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OSCILLATIONS OF THE MEXICO CITY SURFACE LAYER EXCITED BY SURFACE SEISMIC WAVES

A. GÓMEZ-BERNAL (1) and R.G. SARAGONI (2)

(1) Departamento de Materiales, Universidad Autónoma Metropolitana. Azcapotzalco.
Av. San Pablo 180. c.p. 02200. Mexico D.F., MEXICO

(2) Departamento de Ingeniería Civil, Universidad de Chile.
Av B. Encalada 2120. casilla 228/3. Santiago, CHILE

ABSTRACT

Recent ground motions records in Mexico City (the April, 1989, the October, 1993 and the September, 1995 earthquakes), originated in the subduction zone of the Mexican Pacific Coast are analyzed in this paper. Available accelerograms recorded in several downhole stations were included in this study. It is found that the seismic waves arriving to the Valley of Mexico from these distant earthquakes involve basically Rayleigh waves with a broad band frequency between 0.08 to 1.0 Hz. It is concluded that these surface waves greatly contribute to the destructiveness of earthquakes as their frequencies coincide with the site periods encountered at the Lake-bed zone. The incident wave field clearly detected in firm soil records, is composed of Rayleigh waves coming from the epicentral direction. These waves take a considerable time to cross the valley, so accelerometers installed on firm soil do not typically record the entire motion due to the very small amplitude of the later waves. Ground motions recorded at Mexico City Valley during distant earthquakes are often used to illustrate the applicability of the one dimensional soil amplification theory with vertically incident propagating shear waves. It is then important to notice that the records obtained in firm soil basically contain surface waves. Classical local amplification studies based on incident SH waves should be then revised.

KEYWORDS

Seismicity; ground motions; site effects; local effects on ground motion; wave propagation.

INTRODUCTION

The importance of the dynamic soil amplification effect on earthquake ground motion due to soft soil surface deposits has been widely recognized since 1930 (Sezawa, 1930). The old and simple 1-D linear elastic theory normally considers incident vertical shear SH waves obtaining as result important amplification at the natural period of the soil layer T=4H/Vs, where H is the soil deposit depth, and Vs is their shear wave velocity.

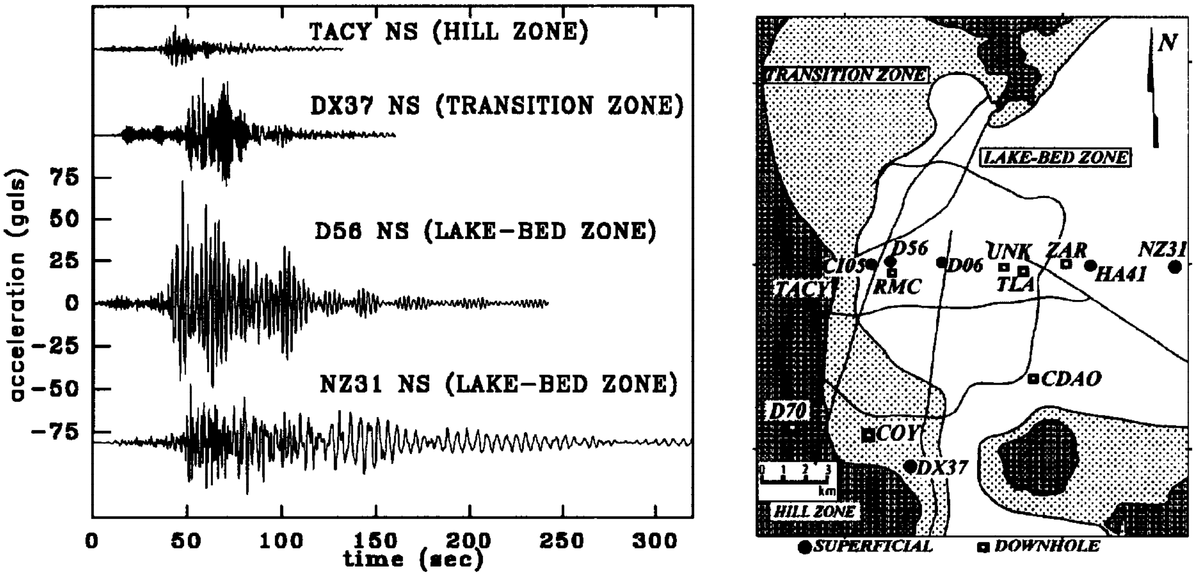
After the 1962 earthquake (Zeevaert, 1964) the observation that very narrow band response spectra with only one strong peak at the natural site period were obtained from the accelerograms of Alameda Park in Mexico City turns to be the classical confirmation of the validity of the soil amplification theory. Since then, Mexico City soils turns to be up today the paradigm of the soil amplification theory having a strong impact on world design spectra which recognize that the natural site period is a key parameter. Also worldwide programs for evaluating site effects as SHAKE (Schnabel *et al.*,1972) are used considering the same assumption. However it must be recognized that this supposition is only a wishful thinking and no experimental evidence support it.

During the destructive Mexico earthquake of 1985 significant duration and amplification at the natural site period were again observed similar to 1957 (Rosenblueth, 1960) and 1962. In order to explain the amplification effect observed in Mexico City, some techniques have been employed, through the use of 1-D and 2-D models (e.g., Bard *et al.*, 1988; Kawase and Aki, 1989, Campillo *et al.*, 1989; Sanchez-Sesma *et al.*, 1989; Chavez-Garcia and Bard 1993). However, this classical theory do not satisfactorily explain the unusual and different long duration of ground motion. The accelerograms recorded on the lacustrine soil during the 1985 earthquake, show a long coda in which the latter part has comparable amplitude to the earlier, major part. This feature has been observed again from records obtained during recent earthquakes with the high density accelerograph array. Since the collapse of most high rise buildings of Mexico City in 1985 probably occurred in the not explained duration of the records. As duration is a key parameter affecting a ground motion destructiveness, it is of great relevance to understand its cause.

The objective of this paper is to analyze several aspects of the seismic response of Mexico City that had not been completely understood, based on the interpretation of all ground motion records since the April 25, 1989 earthquake (Ms=6.9) and some downhole records of the October 24, 1993 (Mc=6.7), and the September 14, 1995 (Ms=7.2) earthquakes. In particular to verify experimentally the assumption of the type of income waves, which is a very violent not justified assumption in most proposed models.

THE 1989 GUERRERO EARTHQUAKE

The uppermost stratigraphy of the valley is divided into three regions; the Lake-bed zone consisting of very soft clays and sand lens, the Hill zone consisting of alluvial and glacial deposits lava flows, and the Transition zone consisting of alluvial sandy and silty layers with clay layers. The thickness of the soft lacustrine deposits that cover the valley of Mexico City (Lake-bed zone and Transition zone) is variable with distance, increasing toward the east from station sites CI05 to NZ31, which are depicted in Fig 1b.



(a)

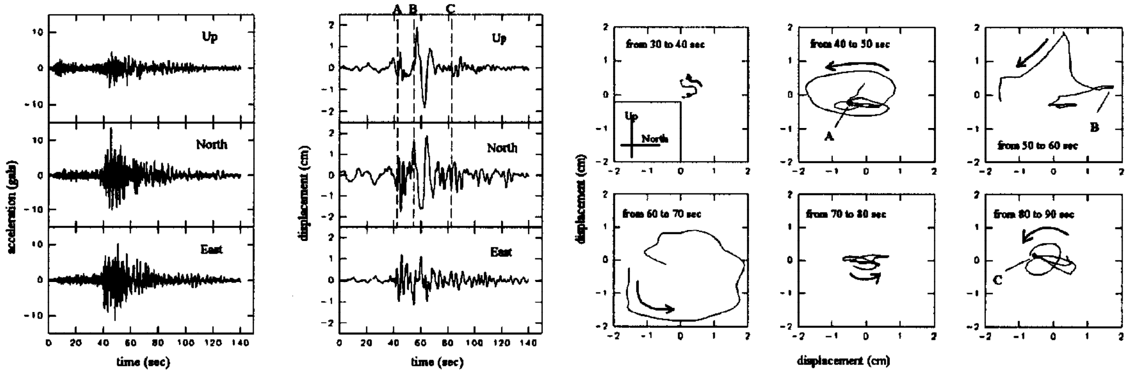
(b)

Fig. 1. Recorded north-south accelerations at 4 stations in Mexico City during the April 25, 1989 Guerrero earthquake, and location map of the city showing accelerometer stations selected in this study.

The Guerrero earthquake of April 25, 1989 (Ms=6.9) was recorded at more than 60 sites in the Mexico City Valley. The epicenter was located at about 300 km south from Mexico City. During this event, a strong amplification and extraordinary duration of the ground motions in the Lake-bed zone with respect to the hill zone was observed again, as it was during the September 1985 earthquake. Fig 1a shows the horizontal ground acceleration time histories in four stations at different sites of the city. Peculiar differences in amplitude and frequency content can be seen among these 4 records. In Transition zone (DX37) and Hill zone (TACY) the record duration's are similar, but the amplitudes are widely different. Moreover, an harmonic effect with beats is clear in DX37 record from 15 sec to 47 sec. A drastic increase in duration is observed in Lake-bed zone: D56 record reaches over 250 sec, while, in NZ31 record the duration is 200 sec more than TACY record. It is interesting to note that the beating effect is present in these accelerograms, but it is delayed with respect to DX37: in D56 starts at 50 sec until the end of the record, while in NZ31 is detected very late, approximately at 100 sec. On the other hand, the major amplitudes were recorded at D56 site.

Ground displacements in firm soil

In an attempt to identify wave types and ground motion characteristics for Hill zone, TACY station has been studied. In Fig 2a the three recorded acceleration components and their corresponding ground displacements are displayed; the waveforms in the displacements strongly suggests the influence of surface wave dispersion. The surface waves arrivals can be identified approximately by plotting the ground displacement components, on a plane comprising the vertical and radial (north-south) directions. The particle motion are presented in Fig. 2b by 6 separated 10 sec duration plots, starting at 30 sec. The arrows indicate retrograde particle trajectory, and the letters correspond to points in which a displacement loop begins; these points are indicated also in Fig 2a. Thus, in the second odogram, surface waves of 5 to 6 sec period are evident (point A). Next, a longer-period wave between 54 and 67 sec (point B) is present on the vertical and radial components (Fig 2a), and particularly clear in their corresponding odogram, which shows a retrograde ellipses typical of Rayleigh waves. After this longest period wave, a group with decreasing period appears, being noted point C as an example, this group consists of short period Rayleigh waves. Although no more points are indicated in the Fig 2, it is apparent that these later waves continued over the entire record.



(a) (b)

Fig 2. Ground acceleration and displacement components in TACY station *(a)* and particle motion trajectories in the vertical-radial plane *(b)*. Retrograde trajectories begin at A (42.5 sec), B (54.3) and C (82.5).

In the east-west component the arrivals apparently consist of a dispersed Love-wave train, according to the period decreasing observed in Fig 2a. In sum, this analysis shows that ground displacements on all three components of motion are strongly influenced by surface waves, and suggests that probably more surface waves with very low amplitude arrived after 140 sec (Gómez-Bernal and Saragoni, 1995).

The presence of the longest period wave and the short period delayed waves was previously detected for the 1985 Michoacán earthquake by Campillo, *et al.* (1989), and also identified for the 1989 Guerrero earthquake by Sánchez-Sesma *et al.* (1993). However, the importance of the low amplitude surface waves observed during the entire record, has not been conveniently studied to date.

Ground displacement waveform in lacustrine soil

The 7 stations selected for this study: CI05, D56, D06, HA41 and NZ31, are aligned approximately at the same latitude on Lake-bed zone (Fig 1). DX37 station (Transition zone) and TACY (Hill zone) are located toward the south. Fig 3 displays vertical ground displacements for the 7 stations. To facilitate detailed comparison between the ground motions in the sites, it is necessary to provide a common time basis and a common orientation of the three components of motion. Then, the seismograms were aligned with respect to the arrival of the long-period Rayleigh wave in the vertical component. Points A, B, and C from Fig 2a are also indicated in Fig 3. In the time delimited by A and C, it can be seen that the waveforms are very similar in all stations. These nearly identical shapes indicate the strong influence of the long period Rayleigh wave on the incident wave field.

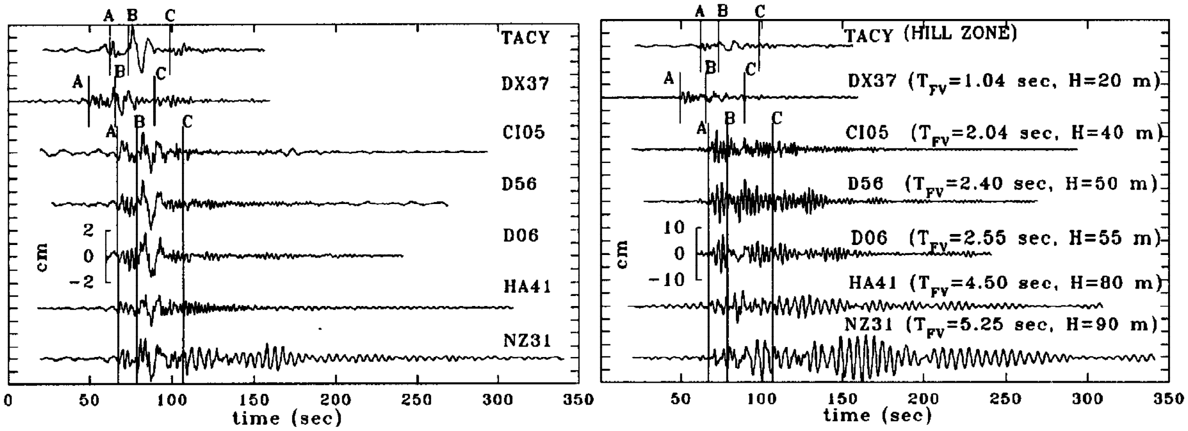


Fig 3. Vertical (*left*) and radial (*right*) ground displacements for the 7 selected stations, with a common time basis. Points A, B, and C correspond to these indicated in Fig 2. T_{FV} represents the observed free vibration period.

Different in the radial component (Fig 3), the long-period waveform (point A through B) is extended in the lacustrine sites, due to the low velocity in the deposit clays relative to the velocity in the substratum (Hanks, 1975). Therefore, elongation in the corresponding ellipses in the radial direction has been observed (not presented here). Additionally, these seismograms show that the surface waves are mixed with harmonic beats.

Relation between the deposit depth and the observed harmonic period

The seismograms depicted in Fig 3 and the accelerograms in Fig 1a indicates that the harmonic region is shifted in the lacustrine sites. This time is delayed according as the deposit depth increase, which are over 20, 40, 50, 55, 80, and 90 meters for the stations DX37, CI05, D56, D06, HA41 and NZ31 respectively (Fig 3). These depth (H) values are related to the observed harmonic periods (T_{FV}): 1.04, 2.04, 2.40, 2.55, 4.5, and 5.25 sec in the horizontal motion.

GROUND MOTION IN DOWNHOLE SITES

The October 24, 1993 earthquake (Mc=6.7) and the September 14, 1995 Ometepec earthquake (Ms=7.2), were recorded in several downhole sites (Fig 1b) by *Centro Nacional de Prevención de Desastres* (CENAPRED). The epicenters of both earthquakes were also located about 300 km south of Mexico City. Fig 4 displays the superimposed vertical ground displacements, for the October event, associated to three different depths for 7 downhole sites. These seismograms were aligned relative to each other without a common time basis. The waveforms for three different depths are almost identical, and show the same pattern respect to the 1989 earthquake: a region with a long period-wave, which confirms the presence of surface waves at several depths.

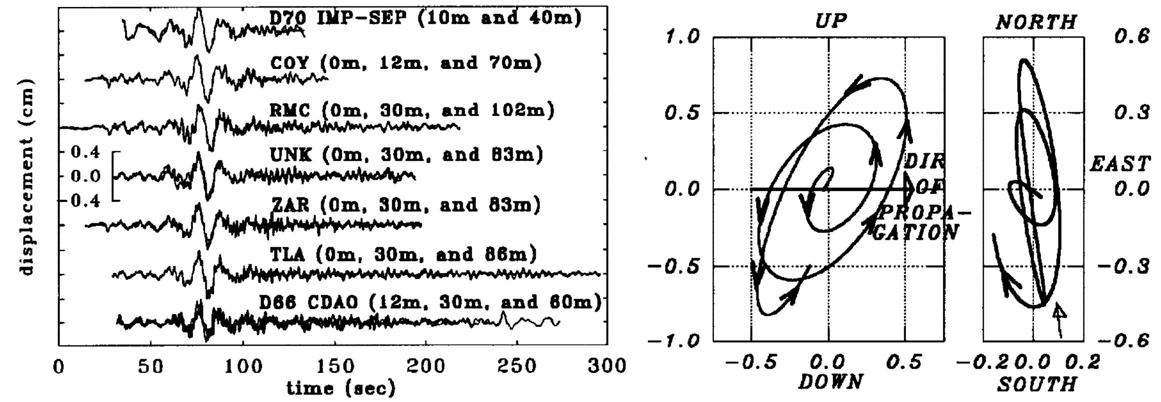


Fig 4 a) *Left* vertical ground displacements for 7 downhole sites during the October 1993 earthquake. Seismograms from three different depths were superposed at each site. Values in parenthesis indicate instrument depth. b) *Right* particle motion for the time interval 83 to 92 sec at RMC 102 m depth, during the September 1995 earthquake, using a bandpass filter between 0.25 Hz and 0.37 Hz.

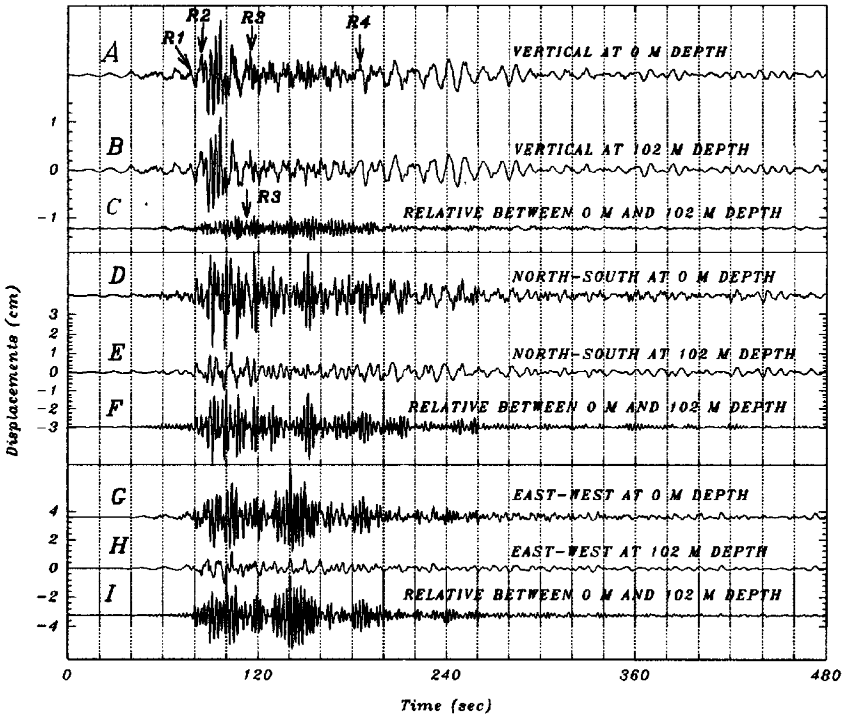


Fig. 5 Estimated total and relative displacements at RMC downhole site, during the September, 14 1995 earthquake

The evidence of the existence of Rayleigh waves is again stronger when the motions on the RMC site during the September 14, 1995 earthquake is analyzed. In Fig 5 the displacements time histories calculated at 0 m and 102 m depths are shown for the first 480 recorded seconds. In this station, the compressible soil thickness is approximately 35 meters (the soil vibration period value is of 2.4 sec); the underlaying subsoil can be considered as firm. Detailed comparison of the seismograms shows that the arriving seismic body waves are mainly seen only during the first 75 seconds of the records with very low amplitudes. Next to this early motion, the movements are dominated by surface waves of longer periods not only in the strong shaking part (80-150 sec) but also in the trailing part (150-480 sec). The first important surface wave has a frequency of 0.12 Hz, and is marked as R1 in Fig 5 with a duration of 40 sec. Next, the most important surface wave (R2) with a frequency of 0.33 Hz (3 sec period) arrives and together with the R1 wave produced the largest vertical displacement. At 117 sec another Rayleigh wave (R3) with a frequency of 0.41 Hz (2.43 sec period) arrives producing an harmonic movement in the vertical direction as it is clearly detected in the relative displacement between 0 m and 102 m depths (Fig 5C), lasting about 20 sec. The trailing part of this ground motion consists essentially of surface waves with a frequency of 0.10 Hz, as it is indicated as R4 at 185 sec.

As an example of the particle motion displacement trajectories for the Rayleigh waves mentioned above, in Fig 4b the odogram for the time interval of 83 to 92 sec of R2 (0.33 Hz) in RMC site at 102 m depth is plotted, the accelerograms were bandpassed from 0.25 Hz to 0.37 Hz in order to clearly observe the retrograde particle motion in this frequency range. The corresponding horizontal motion is also presented in Fig 4b, where it can be observed that the trajectory is strongly polarized in the north-south direction, i.e., a plane surface wave traveling from the epicentral direction.

INTERPRETATION OF GROUND MOTION IN MEXICO CITY (Resonant Response)

Based on the analysis of the data recorded in Mexico City during several recent earthquakes, the cause for the long duration and amplification can be explained considering the following three aspects:

a) Clay deposits dynamic response in the Valley of Mexico is nearly elastic with low capacity to dissipate energy even for large shear strains (Romo, *et al.*, 1988). Then, vertical and horizontal displacements in soil particles produced by the incident surface waves cause damped shear vibration motion. As the mechanical properties are almost linear, the stored seismic energy is then expelled slowly; this phenomenon is repeated periodically throughout the surface waves pass.

b) The accelerograms obtained from distant earthquakes exhibit mainly surface waves with different associated arrival times, and with a band frequency between 0.08 and 1.0 Hz, which coincide with the site period interval of the different sites of the Lake-bed zone (1.0-5.5 sec). When the frequency of the surface wave is close to that of the vibrating compressible soil the phenomenon of beating may be observed. Although several incident Rayleigh waves with different frequencies are observed during the strong shaking part of the records, the trailing part only contains low frequency waves. For this reason, and despite their very low amplitude, the beating effect is clearly observed in the trailing part of the soft soil accelerograms (sites with high period).

c) The lapse of time in which the sedimentary deposits are driven into resonance depends on their thicknesses (period value). When this time has been elapsed, resonant response may be observed, as Figs 1 and 3 illustrate. In the trailing part, the delayed waves, despite their very low amplitude, prolong the strong motion in the soft ground when the clay column is vibrating. Thus, DX37 station with 1.05 sec of free vibration period, reaches the resonant response approximately at 15 sec, and with the long-period arrival, the amplitudes increase considerably. In intermediate site periods, from 2 to 3 sec (e.g. station D56), the harmonic beats start at the stronger motion region of the record, close to the long period surface wave arrival, so the amplitudes are highly magnified at this point. Finally, the soil at NZ31 station, with a 5.25 sec period, needs a very long lapse of time (100 sec aprox) to reach the resonant effect. In this case, the steady shaking duration is considerably large due to the long period associated to the soil vibration.

Similar studies have been done for the accelerograms recorded during the aftershock of the 1985 Chile earthquake (Saragoni, Gómez-Bernal, and Lobos, 1995). The results show the existence of important Rayleigh waves of about 1.0 sec period in the Viña del Mar, Llolleo and UTFSM records. Important influence of these Rayleigh waves on the absolute acceleration response spectra has been found.

CALCULATED ACCELEROGRAM

In an attempt to reproduce the indicated features in the time histories records, accelerograms from multiple degree of freedom (MDOF) systems (shear elastic beams) with 2% of critical damping are presented, which represent different stratums with natural periods corresponding to the soil column under shear deformation.

Case I. In Fig 6a accelerograms from 2 models with fundamental periods equal to 2.4 sec and 5.25 sec are plotted. The input motion is the horizontal north-south accelerogram in TACY recorded during the 1989 earthquake. This Fig shows that the shape (amplitude and frequency content) of the acceleration response obtained corresponds approximately to typical recorded accelerograms in Lake-bed zone, although TACY record contains only 140 sec. When a two-mode model is considered with T_1=2.36 sec and T_2=0.87 sec, it is interesting to notice that a strong amplitude begins before that corresponding to firm soil, and the strong motion region increases considerably due to the superposed response of the two modes. A succession of monotonically decaying envelope typical of damped free vibration is observed. In the second MDOF model with T_1=5.25, T_2=1.87 and T_3=1.1 sec, the total duration increases due to the long cycle duration of the first mode, which dominate in the latter part of this calculated accelerogram with an important amplitude even when the input motion is very low, because the frequency of the coda is close to that of the fundamental soil. In the other hand, the influence of the highest modes is appreciated on the first part of this record.

Case II. The input motion is the horizontal north-south accelerogram in UNK at 83 m depth during the 1995 earthquake. The fundamental period in this site is estimated as 3.4 sec. In this case different to case I, the effect of the long duration of the coda recorded on firm soil allows to see the effect on the lacustrine records: the very low amplitude in the trailing part supply a nearly free motion. Comparison of the observed and calculated records at the surface and borehole bottom, indicate an agreement in amplitude and shape.

It is worthnoting that these models consider only viscous damping; no radiation damping is considered as opposite to classical propagation models. Due to the incident wavefield and to the characteristics of the soft soils in Mexico City, it is our belief that the viscous part of the damping effects is predominant in these soils.

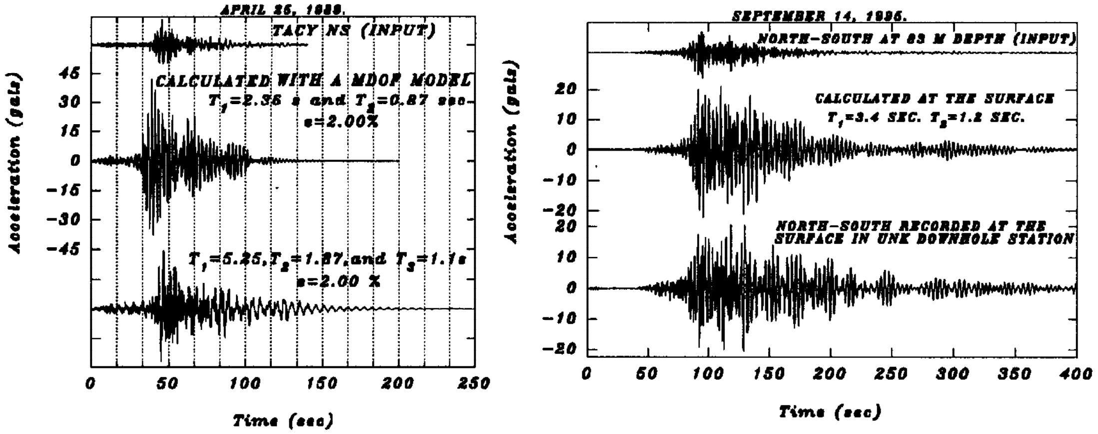


Fig 6. Calculated accelerograms using a linear model (MDOF system) without radiation damping: a) **Case I**, April 1989 TACY NS record as input. Notice that a great amplitude is obtained at 35 sec, even before the stronger input excitation. b) **Case II**, using the September 14, 1995 earthquake.

CONCLUSIONS

The presence of important surface waves in accelerograms recorded in Mexico City is demonstrated. These waves arriving from the subduction zone of the Mexican Pacific Coast, consist mainly of Rayleigh waves with a band frequency between 0.08 Hz to 1.0 Hz. These long-period surface waves cross the valley during a considerable time, and due to their small amplitude accelerometers installed in firm soil do not usually record the entire ground motion. It is concluded that these surface waves greatly contribute to the destructiveness of earthquakes as their frequencies coincide with the site periods encountered at Lake-bed zone. The incident wave field, clearly detected in firm soil records, is composed of plane surface waves with trajectory strongly polarized in the epicentral direction.This feature indicates that the detected Rayleigh waves arrive from the epicenter. Another important conclusion, is that the long duration observed in soft soil records is produced by a shear resonant response due to the low amplitude of the delayed Rayleigh waves, detected at the bottom of the downholes.

Ground motions recorded at Mexico City Valley from distant earthquakes, are often used to illustrate the applicability of the one dimensional model with vertically propagating shear waves. However, it is important to notice that, the records obtained in firm soil contain basically Rayleigh surface waves. Classical local amplification studies based on incident SH waves should be then revised, in regard to the acceleration response spectra and the effects of strong motion duration of the records on structural response.

Starting from the fact that the dynamic clay deposit behavior in the valley of Mexico is nearly elastic, the response of linear systems subjected to accelerograms recorded in firm soil were studied with reference to the particular strong ground motions characteristics observed in Mexico City Valley. It was found that the response of a simple 1-D linear model can approximately represent the observed records, which have a succession of monochromatic beats of considerable amplitude even when the firm soil records have been terminated. Damping effects are adequately represented by a viscous model, being the radiational part negligible for Mexico City soft soils. The results obtained in downhole site suggest that the vertical and horizontal ground motions are coupled.

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