Local site effects on Mexico City ground motions

Les effets du site local sur les mouvements de terrain de la ville de Mexico

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SYNOPSIS: Response spectra obtained from ground motions recorder during several earthquakes in Mexico City are used to show that the seismic response of the subsoil varies considerably from one site to the other. A broad classification of soil types provides geotechnical microzones within seismic response is directly related to local soil conditions. Even within the zone of deep, soft clay strata, seismic motions show a large variability. The paper demonstrates that local distribution of shear wave velocities and the depth of the soft clay deposits are of paramount importance in determining the spectral characteristics of seismic response. Spectra calculated at the same sites from earthquakes having different characteristics are used to show that the frequency content of the incoming excitation also bears an important role on the seismic behavior of soil deposits. Observational evidence indicates that even for very large magnitude events, the behavior of Mexico City clays remains mainly within the elastic range. Local site conditions and frequency distribution of seismic movements may combine to produce damage in zones of Mexico City that have not been severely damage in the past.

1 INTRODUCTION

Earthquakes affecting Mexico City originate at different tectonic regions having different source mechanisms. The most damaging shocks, however, are generally associated to the subduction of the Cocos Plate into the Continental Plate, off the Mexican Pacific Coast. Even though epicentral distances are rather large, these earthquakes have recurrently damaged structures and produced severe losses in Mexico City. The earthquakes of September 19 and 20, 1985, for example, were originated some 450 km SW of Mexico City.

Information accumulated over the last three decades has firmly established that the singular geotechical environment that prevails in Mexico City is the one most important factor to be accounted for in explaining the huge amplification of seismic movements (i. e., Herrera and Rosenblueth, 1965; Romo and Jaime. 1986; Romo, Jaime and Reséndiz, 1988). Recent observational evidence has also made it clear that seismic movements within the Basin of Mexico can differ considerably from one site to the other (Romo and Seed, 1986). These facts have been taken into account in statutory regulations ever since 1962. The revised (1987) building code for Mexico City, for example, establishes geotechnical zones within which specific provisions regulate the design of foundations and structures.

A geotechnical microzonation map should not preclude careful analysis; it should rather be taken as a means of gaining broad insight into the gross overall properties of a particular site. In seismically active regions, the influence of local site conditions on the response of soil deposits and structures is then a crucial aspect in the analysis. The object of this paper is to illustrate a manner in which this aspect can be dealt with for the case of Mexico City soils, making use of response spectra calculated from the motions recorded at different sites during the events of September 19 (M = 8.1) and 20 (M = 7.5), 1985, and February 8, 1988 (M = 5.6). The variations in the spectral shapes are also related to local site conditions.

2 GENERAL SOIL CHARACTERISTICS

Soils in Mexico City were formed by the deposition into a lacustrine basin of air and water transported materials. Some of them are the product of volcanic effusions that took place within the last one million years. From the view point of geotechnical engineering, the relevant strata extend down to depths of 50 m to 80 m, approximately. The superficial layers formed the bed of a lake system that has been subjected to dessication for the last 350 years.

The geotechnical zoning of Mexico City proposed by Marsal and Mazari (1959) was recently modified by Jaime (1987) to include the Xochimilco-Chalco basin as depicted in Fig 1. Three types of soils may be broadly distinguished: in Zone I, firm soils and rock-like materials prevail; in Zone III, very soft clay formations with large amounts of microorganisms interbedded by thin seams of silty sand, fly ash and volcanic glass are found; and in Zone II, which is a transition between Zones I and III, sequences of clay layers and coarse material strata are present.

In Zone I, the soft lake deposits are underlain by a very stiff hard formation that extends throughout most parts of Texcoco Lake and crops up towards the western part of Mexico City to form the Hilly Zone (see Fig 1). Due to their high stiffnesses, in most engineering problems the hard deep deposits are considered the bottom of the soil profile. In recent studies (Romo and Jaime, 1986; Romo and

Seed, 1986) it has been shown that in the evaluation of ground motions it is sufficiently accurate for practical applications to assume that the half space starts at this depth. Thus it is a matter of practical significance to know the spatial variation of the clay deposit thicknesses. A map showing this type of information is presented in Fig 2 (Reséndiz et al, 1970; Jaime, 1987). It is expected that this map will be modified periodically as further information is produced.

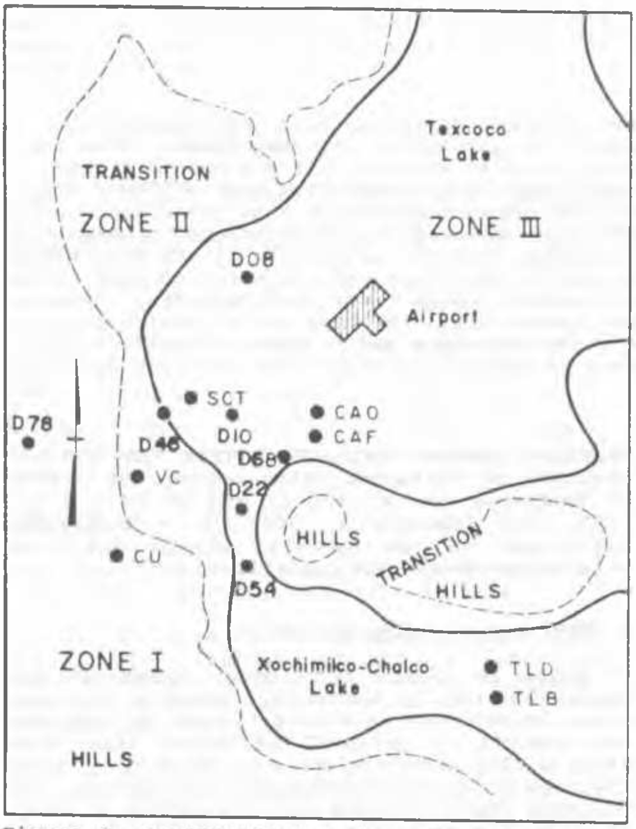

Figure 1. Geotechnical zoning and location of observatories.

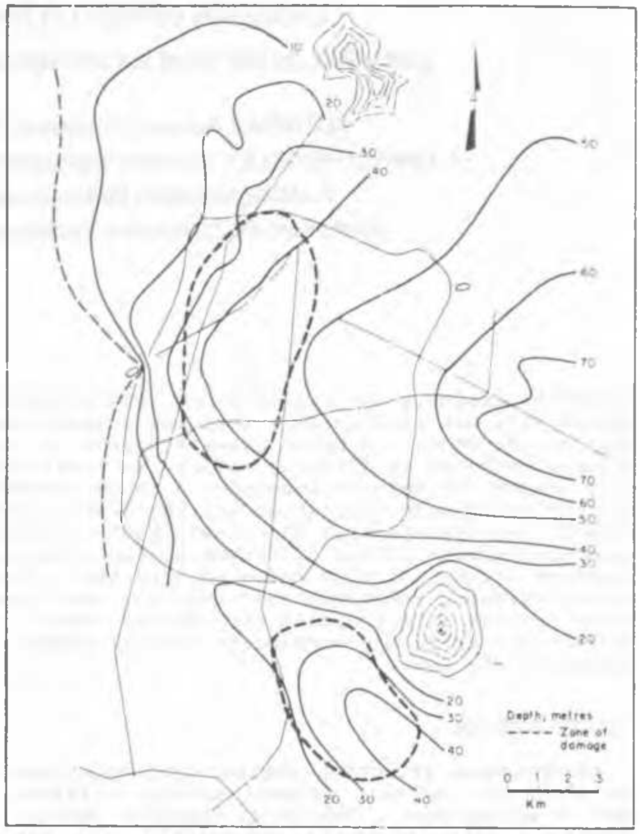

Figure 2. Thichnesses of soft clay deposits.

3 GROUND MOTIONS

Seismic ground motions have been measured in Mexico City during different earthquakes in the past. In this paper, however, reference is made only to three seismic events: September 19 and 20, 1985, and February 8, 1988. The motions that are discussed herein were recorded at the sites shown in Fig 1 (except TLD and TLB). The recording stations are located on different soil conditions, thus providing very valuable information for the evaluation of the soil characteristics effects on ground motions.

3.1 Earthquake of September 19, 1985

Zone I. The acceleration response spectra of the horizontal components of the motions recorded in the National University Campus (CU) are shown in Fig 3. Although the spectra show some variation they have general similarities: they have peaks at 0.5 and 1.2 Hz, the maximum ground response was about 0.038 g and the maximum spectral amplitude was of the order of 0.13 g.

The subsoil conditions at this site are shown in the lower part of Fig 3. There is a layer of fractured lava some 12 m thick with shear wave velocities from 120 to 180 m/s. Underlying this layer is the stiff, hard formation found underneath the clay deposits. The shear wave velocity in this formation varies from about 500 m/s to 800 m/s.

Zone II. The accelaration response spectrum of the average of the horizontal components of the ground motions recorded at Viveros Coyoacán (VC) station are shown in Fig 4. It may be seen that a predominant frequency is clearly defined at about 1.5 Hz. The intensity of the motion in this site was slightly higher than that of CU. The maximum ground acceleration reached 0.043 g and the peak spectral acceleration was about 0.16 g.

The N values from a standard penetration test are shown in the lower part of Fig 4. Estimated values of the shear wave velocities vary between 80 m/s and 120 m/s in the clay layers, and between 247 m/s and 330 m/s in the silty sand layers.

Zone III. The acceleration response spectrum of the average of the horizontal motions recorded at Secretaría de Comunicaciones y Transportes (SCT) site is depicted in Fig. 5. Two peaks at 0.5 Hz and 1.5 Hz stand out clearly. These two frequencies correspond to the first and second natural frequencies of the clay deposit.

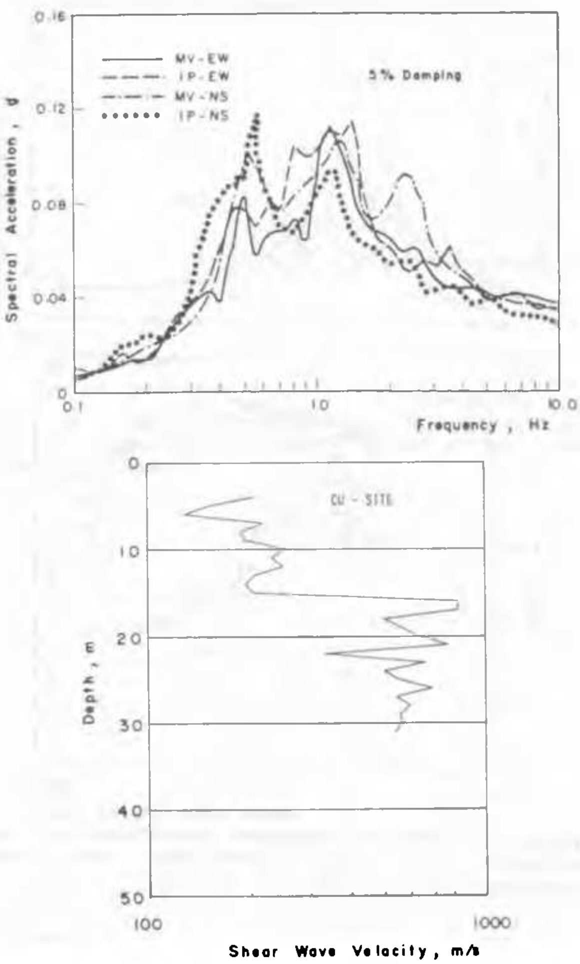

Figure 3. Average response spectra for the September 19, 1985 earthquake and soil characteristic at different sites within the University Campus (Zone I).

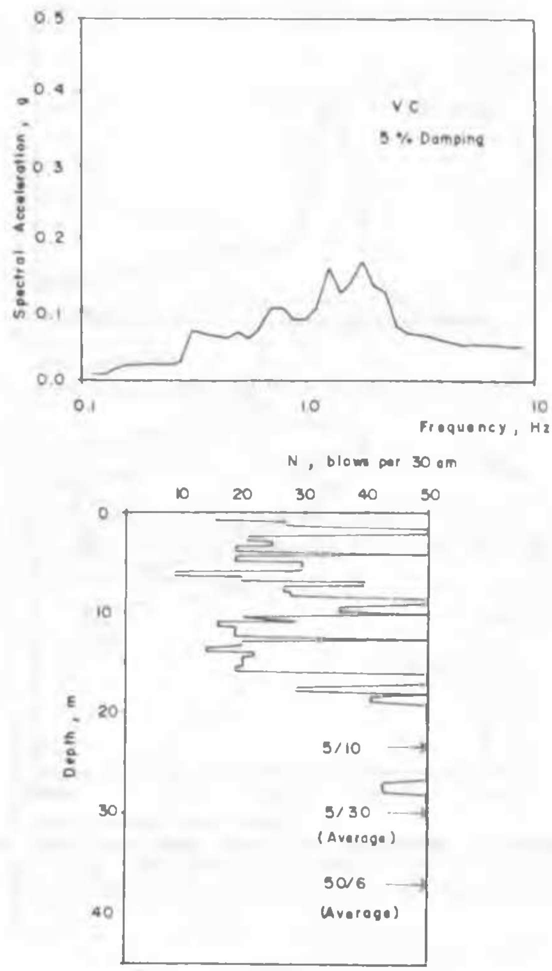

Figure 4. Average response spectrum for the September 19, 1985 earthquake and SPT sounding for the VC site (Zone II).

Comparing the ground motions in this site with those at CU it is evident that the soft clay deposits played a prime role in the development of the huge ground motion amplifications observed. The maximum ground acceleration reached a value of about 0.18 g and the peak spectral amplitude was around 1.0 g.

The soil characteristcs at SCT site are shown in the lower part of Fig 5. It may be seen that the shear wave velocity in the clay has values as low as 40 m/s and then increases with depth to some 90 m/s. The hard formation which is found at 40 m deep in this site has shear velocities that vary from about 400 m/s to 800 m/s.

The acceleration response spectra of the average of the horizontal motions recorded at two sites in Central de Abasto Oficinas (CAO) and Central de Abasto Frigorífico (CAF) are shown in Fig 6. It is interesting to note that even though these sites are some 0.8 km apart from each other the subsoil conditions are somewhat different, in particular, the depth to the hard formation. While in CAO it is found at a depth of 60 m, in CAF it is 45 m deep (see lower part of Fig 6). As shown in the upper drawing of Fig 6, the ground motion characteristics at both sites were appreciably different indicating the importance of subsoil conditions on the development of seismic motions. In fact if the velocity profiles of SCT and CAF sites are compared it can be concluded that for practical purposes they are similar. However, the motions recorded were significantly different remarking the importance of the effect of small variations in soil profiles on ground response analyses.

The average acceleration response spectra of the motions recorded at CU, VC, SCT, CAO and CAF are plotted in Fig 7. The variability of the ground motions felt throughout Mexico City during the earthquake of September 19, 1985 may be readily seen. It may be observed that the clay deposits amplified significantly the rock-like motions and modified appreciably the frequency content of the in-coming seismic waves. It is also evident that even within the Texcoco Lake Zone the ground motions were drastically different, explaining why the damage was severe in parts of the City where the clay deposits thicknesses were between 30 m to 45 m, mild for lower and higher depths, and negligible for Zone I (see Fig 2).

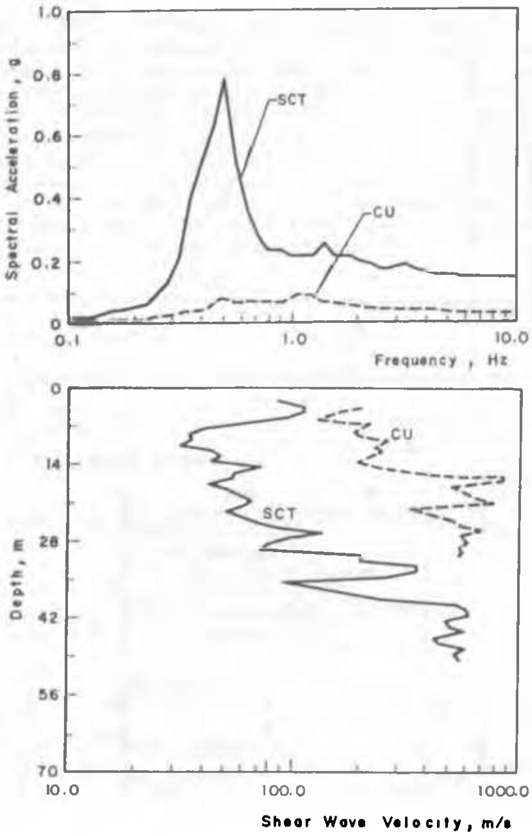

Figure 5. Average response spectrum for the September 19, 1985 earthquake and soil characteristics for the SCT site (Zone III).

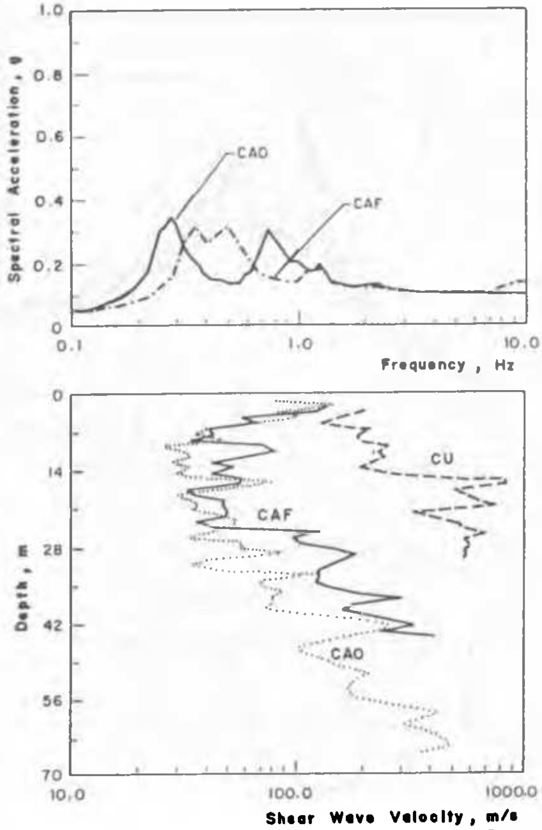

Figure 6. Average response spectrum for the September 19, 1985 earthquake and soil characteristics at CAO and CAF (Zone III).

3.2 Earthquake of September 20, 1985

Zone I. The acceleration response spectra of the horizontal components of the motions recorded at the CU stations are depicted in Fig 8. These spectra show the same general trends of those of the September 19 event, although their frequency content is higher as indicated by the comparison between the normalized average spectra included in the lower part of Fig 8. The relatively high frequency content is typical of motions recorded on firm ground. It is interesting to note that the similarities between both spectral curves denote that the two events were generated by the same source mechanism and followed similar paths from the source to Mexico City.

Zone II. A comparison of the average response spectra of the motions recorded at VC during the September 19 and 20 earthquakes is given in Fig 9. The ground motions had similar general characteristics, although the frequency content is slightly higher for the aftershock, reflecting the higher frequency content in the motions recorded on rock-like ground (CU). It is convenient to note that the ratio of maximum ground acceleration to peak spectral amplitude for both motions is similar. This and the fact that the maximum spectral amplitudes occur at the same frequency indicate that non linear effects were not induced by the shaking of the September 19 earthquake.

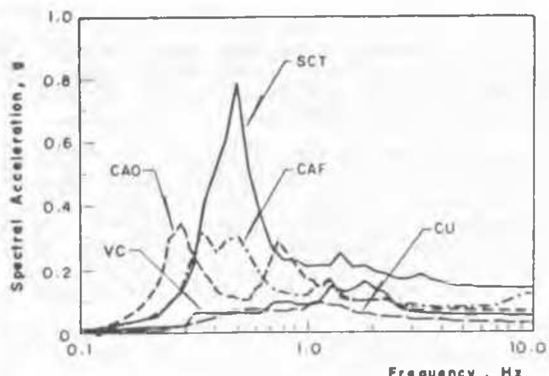

Figure 7. Average response spectra for the September 19, 1985 earthquake in Zoness I, II and III.

Zone III. Earthquake motions recorded at the CAO and the CAF sites during this event provided a unique apportunity to evaluate the effects of two earthquakes with similar general characteristics but having significantly different intensities. Average response spectra of the motions recorded at CAO during the two events of September are compared in Fig 10. Both curves have a striking resemblance and the peaks occur at practically the same frequencies. Similar information is presented in Fig 11 for CAF. Again, the spectral shapes

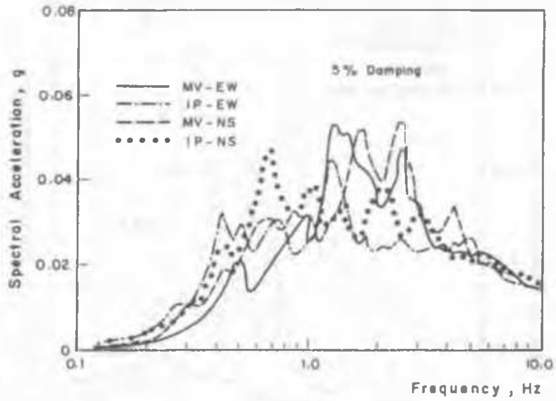

Figure 8a. Response spectra for the September 20, 1985, event at diferrent sites within the University Campus.

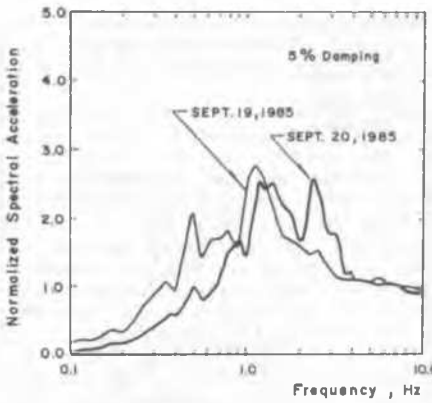

Figure 8b. Normalized average response spectra at the CU site fot the September 19 and 20, 1985 events.

are alike and the peaks show up at about the same frequencies. These results clearly demonstrate that non linear effects were negligible, even in the soft clay deposits. Thus, to a close approximation, the clay remained within the linear elastic range of behavior during the very intense motions caused by the September 19 earthquake.

It may be argued that in other parts of the City where the damage was severe, non linear effects could have been generated in the soil during the event of September 19. Fig 12 shows a comparison between the average spectra of the motions recorded at the SCT site during this earthquake and the March 14, 1979 seismic event that had a Richter magnitud of 7.6 and an epicentral distance of some 500 km, SW from Mexico City. It may be seen that the spectral curves resemble each other and the peaks occur at practically the same frequency. This indicates that even in the area of severe damage the free field ground response was nearly elastic during the earthquake of September 19, 1985.

3.3 Earthquake of February 8, 1988

Zone I. The normalized average response spectrum of the horizontal motions recorded at the D78 site is plotted in Fig 13, where it is

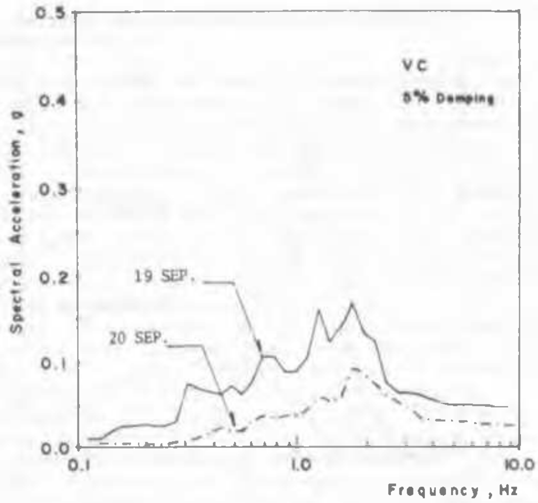

Figure 9. Average response spectra at the VC site for the September 19 and 20, 1985 events.

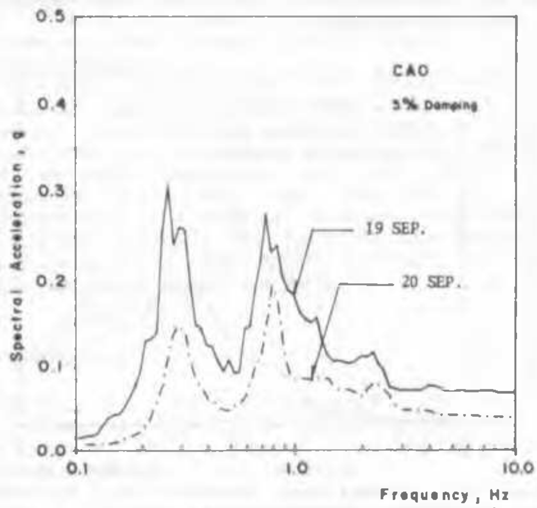

Figure 10. Average response spectra at the CAO site for the September 19 and 20, 1985 events.

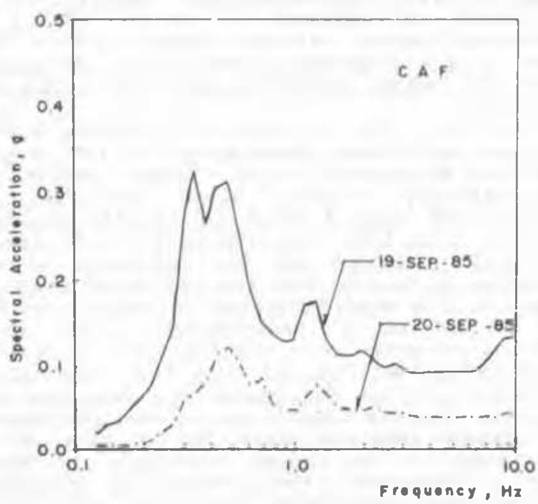

Figure 11. Average response spectra at the CAF site for the September 19 and 20, 1985.

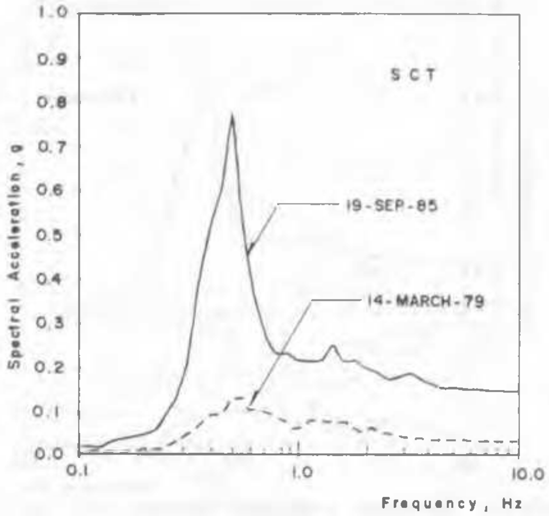

Figure 12. Average response spectra at the SCT site for the March 14, 1979 and the September 19, 1985 earthquakes.

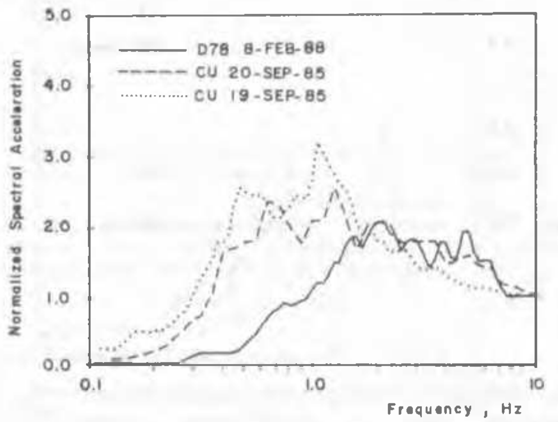

Figure 13. Normalized spectra for different events in sites located within zone I.

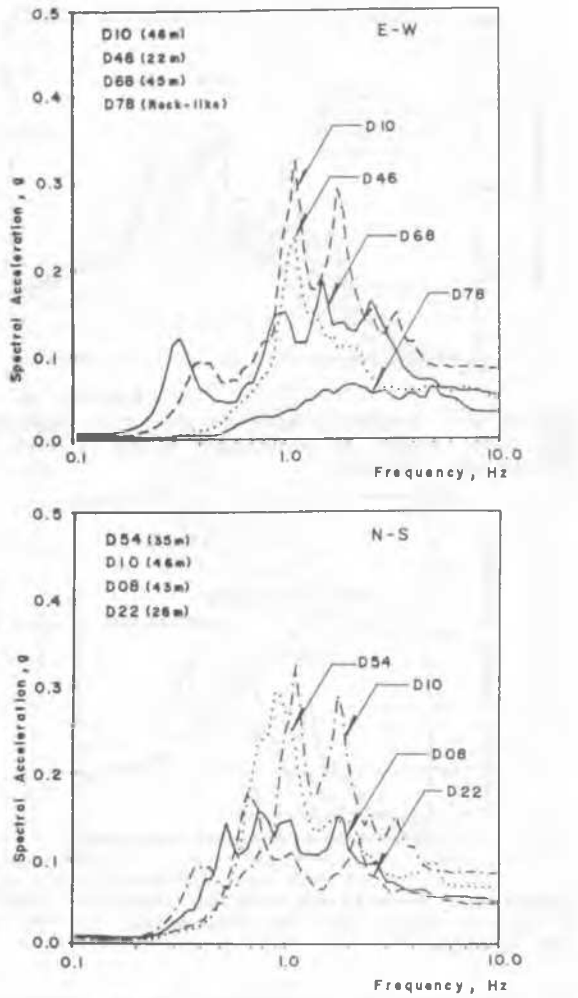

Figure 14. Average response spectra along N-S and E-W Axes for the February 8, 1988 event.

compared with the normalized spectra of the earthquakes of September 19 and 20, 1985. The frequency content was much higher in this event than in the September earthquakes, indicating that the source mechanims and wave paths were different.

Zone III. Fig 14 gives the response spectra of the horizontal components of the motions recorded at several sites. These stations are approximately aligned along East-West and North-South axes. A great variability of ground motions in the clay deposits is readily apparent, pointing out the relevance of site effects. At the D10 and the D68 sites where the depth to the hard formation is nearly the same (46 m and 45 m, respectively), the ground motions recorded were significantly different. This indicates that not only the clay deposit thickness varies throughout the City but also the clay dynamic properties. These two aspects of ground response seem to be particularly important in the clayey materials in Mexico City. Therefore, they should be adequately defined when performing analytical evaluations of ground motions for seismic design purposes.

3.4 Effect of Input Motion Characteristics on Soft Ground Motions

Recent investigations (Romo and Jaime, 1986; Romo and Seed, 1986; Romo and Jaime, 1987; Romo 1988) have demonstrated that ground motions on Zones II and III may be evaluated with sufficient accuracy using appropriate one dimensional models that consider vertical propagation of horizontal shear waves. In these analyses, accelerations recorded at Zone I (rock-like motions) were used as input motions and the control point was considered to be at the contact of the hard formation and the clay deposit. On the basis of these analytical results and the nearly linear elastic behavior of the clay during past seismic events, one may evaluate the potential effect of input motion characteristics on the motions recorded on the clay deposits of Mexico City.

Rock-like motions recorded in Zone I have considerable differences for the September 19 and February 8 seismic events. Hence, a unique opportunity is at hand in order to evaluate the importance of the effects that these differences might have on the response of the

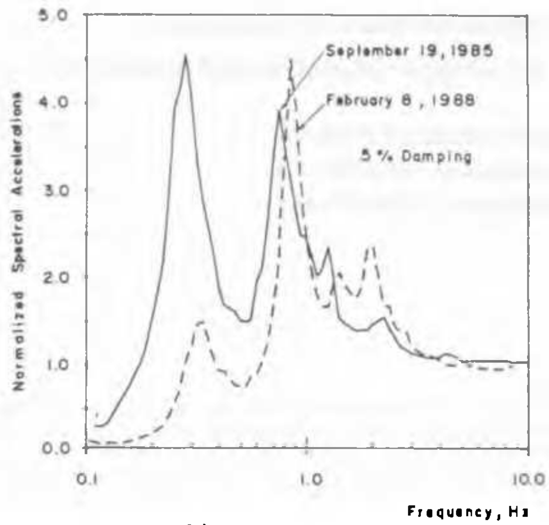

Figure 15. Normalized spectra for the CAO site for events having different characteristics.

soft deposits. In this respect, the CAO site is particularly interesting because ground motion records are available for these two events. Acceleration response spectra, normalized to yield unitary maximum ground motion, are compared in Fig 15. It may be seen that both spectral curves have similar shapes; however, the frequency content is higher in the February 8 response spectrum, denoting the effect of the input motion characteristics. This has an important practical implication, as it indicates that relatively stiff structures on soft ground may be strongly shaken if large magnitude earthquakes having high frequency content hit Mexico City. This problem may be enhanced in those zones of the City where stiffer soils are present.

It was previously argued that the Mexico City clay had had a nearly elastic response during the September 19, 1985 event. To stress this point even further, the normalized spectra of the motions recorded at CAO during the September 19 and Febrary 8 earthquakes are compared in Fig 15. The first natural frequency of the clay deposit changes from 0.32 Hz for the February event to 0.29 Hz for the September earthquake. This represents a decrement of about 10 % in the overall shear modulus (G) of the clay deposit, wich is small considering that relatively large shear strains of the order of 0.3 % were induced by the earthquake of September 19, 1985. As compared to other soft clays, Mexico City clay has a wider range of elastic behavior. In fact for shear strain values of 0.3 %, the G modulus of most Mexico City clays drops to about 60 % of their maximun G value.

4. CONCLUSIONS

Mexico City has been shaken by a number of earthquakes of different characteristics during the past few years. Ground motions have been recorded at various sites with different soil conditions throghout the City. In some cases ground motions induced by two or three seismic events have been recorded at the same site providing very valuable information for the evaluation of subsoil conditions on motion characteristics.

On the basis of the recorded ground motions during the September 19 and 20, 1985, and February 8, 1988 earthquakes, it was shown that there exists a close correlation between local site conditions and ground motion characteristics. The intensity and frequency content of motions vary significatly from the Hilly area (Zone I) to the Lake area (Zone III) clearly indicating motion soil-dependence and the enormous capability of the clayey deposits for amplifying rock-like motions.

The information shown here also indicates that in the free field, the behavior of the soft clay was nearly elastic during the September 19 event. Given the severity of this earthquake, it is unlikely that important non linear effects be induced on the clay deposits (in the free field) by future events.

The importance of determining properly shear wave velocities and depths to the base of the clay deposits was made evident from the comparisons of the motions recorded in Zone III. Relatively small variations in these two parameters may significantly modify surface ground motions.

Another aspect that may prove to be of practical importance is that high frequency content earthquakes may damage stiffer structures, as suggested by the comparison of the motions recorded at CAO during the September 19, 1985 and February 8, 1988 earthquakes. Seismic events with higher frequency contents may be more detrimental on relatively rigid structures founded on stiffer soils as those found in Zone II.

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