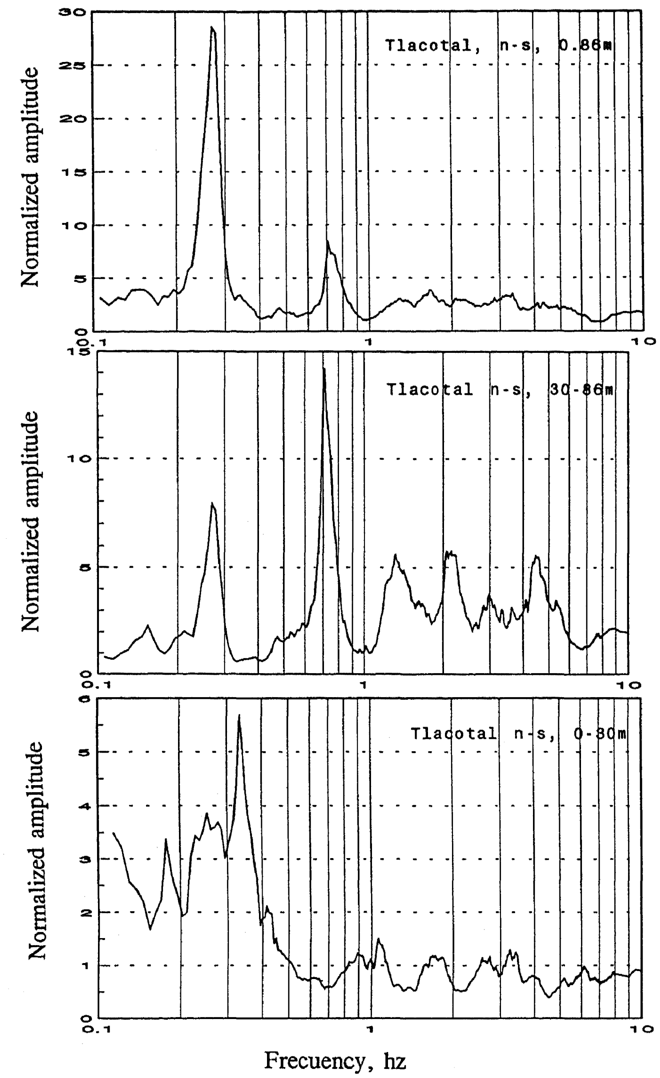


Fig 10 Empirical transfer functions at Tlacotal, vertical array, N-S components, 31 May, 1990

seismic motions between successive depths. The cross correlation function obtained at the Roma station are given in fig 12 and fig 13 gives the same function for the Tlacotal station. The time lag at each pair of stations was determined directly from these figures as the time at which the cross correlation function adopts its maximum value. Assuming that the recorded acceleration histories are due primarily to the vertical propagation of shear waves, wave velocities and shear moduli can be obtained knowing the time lag.

Time lags at the Roma station obtained from fig 12 were 0.9, 0.7 and 0.97 s for the 00 to 102 m, the 00 to 30 m and the 30 to 86 m records, respectively. Shear wave velocities derived from these values are 40.0, 96.5 and 99.0 m/s. In Tlacotal the time lags were 0.69, 0.74 and 104 s and the shear wave velocities 47.0, 77.0 and 83.0 m/s.

These shear velocities fall within the range of reasonable values one can expect for the soils and the conditions of Mexico City but, for more closely spaced instruments or for stiffer soils, the procedure may be quite sensitive to errors brought about by the rate at which the acceleration histories were digitized.

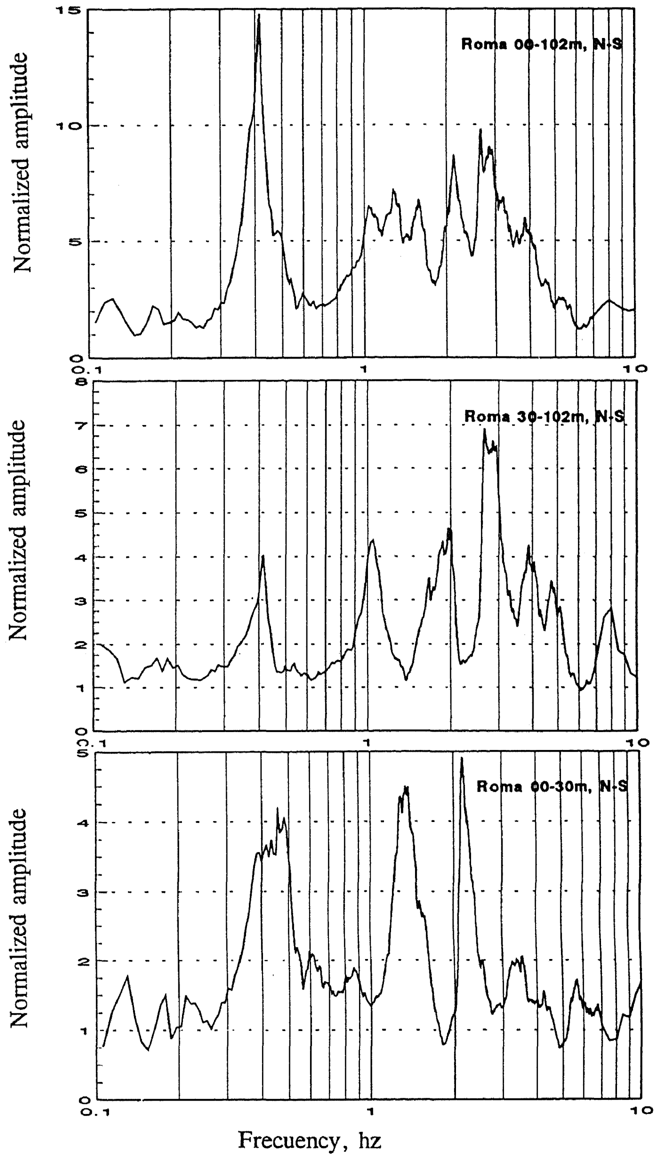


Fig 11 Empirical transfer functions at Roma, vertical array, N-S components, 31 May, 1990

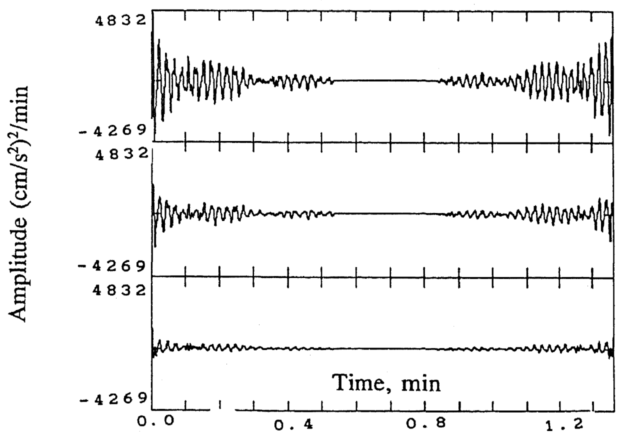
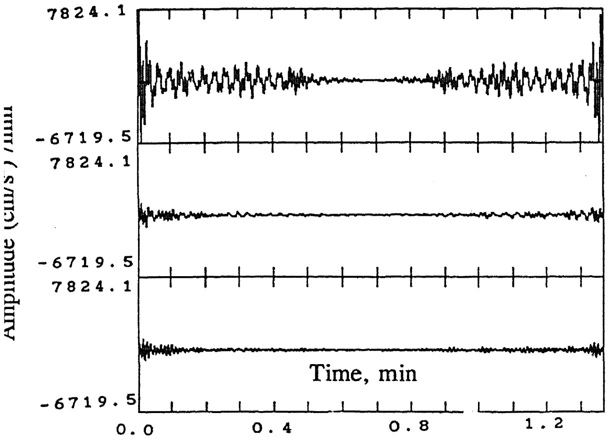


Fig 12 Cross correlation functions from the Roma vertical array



ig 13 Cross correlation functions from the Tlacotal vertical array

ONCLUSIONS

A purely observational approach was used to demonstrate that useful nformation can be obtained about the nature and characterisitics of eismic movements on the basis of analyses performed in a relatively ense array of accelerographic stations. A case history illustrating this or Mexico City was built with accelerations recorded there in three ecent earthquakes.

Broad, regional analyses demonstrate that the distribution of ormalized seismic intensities changes in the valley of Mexico from ne event to the other. These changes are mainly concentrated in the outh and western parts of the city, along the limits of the lake zone. Directivity effects may be responsible for them. In the two arthquakes analized, the zone of maximum intensity is roughly the ame and coincides with the zone which has repeatedly been more amaged during past large events.

Accelerograms obtained from instruments installed in boreholes at ifferent depths allowed us to show by means of spectral ratios that he movement at the base of the clay deposits in the three sites examined, is fairly uniform. As a consequence of the uniformity of motions, an average empirical transfer function between

Transfer functions derived from accelerograms measured in two vertical arrays illustrated the filtering effect of the soil strata and showed that, at least broadly, seismic response in these two sites agrees with what could be expected from established elastic procedures. Average shear wave velocities obtained from cross correlation functions yielded reasonable values, given the characteristics of soils in Mexico City. Unless high sampling frequencies are employed for digitizing accelerograms, it is unlikely that this procedure be useful in other locations having stiffer soils or in other more closely spaced arrays.

REFERENCES

Arias A (1973), "Earthquake intensity and smoothed earthquake spectra", *Proc. 5th World Conf. on Earthquake Eng.*, Rome

Espinoza J M, Uribe A, Ibarrola G and Contreras O (1988), *Acelerogramas captados en la ciudad de México. Sismo del 8 de febrero de 1988,* México: Barros Sierra Foundation, Rep. No. CIRES-RA-DF-2.

Ovando E and Romo M P (1990), Direcciones principales de movimiento en la ciudad de México, México, Institute of Engineering, UNAM, Internal Report.

Rice S O (1954), "Mathematical analysis of random noise", Chap. 4 in: *Selected papers on random noises and stochastic processes*, Wax N, editor. New York: Dove Publications Inc.

Romo M P and Seed H B (1987), "Analytical modeling of dynamic soil response in the Mexico earthquakes of September 19, 1985" *Proc. Int. Conf. The Mexico Earthquakes-1985*, ASCE, 148-162.

Quass R, Guevara E, González R, Medina S and López B (1990b), *Registros del temblor de mayo 31 de 1990*, México: Centro Nacional de Prevención de Desastres.