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The Mexico Earthquake of September 19, 1985— A Theoretical Investigation of Large- and Small-scale Amplification Effects in the Mexico City Valley

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The linear, large-scale and small-scale amplification effects in the Mexico City valley, related to both the surficial clay layer and the underlying thick sediments, are investigated with two-dimensional (2D) models and compared with the results of simple one-dimensional (1D) models. The deep sediments are shown to be responsible, on their own, for an amplification ranging between 3 and 7, a part of which is due to the 2D effects in case of low damping and velocity gradient. This result is consistent with the observed relative amplification around 0.5 Hz at CU stations with respect to TACY station. The amplification due to the clay layer is much larger (above 10), and the corresponding 2D effects have very peculiar characteristics. On the one hand, the local surface waves generated on any lateral heterogeneity exhibit a strong spatial decay, even in case of low damping (2%), and the motion at a given site is therefore affected only by lateral heterogeneities lying within a radius smaller than 1 km. On the other hand, these local 2D effects may be extremely large, either on the very edges of the lake-bed zone, or over localized thicker areas, where they induce a duration increase and an overamplification. The main engineering consequences of these results are twofold: i) microzoning studies in Mexico City should take into account the effects of deep sediments, and ii) as the surface motion in the lake-bed zone is extremely sensitive to local heterogeneities, 1D models are probably inappropriate in many parts of Mexico City.

I. Introduction

The huge damage in Mexico City during the September 19^{th}, 1985, "Guerrero-Michoacan" earthquake is undoubtedly due to the existence of large amplification effects related to the specific geological conditions within the Mexico City valley (in conjunction, of course, with the large magnitude of this seismic event).

Since the pioneering work by Zeevaert (1964), the engineering community generally identifies the surficial lacustrine clay deposits as the main, if not only,

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responsible for the observed strong amplification of ground motion. And indeed this interpretation is strongly supported by various observations:

- most of the damages observed in Mexico City after the 1957, 1979 and 1985 (coastal) earthquakes occurred in the so-called "lake-bed zone", *i.e.* that zone overlaid by the now famous, extremely soft, water-saturated, lacustrine clay deposits (Anderson *et al.*, 1986).
- the spectral contents of the accelerograms recorded in Mexico City within this lake-bed zone during various earthquakes systematically exhibit a very sharp peak at frequencies ranging between 0.2 and 0.5 Hz (Anderson *et al.*, 1986; Singh *et al.*, 1988), while those recorded, during the same earthquakes, on other geological formations of Mexico City, do not exhibit such low-frequency peaks.
- finally, these spectral peaks may be satisfactorily (and easily) interpreted with the now classical one-dimensional (1D) resonance theory (Haskell, 1960), and its engineering derivatives such as, for instance, the program "SHAKE", as shown by Romo and Jaime (1986), and Singh *et al.* (1988), provided an adequate choice of the geometrical (thickness) and dynamic (velocity, damping) properties of the clay layers.

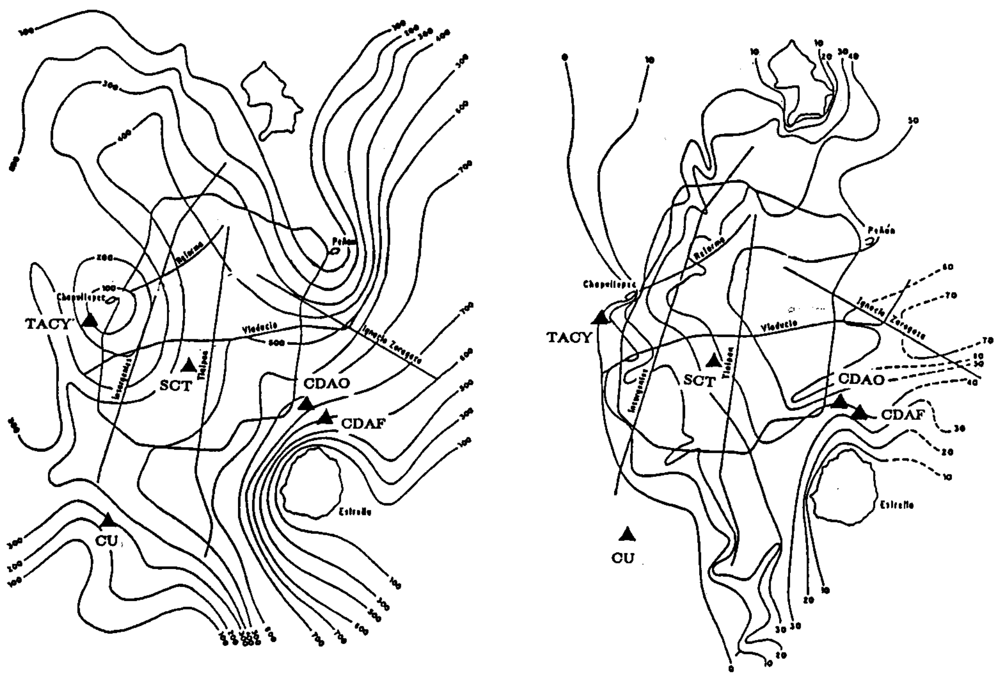


Figure 1 : *Thickness contours of the two main sedimentary units of Mexico City subsoil (after Suarez et al., 1987). The black triangles show the sites where the accelerograms shown in Figure 2 were recorded.*
(Left, a) "Deep sediments".
(Right, b) Lacustrine clay.

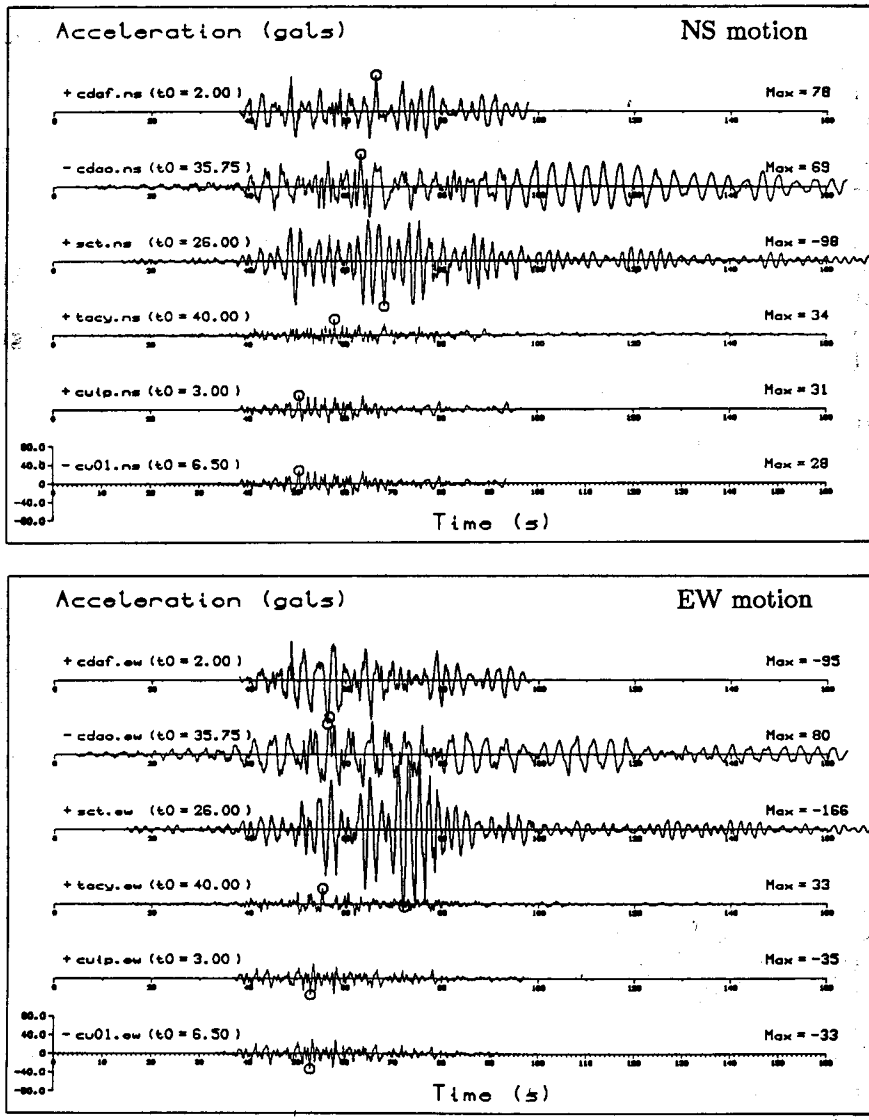


Figure 2 : *Horizontal components of acceleration recorded at stations* CU01, CUIP, TACY *("hills zone"), and* SCT, CDAO and CDAF *("lake-bed zone").*

(Top, a) NS component ; (Bottom, b) EW component.

These - corrected - accelerograms are shifted by a time t0 (the value of which is given for each station), so that the vertical displacements be in phase, as shown and discussed in Campillo et al., 1988.

In that respect, the differences between the records obtained in the lake-bed zone (SCT, CDAO, CDAF in Figure 2), and those obtained in the "hills zone" (TACY, CUIP, CU01) on September 19^{th}, 1985, were not a surprise. (The only surprises came from the size of the earthquake, and from the almost linear behavior of this lacustrine clay, despite the high strain level; this latter observation has been explained by post-earthquake laboratory analyses (Rome and Jaime, 1986), and will no longer be addressed in the present paper, unless to justify the use of linear, viscoelastic models.)

Nevertheless, several intriguing points, listed below, lead us to look for complementary explanations for these huge amplification effects within the Mexico City valley:

a) some characteristics of the strong motion records displayed in Figure 2 cannot be explained with the 1D vertical resonance theory:

- the CDAO time history exhibit a very long duration with an almost rectangular envelope, while 1D models would predict an exponential decay for the last part of the signal (such as in SCT records, for instance).
- the CDAO and CDAF stations, though very near to one another (see Figure 1, or Quaas *et al.*, 1985), exhibit completely different behaviors, especially as to their duration. Although CDAF accelerograph did not work properly on September 19, 1985 (the original record contains many gliches beyond about 60 s, see Quaas *et al.*, 1985), we do think, following Kobayashi *et al.* (1986), that there exist huge differences between CDAO and CDAF, for the following reason: the records obtained from the September 21, 1985 aftershock, during which CDAF worked properly during more than 100 seconds (see figure 4 of Singh *et al.*, 1988) also exhibit a much larger duration at CDAO than at CDAF.

b) the numerous theoretical studies achieved during the last decade, a review of which may be found in Sanchez-Sesma (1987) and Aki (1988), have emphasized the specific effects related to lateral variations of the geological structure, and therefore drawn the attention on the possible inadequacy, or even failure, of 1D models to accurately predict site effects.

c) the global geological structure of Mexico City valley, as outlined in Figure 1, exhibits such lateral variations, within the surficial lacustrine clay layer (Figure 1b) as well as within the underlying "post-Chichinautzin" thick sediments (Figure 1a).

Based on these results and observations, we therefore started a numerical study in order to assess the importance of these possible multi-dimensional site effects in the Mexico City valley, the main results of which are presented in the following sections, after a short and rough description of the geological setting of Mexico City valley. We looked mainly for three kinds of multi-dimensional effects:

- those related with the valley-shape of the underlying thick post-Chichinautzin sediments.
- those related with the *large*-scale variations of the clay layer thickness (*i.e.*, its closure to the East and South of Mexico City).
- those related with the *small*-scale variations of the clay layer thickness.

Although all these results have been obtained with sophisticated numerical codes, we consider that this study is mainly a qualitative one, in that sense that it is intended to describe some effects which may have played a significant role in Mexico City, and to draw the attention on them for future hazard studies. Their quantification, for microzoning purposes for instance, is still premature because of the lack of adequate geotechnical information.

II. Geological setting of Mexico City: from reality to models

As described in Sanchez-Sesma *et al.* (1987), the Mexico City area was, before the Pleistocene, a river valley drained to the South. The series of volcanoes which built up during the Pleistocene and now compose the Sierra Chichinautzin, closed this valley and transformed it in an undrained sedimentary basin. The lake thus formed has progressively dried, leaving behind it eruptive products interbedded with clayey lacustrine deposits, which are less and less consolidated as depth (and age) decreases. The most recent such lacustrine deposits consist of the present-day surficial clay layer, famous for its high water-contents and very low rigidity. The Mexico City valley presents therefore two main geological units overlying the pre-Chichinautzin basement, *i.e.* a thick, consolidated unit, which will be called in the remaining of this paper the "deep sediments", overlied by a thin clay layer with very weak mechanical characteristics.

The geometrical and mechanical characteristics of these "deep sediments" are very poorly known. The "pre-Chichinautzin" topography, displayed on Figure 1a, has been estimated from some scarce borings, and from an interpretation of gravimetric data reported in Sanchez-Sesma *et al.* (1987). It shows the existence of three main basement outcrops (Peñon-Airport to the East, Chapultepec-Tacubaya to the West, and Cerro de la Estrella to the South-East), separated by thick deposits (h > 400 m) corresponding to old canyons oriented NW-SE, EW, and NS, which are between 10 and 15 km wide.

The location of these sediment-filled canyons is probably quite reliable, but the uncertainty on their thickness may be as large as a few hundred meters. The information on their mechanical properties is even worse. Zeevaert (1964) estimates the S velocity just beneath the lacustrine clay layer at about 250 m/s, but this value must rapidly increase with depth: reasonable values lie between 300 to 400 m/s in the upper part and about 1. to 1.5 km/s near the basement. We do not know of any damping measurements, and think reasonable values are between 0.5% and 2%.

The geometrical and mechanical characteristics of the surficial lacustrine clay layer are much better known, from numerous borings and laboratory tests. Although there certainly exist some localized variations in its thickness (as suggested in the compilation by Suarez *et al.*, 1987), it exhibits a clear, regular increase towards the East, as shown in Figure 1b, adapted from Sanchez-Sesma *et al.* (1987).

It may be pointed out that, in the most part of the damaged area, the clay thickness is larger than 30 m and smaller than 60m.

The mechanical properties of this clay have been thoroughly investigated, before and after the quake, by many authors . They exhibit a large variability, in connection with the water contents: the S velocity ranges from as low as 30 m/s to 150 m/s (for the surficial, unconsolidated, water-saturated clay only), and the density between 1.2 and 1.6 g/cm3. As to the damping, it was generally thought, before the quake, to be about 5% for a strain level of 0.2 to 0.5 % (that actually experienced during the main shock), but the post-earthquake measurements (Romo and Jaime, 1986) suggest an almost linear behavior up to this strain level (in agreement with strong-motion observations, see Singh *et al.*, 1988), and, therefore, a much lower damping, about 2%.

These uncertainties and variabilities make it very uneasy to construct a relevant model in order to obtain reliable quantitative estimates of the amplification effects. Nevertheless, as our main concern here is a qualitative understanding of the physics of site effects in Mexico City, we believe that a "rude" model taking into account the gross characteristics (geometrical and mechanical) of both the deep sediments and the surficial clay layer is appropriate.

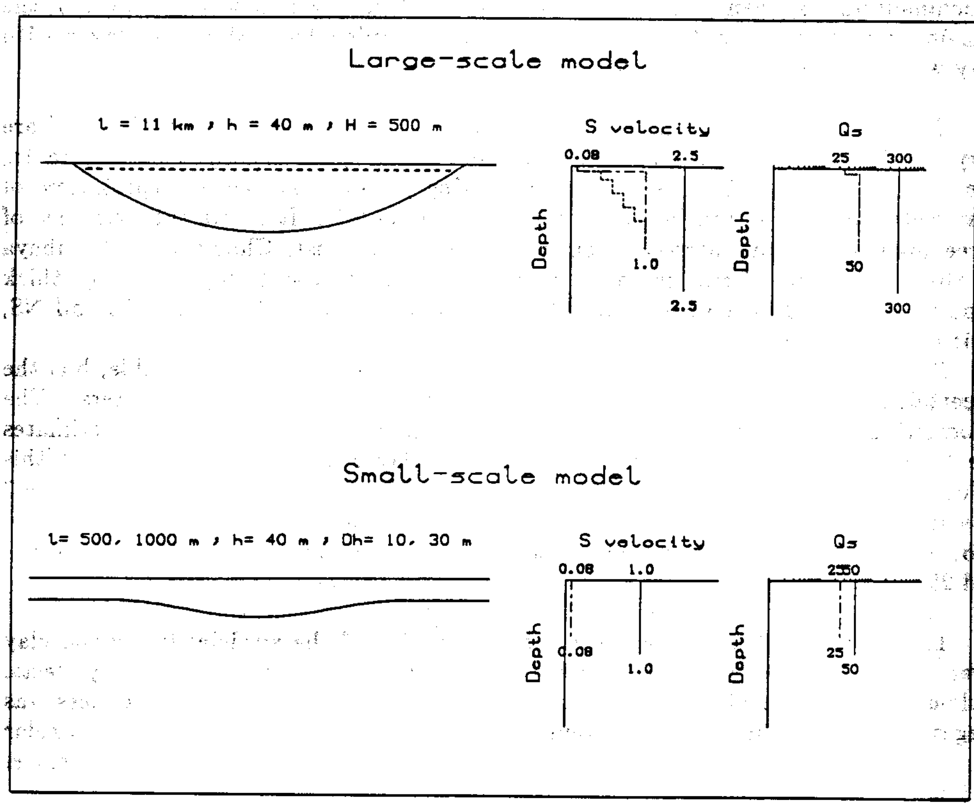


Figure 3 : *Geometrical and mechanical characteristics of the large-scale (top, a) and small-scale (bottom, b) models considered in this study. The vertical scale has been extended four times for the large-scale model.*

We therefore chose as our basic model the one shown in Figure 3. Its shape (a 11 km wide, 500 m deep parabolic arc) is approximately representative of the three cross-sections Chapultepec-Peñon, Peñon-Estrella and Chapultepec-Estrella (see Figure 1a). Moreover, as the clay layer exhibits some localized, small-scale thickness variations, we also considered a second series of models, with much smaller lateral extent (typically 1 km), and ignoring the basement (bottom of Figure 3). The mechanical characteristics of the surficial clay layer correspond to an average of their measured properties: thickness = 40 m; velocity = 80 m/s; density = 1.5 g/cm3; damping = 2% (Q = 25). As to deep sediments, we chose two extreme models, which, in our opinion, should illustrate their possible maximum and minimum effects; we checked, however, the reliability of our qualitative results through a study of their sensitivity to some critical parameters such as maximum thickness, velocity and damping values; this sensitivity study has been reported elsewhere (Bard,1987), and will not, therefore, be reproduced here.

We considered only (linear) 2D models, though the contours shown in Figure 1 suggest that 3D models would be better suited: as we are concerned here only with qualitative phenomena, we think that 2D models are suitable for that aim, at least in a first stage. We considered only vertically incident SH waves: the computational cost would have been prohibitive for other (P, SV or Lg) incident wavefields, and the results presented in Campillo *et al.* (1988) show that there are no basic differences in the response to oblique and vertical SH waves, and to Lg waves. We used, for our computations, the modified version of the Aki-Larner method presented in Bard and Gariel (1986), except in one case (Figure 13), for which the discrete wavenumber method of Campillo and Bouchon (1985) was applied.

III. Effects of the deep sediments

In order to isolate the effects due only to these "deep sediments", we considered the generic model shown at the bottom of Figure 4. The geometrical shape is the same as in Figure 3, the only difference is that the clay layer is ignored.

Because of the drastic lack of information about these deep deposits, we performed numerous computations with different maximum thickness (ranging from 300 to 700 m), different velocity models (from 400 to 1000 m/s in the sediments, with or without vertical gradient, and from 2000 to 2800 m/s in the basement), and different damping values (1 and 2 %), as presented in Bard (1987). Nevertheless, for conciseness purposes, we present here the results obtained with two extreme models, differing only by their velocity and damping values: the reader is asked to trust that the effects obtained with other intermediate models are qualitatively similar and quantitatively intermediate.

Model DS1 is intended to estimate the maximum possible effects, because of its large velocity gradient and low damping, while model DS2 will estimate minimum effects (small impedance contrast, larger damping). For both models, we also made, for each site, 1D computations (using Thomson-Haskell formulation), considering the local sediment thickness.

The effects corresponding to these models are illustrated in Figure 4, in both

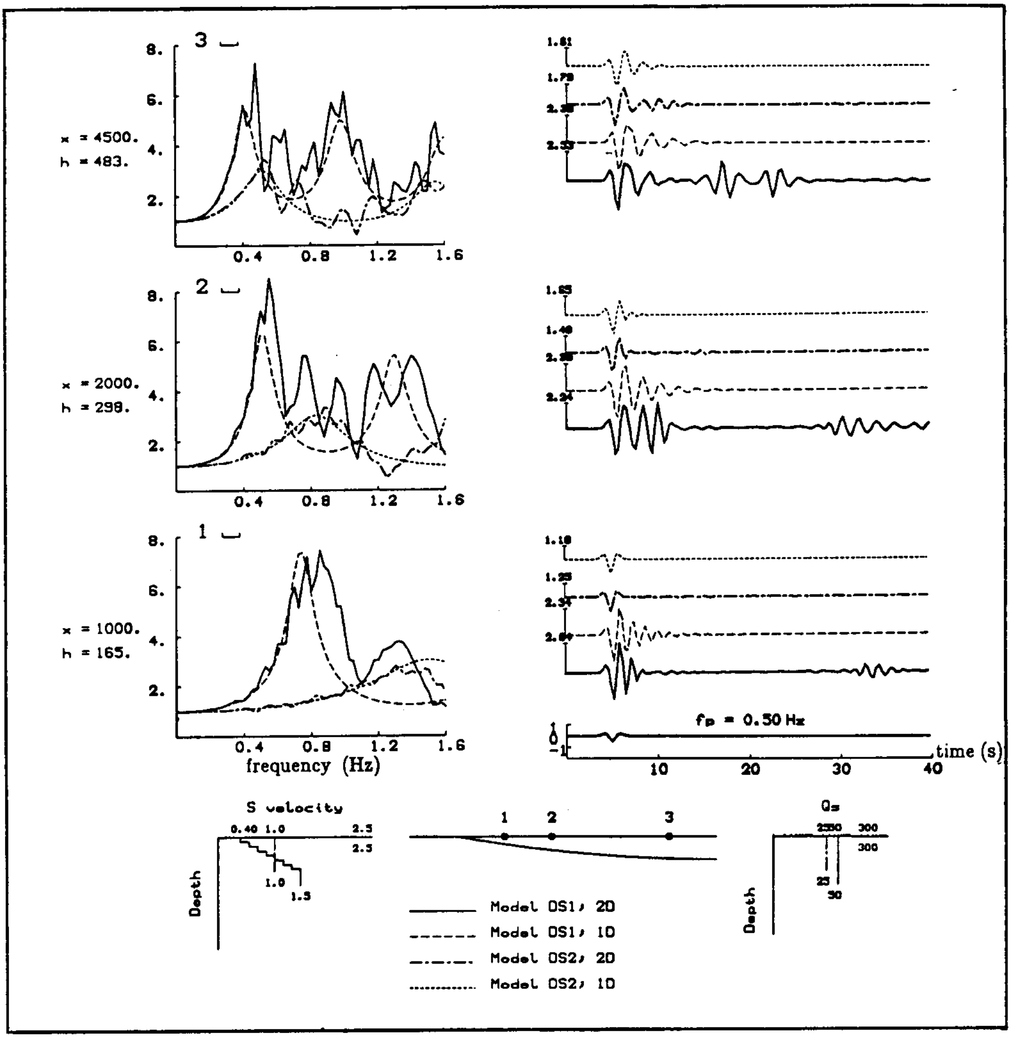


Figure 4 : *Effects of the deep sediments alone at three surface sites. These effects have been computed, in both 2D (thick lines) and 1D (thin lines) cases, with the two velocity models, DS1 and DS2, shown at bottom left.*

(Left, a): Fourier transfer functions at three surface sites. The horizontal axis is the frequency axis (labeled in Hz), and the vertical one represents the amplification with respect to a suface rock site (i.e., the free-surface effect has been removed). In order to provide a better readibility, the Fourier transfer functions are smoothed with a triangular runnig window having a 0.1 Hz width (represented by the length of the small segments on top of each frame).

(Right, b): Time domain synthetics in response to an incident Ricker wavelet having a fp=0.5 Hz central frequency (bottom trace), at the same three sites.

For each of the three sites, the distance to valley edge (x) and the local sediment thickness (h) are given.

the frequency and time domains, through the Fourier transfer functions and the response to an incident Ricker wavelet at three different surface locations.

As expected, the effects in the time domain are an amplification and resonance of the primary arrival (similar in 1D and 2D computations), and the lateral propagation of surface (Love) waves generated on the edges (not predicted by 1D models). These effects are much larger for model DS1, especially as far as surface waves are concerned. The phase and group velocities of these surface waves are very sensitive to the velocity profile within the sediments (about 1 km/s for DS2 model, and 500 m/s for DS1 model), but the delay between the primary arrival and the surface wave never exceeds 30 s; on the other hand, the spatial amplitude decay of the surface waves is controlled by the velocity profile and the damping, but in the "worst" case (model DS1), the amplitude ratio between the primary arrival and the Love wave is about 3 for sites located on the edge of the valley. These two numerical results must be compared with the CDAO record, where a *second* wave is clearly seen about *60 s* after the direct wave, with a *comparable* amplitude.

In the frequency domain, though there are large differences between the 2D models, the Fourier transfer functions show that the deep sediments are responsible for a spectral amplification ranging between 3 and 7, for frequencies ranging between 0.3 and 1.2 Hz, depending on the site location and the velocity model. These values are consistent with those of about 5 found in our companion paper (Campillo *et al.*, 1988) regarding the response to incident Lg waves. Moreover, the comparison with 1D results show that the effects of lateral variations are large, especially in case of velocity gradient.

Although these results are only partial since they do not take into account the coupling with the surficial layer, the following conclusions may be pointed out:

- the effects of the deep sediments are significant, especially as they occur in the frequency range which has proved to be critical in Mexico City: 0.3 to 1.5 Hz.

- the amplitude of these effects is clearly related to the velocity (and damping) law within the sediments, as expected from simple 1D models.

- the geometrical (2D) effects are important in two cases: when there exist a steep velocity gradient (model "DS1"), or when the maximum sediment thickness reaches or excesses about 1 km (not shown here). In both cases, the 2D geometry then affects mainly the motion duration. Further studies therefore require careful surveys of the actual pre-Chichinautzin geometry and of the actual velocity law.

Comparing these results with the strong motion records shown in Figure 2 leads to two main observations:

- the long duration, large amplitude record obtained at CDAO station might be explained by the late arrival of a surface wave propagating in the deep sediments if, and only if, (a) the surficial velocity in these sediments is much lower than 400 m/s (about twice lower), or if the valley width is much longer (about twice longer), and (b) if the damping is much lower (so that the surface wave amplitude be comparable to that of the direct arrival). These 2 conditions are not likely to be simultaneously met, and furthermore this surface wave should then be clearly seen in SCT record too. We therefore do not think that the CDAO record might be explained by the arrival of waves generated at Peñon or Chapultepec outcrops, and subsequently propagating in the deep sediments.

- According to Figure 1a, CUIP and CU01 stations are located on a lava flow overlying approximately 300m of "deep sediments", while TACY station is located near Chapultepec on a much smaller thickness (< 100 m) of "deep sediments". Therefore, according to the present results, they should have significantly different low frequency responses: the instrumental spectral ratios displayed in Figure 5 do exhibit such a relative amplification (between 2 and 3) at CU stations in the 0.3 - 0.7 Hz frequency range. The strong-motion observations thus support our conclusion that these "deep sediments" have an amplification effect, and the rather small observed values of the CU/TACY spectral ratios favor the "minimum effects" model, DS2, which will therefore be somewhat emphasized in the remaining of this paper. Nevertheless, it must be once again emphasized definite conclusions regarding the "best" model cannot be reached without a careful geophysical survey aiming at measuring the mechanical and geometrical characteristics of these deep sediments.

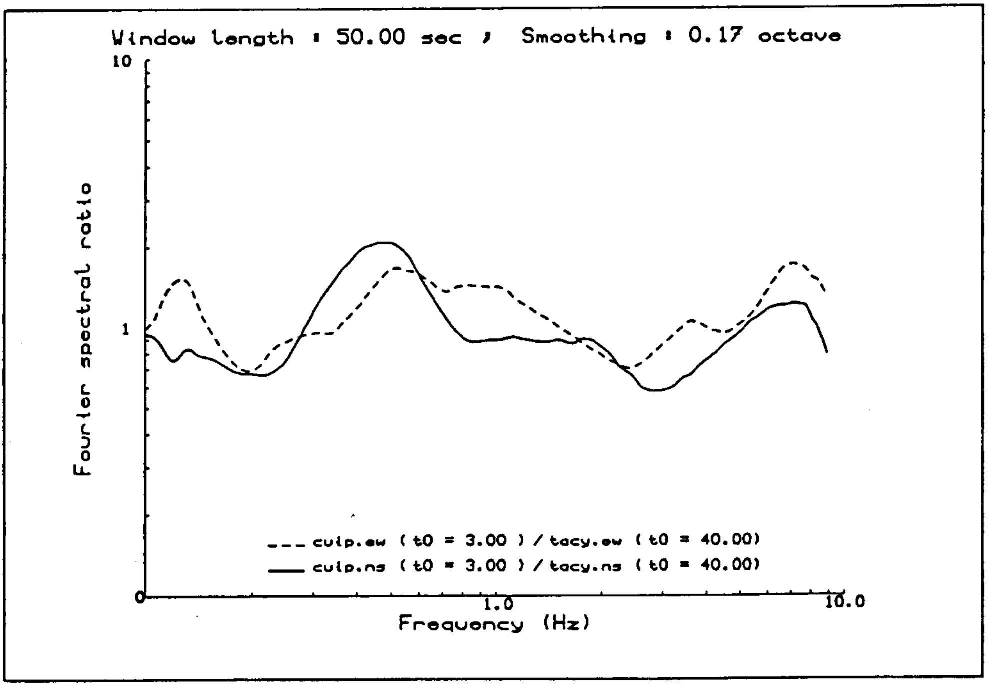


Figure 5 : *Spectral ratios between* CUIP *and* TACY *strong motion records. These spectral ratios have been computed from the Fourier spectra of the records shown in Figure 2, windowed between $t = 40$ s and $t = 90$ s, and smoothed with a triangular window having a 1/3 octave total width.*

IV. Effects due the clay layer

In the first subsection, we assume - though it is not true in Figure 1b - that the clay layer is a thin, extremely wide horizontal plane layer, just closed on each side, over a few hundred meters, by a parabolic arc: Mexico City has been compared to a "bowl of jelly", and this simple model is merely intended to investigate whether the geometrical term "bowl" is appropriate or not ("jelly" giving an adequate image of the mechanical characteristics of the clay). The model considered in this subsection is the model depicted in Figure 3a.

The second subsection is devoted to a study of the effects of localized thickness variations within the clay layer, and therefore considers models of much smaller lateral extent (about 1km). The model considered in this subsection is the model depicted in Figure 3b.

IV.1 - Effects of large-scale thickness variations

a - *Effects related only to the lateral finiteness of the clay layer*

In this first stage, we ignore the existence of the Pre-Chichinautzin basement, and therefore consider an 11 km wide, 40 m thick clay layer overlying a homogeneous half-space having the characteristics of the deep sediments (model DS2).

The Fourier transfer functions obtained with such a model are displayed in Figure 6 for some surface locations, selected near the very edge or in the central part of the valley, together with the results obtained with 1D models. It clearly shows that, despite the rather low damping of the clay (2%), and whatever the velocity model of the deep sediments, multidimensional effects take place only near the edge: for such a model, 1D approximations are therefore very good in the whole central part of the valley, and the term "bowl" is inappropriate.

The physical explanation of this observation appears clearly on the time domain synthetics shown in Figure 7: high amplitude surface waves are generated on valley edge but, because of their huge dispersion and their very low group velocity (as small as 20 m/s), they cannot propagate over long distances: their amplitude after a 500m travel (between sites located at x=500 m and x=1000 m) is reduced by about 70 %. These observations remain valid whatever the velocity in the underlying deep sediments, though there are obviously some variations in the phase and group velocities.

A main outcome of the previous section was, however, the importance of multidimensional effects in the deep sediments. The question then arises of the coupling between the surficial clay layer and the deep sediments: this question is addressed in the next paragraph.

b - *Large-scale combined effects of surficial clay and deep sediments*

We consider here, at last, the "complete" model of Figure 3, which takes into account simultaneously the deep sediments and the surficial clay layer. We will focus our discussion on the results obtained with "DS2" velocity law in the deep

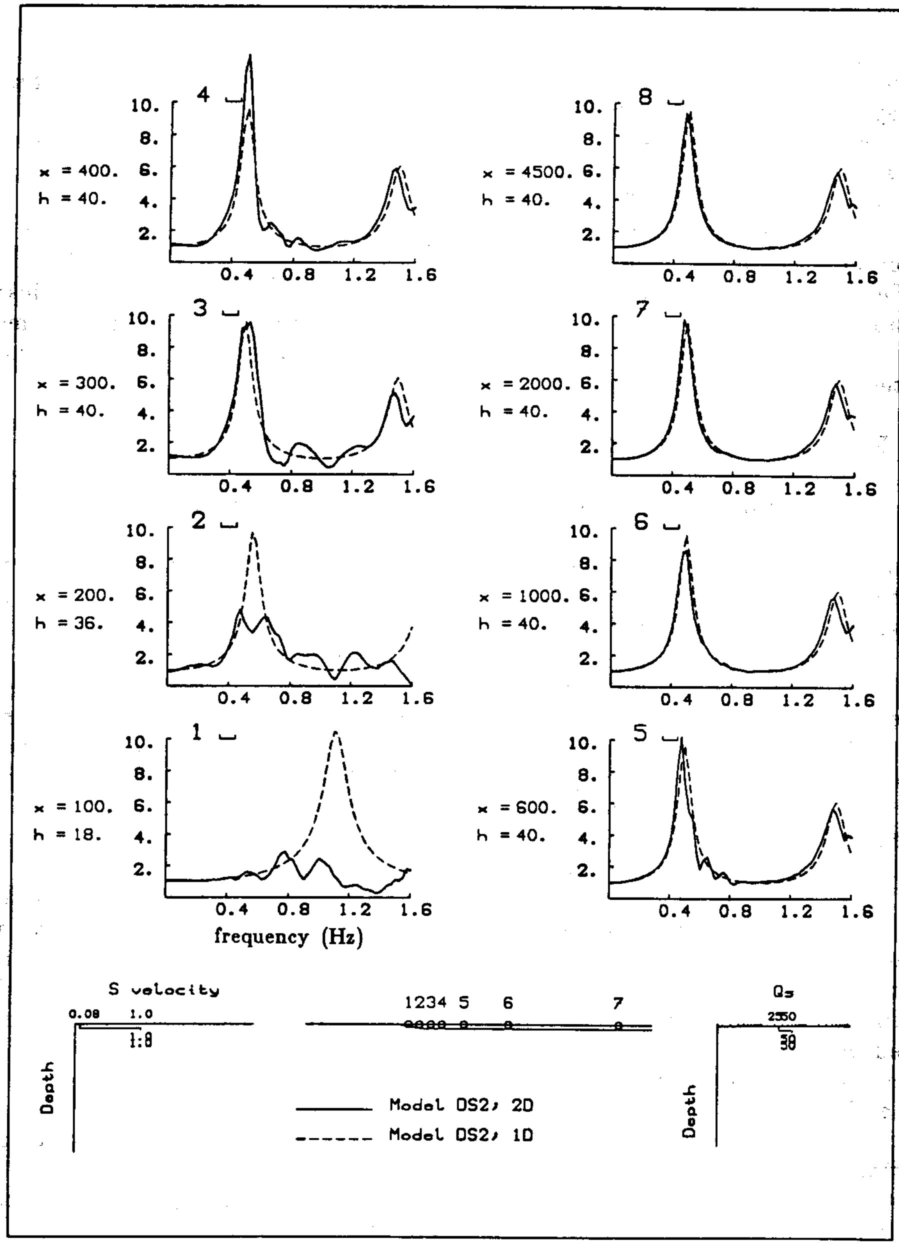
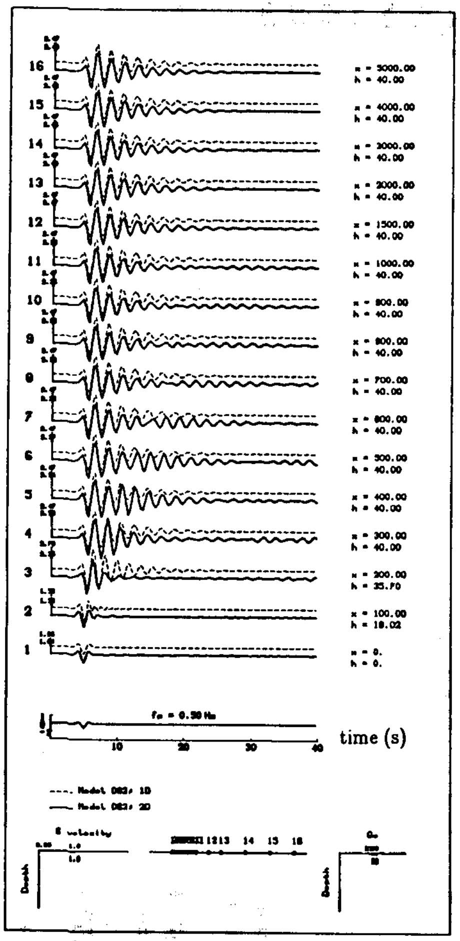
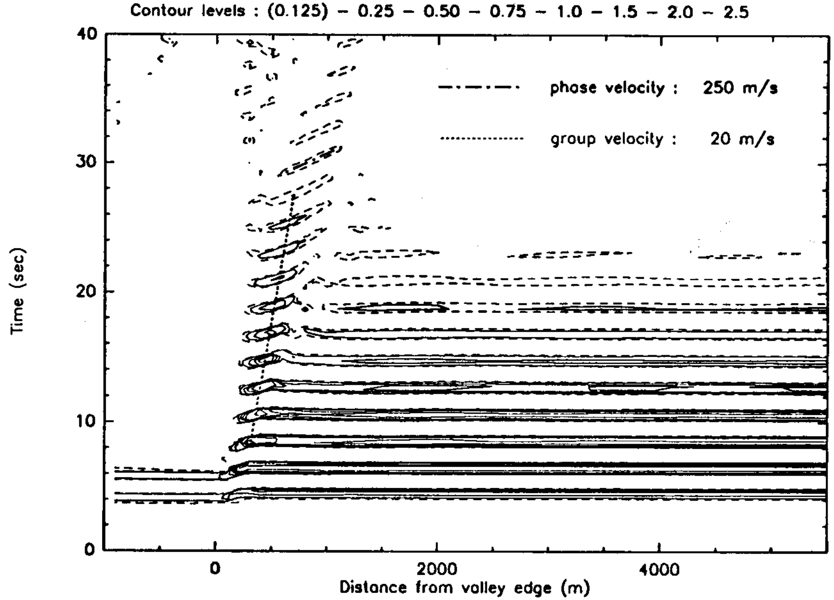


Figure 6 : *Large-scale effects due only to the clay layer, in the frequency domain. Smoothed Fourier transfer functions at 8 surface sites, located from the very edge (# 1 through 4) to valley central part (# 8). x and h have the same meaning as in Figure 4, except for h which represents here the clay thickness. Both 2D (solid line) and 1D (dashed line) results are shown. See Figure 4 caption for further details.*





(b) Same as (a) for the 2D model only, except that the synthetics are now shown for 65 equally spaced sites ($dx = 100$ m), from valley center (right) to valley edge (left), and contoured at the amplitude levels detailed on the figure. Such an imaging points out very clearly the very low group velocity of the surface waves generated on the edge, and allows a measurement of both their phase and group velocities (as indicated in the figure), and of their spatial amplitude decay.

(a) Time domain synthetics in response to an incident Ricker wavelet having a $fp = 0.5$ Hz central frequency (bottom trace), for the two same models (1D and 2D) as in Figure 6, and for 16 unequally spaced sites.

Figure 7 : *Large-scale effects due only to the clay layer, in the time domain.*

sediments, but we will also mention shortly the results obtained with the alternate velocity law, "DS1".

The main features of the response of such "complete" large-scale models are the following:

i) the main differences between 1D and 2D models still occur only on the edges, *i.e.* within about 1 km from the vanishing of the surficial clay layer, but, at these sites, they are both very large and versatile: on the very edge (x < 300 m), 1D model is very pessimistic (sites 2 and 3 in Figure 8), while at somewhat more distant sites (sites 4 to 6), 1D model proves to be optimistic. At valley center, there are only slight differences between 1D and 2D predictions, although 2D amplification values are generally somewhat larger. This behavior is very similar to the one depicted in Figure 6 for the clay layer alone,and the physical reasons for that are similar: the synthetics in Figure 9 show that local surface waves induced by the 2D geometry are observed only on the edges, because of their very large dispersion and their very low group velocity (about 20 m/s), resulting in a clear increase in signal duration between x = 400 m and x = 1000 m. The overestimation of amplification on very edges by 1D model comes from the fact that it does not take into account the deviation of incoming rays towards valley center; although this pheneomena is extremely sensitive to the actual geometry of the clay - (basment - deep sediments) interface, we think that it might explain the small amplification observed in strong motion records at SXVI station, located exactly on the edge of the clay layer. The slightly larger amplification observed in the frequency domain at valley center in 2D model shows up in the time domain through an increase in signal duration.

The same observations remain valid when the DS1 velocity law is considered for the deep sediments (not shown in Figures 8 to 10). Nevertheless, the lower impedance contrast between the surficial clay and the underlying sediments somewhat lessens the relative importance of clay layer, and the simultaneous higher impedance contrast between basement and top of deep sediments enhances their role, and especially the importance of their 2D (3D) geometry.

ii) Though the respective "one-layer amplifications" found in Figures 4 and 6 depend significantly on the deep sediments velocity law, the overall surficial amplifications computed with the "complete" models are comparable: the Fourier transfer functions displayed in Figure 10 show that the lake-bed surface amplification is mainly controlled by the total impedance contrast between the the very surface deposits and the deep basement (together with the damping of the surficial clay, of course), and has only a weak dependence on the actual velocity law in-between (at least as far as "reasonable" models are considered).

iii) the maximum spectral amplifications are about 80 % larger when the deep structure is taken into account (between 16 and 20, depending on the site location), than what was obtained with the only surficial clay (between 10 and 12, see Figure 6). (This increase in surface amplification due to the deep sediments is, of course, even larger when the velocity at their top is smaller, as in the case of model DS1.) This is, in our opinion, an important result to keep in mind in site effect studies in Mexico City: if one is concerned only with differences between motions at top and

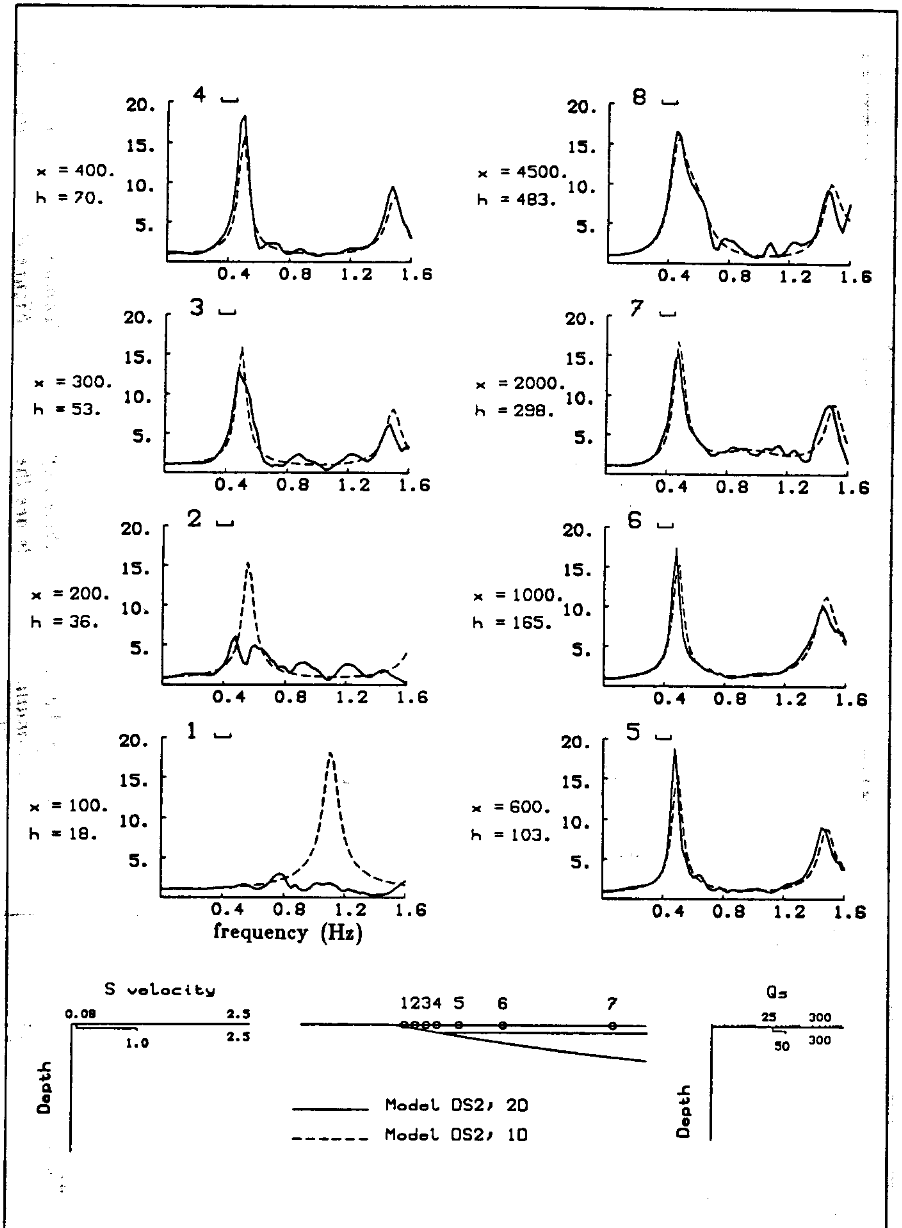
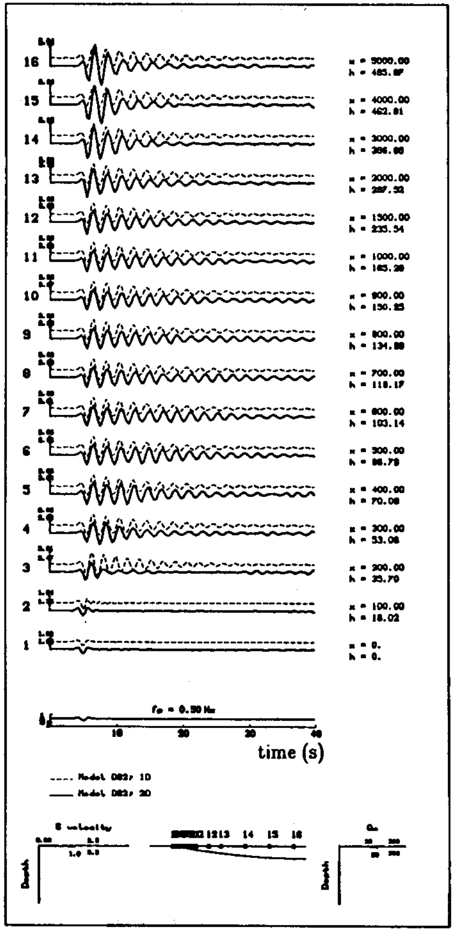


Figure 8 : *Large-scale, combined effects of the "complete" valley model, in the frequency domain. Both the clay layer and the "DS2" deep sediments are taken into account, as explained in the text. See captions of Figure 4 and 6 for further details.*



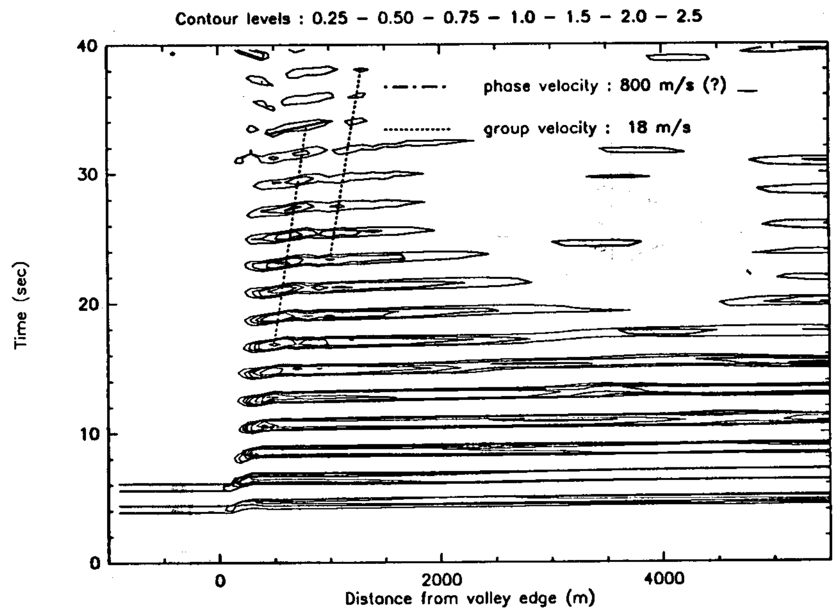


Figure 9 : *Large-scale, combined effects of the "complete" valley model, in the time domain. The models are the same as in Figure 8. See Figure 7 for further details.*

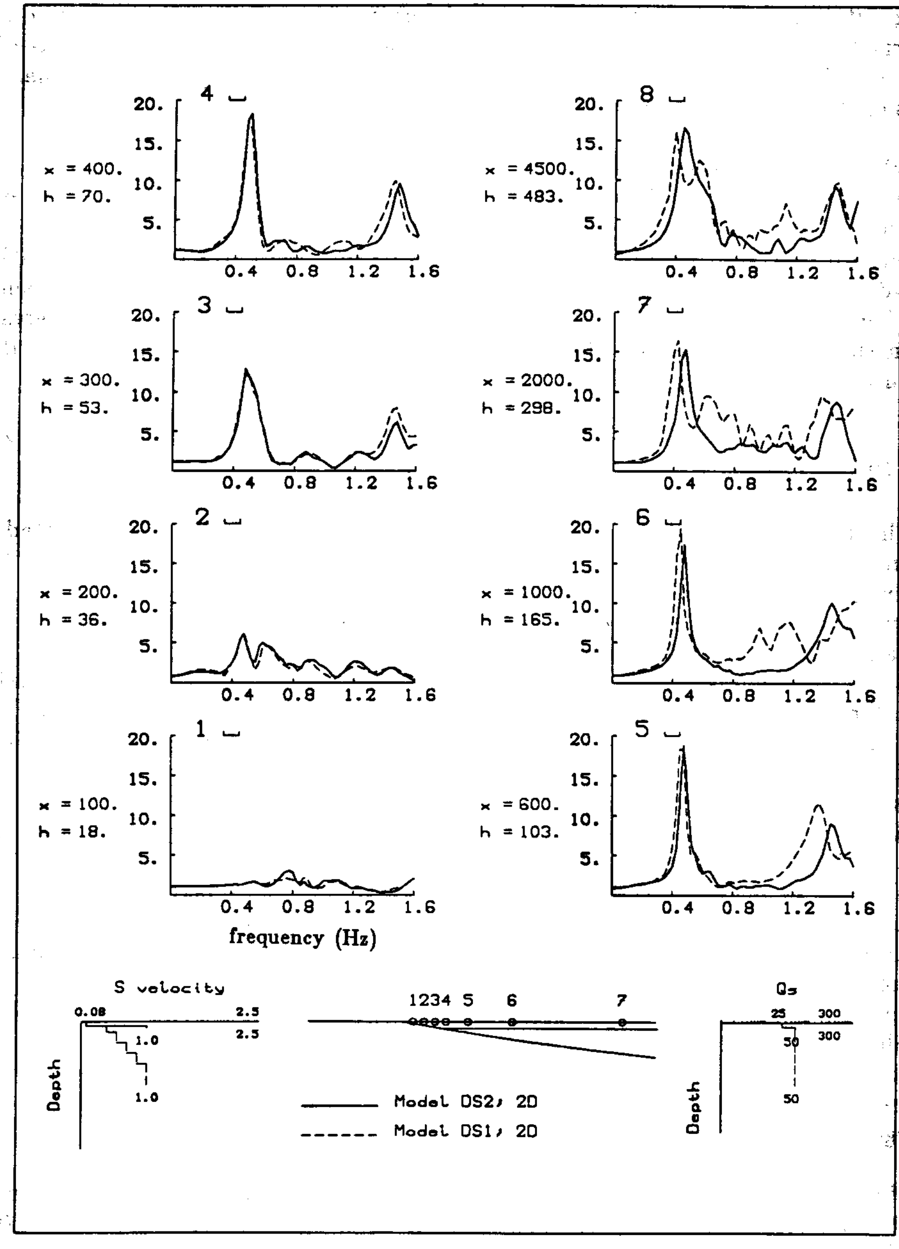


Figure 10 : *Large-scale, combined effects of the "complete" valley model, in the frequency domain: comparison between results obtained with "DS1" (dashed line) and "DS2" (solid line) velocity models. See captions of Figures 4 and 6 for further details.*

bottom of surface layer (in order to design a building foundation for instance), taking into account the only clay layer is probably sufficient; but when one is concerned, for microzoning purposes for instance, with differences between lake-bed sites, and basement outcrop sites such as Chapultepec, Peñon or Estrella, the effects of deep sediments must be accounted for.

iv) Finally, as expected from previous subsections, taking into account the 2D geometry *through these large-scale models* does not allow to explain the huge duration differences between nearby stations CDAO and CDAF (which, in our opinion, are real, see above). As the clay thickness is different at these two stations (58 and 42 m, respectively), we are now going to investigate the effects of small-scale, localized variations in the clay thickness. In this study, as we are interested only in the relative responses of lake-bed sites, we shall no longer consider the deep structure of Mexico City valley.

IV.2 - Effects of small-scale thickness variations in the clay layer.

The model considered in this section is the "clay pocket" model depicted on bottom of Figure 3. The velocity model is the same as in Figures 6 and 7 (the underlying half-space has the characteristics of the "DS2" deep sediments), so that the results presented here may be considered as an upper bound of the expected localized effects, since the velocity contrast is very high in our model.

We chose a sinusoïdal shape for the clay-sediments interface. The geometrical parameters of our model are the thickness increase Dh and the width l of this localized clay pocket: we consider both small (Dh = 10 m, l = 1000 m) and large variations (Dh = 30 m, l = 500 m). It is worth to mention, however, that the results shown below are also valid for other geometrical configurations, provided that a consistent scale is applied on the relevant quantities (length, velocity, and time - or frequency): for instance, results shown in Figure 12 are also valid for a 250 m wide, 15 m deep pocket in an otherwise 20 m thick clay layer having a S velocity of 40 m/s, overlying a half-space with a S velocity of 500 m/s. We computed the response of such pockets to vertically incident SH waves, and to a SH point-source located at a distance of 5 km and a 300 m depth in the case of the deep pocket (this latter case, for which the discrete wave number method of Campillo and Bouchon (1985) was used, was considered as being a rough approximation of the lateral waves propagating in the underlying deep sediments). The results obtained in case of small variations are shown in Figure 11, and those for large variations in Figures 12 and 13.

The synthetics in Figure 11 show that surface motion is sensitive even to smooth thickness variations (the maximum interface slope is 1.8 ° for Dh = 10 m and l=1000 m), which give rise to local surface waves propagating towards increasing thicknesses, with a large dispersion and a small group velocity. As a consequence, the surface amplification is larger than expected with simple 1D models at "pocket" center (site 6), while the duration is significantly increased in thicker areas; this results in significant differential motion over short distances, which may have important engineering consequences.

(a) Smoothed Fourier transfer functions at 12 surface sites located from one edge of the "clay pocket" to the other.

(b) Synthetic seismograms, at the same 12 sites, in response to an incident Ricker wavelet having a fp = 0.5 Hz central frequency (bottom trace)

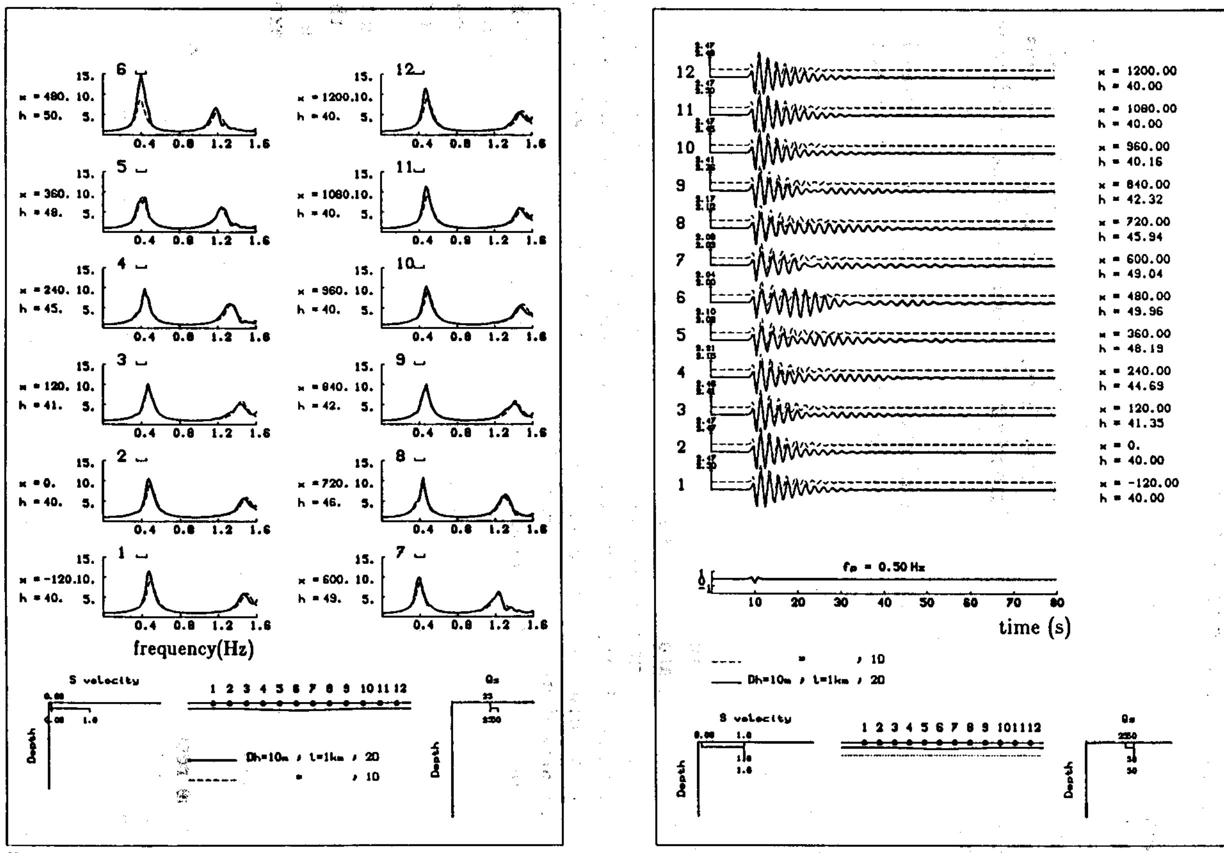


Figure 11 : *Small-scale effects of a small, localized increase in the clay layer thickness, and comparison between the results given by 2D (solid line) and 1D (dashed line) models.*

A small parameter study, reported in Bard (1987), showed that the amplitude of these surface waves, and the correlative supplementary amplification, increases with increasing Dh or decreasing l, and also, of course, with increasing velocity contrast and decreasing damping. In our present model, the supplementary amplification reaches 70 % at site 6.

When the clay pocket is very deep, as in Figures 12 and 13, these geometrical effects become extremely important, whatever the incident wavefield: the increase in amplification reaches 100 % in the frequency domain at "pocket" center (where one may also notice the -obviously expected - low-frequency shift), significant differential motion are showing up over distances as short as a few tens of meters, and the duration increase is so important that our 80 s time window is not long enough...

The effects of local decreases of clay thickness, though not investigated here, may be inferred from the present results: the defocusing of seismic energy over such buried "bumps" will result in a local deamplification, and will cause the outward propagation of highly dispersed, rapidly decaying, surface waves: in that case, the hazard is lower over the bump, and higher on the edges, as it has been clearly shown also in Campillo *et al.* (1988).

Though the detail of the response of such pockets is somewhat different depending on the nature of the incident wavefield (compare Figures 12 and 13), the above phenomena may be considered as very robust, and are therefore likely to have occured in Mexico City during the Guerrero-Michoacan earthquake. It is thus worthwhile to discuss these results in the light of the usual engineering practice, and of the actual strong motion records:

- the inadequacy of 1D models to provide satisfactory predictions of the actual response of such clay pockets is obvious in both Fourier transfer functions and time domain synthetics of Figure 11 and 12 (site 6 on Figure 12, sites 4 through 8 on Figure 12), and this result should be highly emphasized amongst the engineering community, where the use of 2D methods is still occasional.
- on the other hand, the phenomena described in this section are not able to explain the differences between CDAO and CDAF stations (which, we think, are real and not due only to instrument malfunction): despite the huge duration increase at sites 5 through 8 in Figure 12, the computed signals do not exhibit any clear late arrival as observed on CDAO record (Figure 2).

These results thus draw the attention on the importance of a careful survey of the geometrical characteristics of the clay layer in the whole lake-bed zone. Moreover, this extreme sensitivity of the surface motion, in the lake-bed zone, to even very smooth geometrical irregularities, emphasizes the need for an investigation of the effects of other kinds of local heterogeneities: rheological ones (such as those due to changes in the clay water contents, or to local consolidation under buildings), which are very important as indicated by S wave velocity measurements, and also those related with the geometrical characteristics of the thin, much more rigid fill which overlies the clay layer in many places.

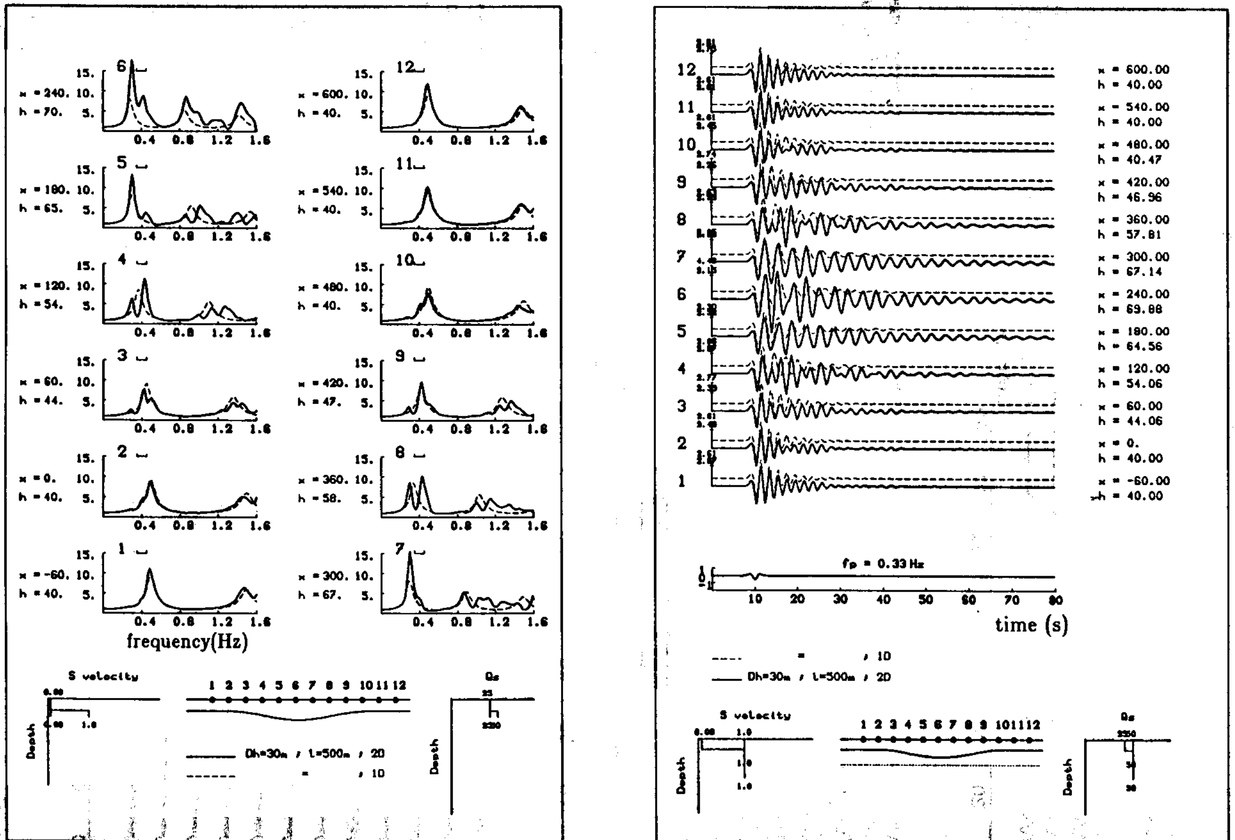
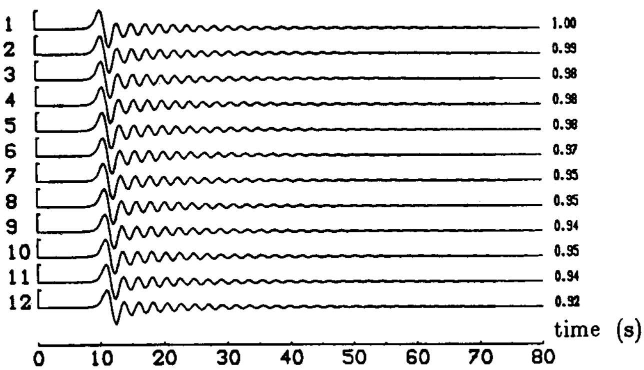
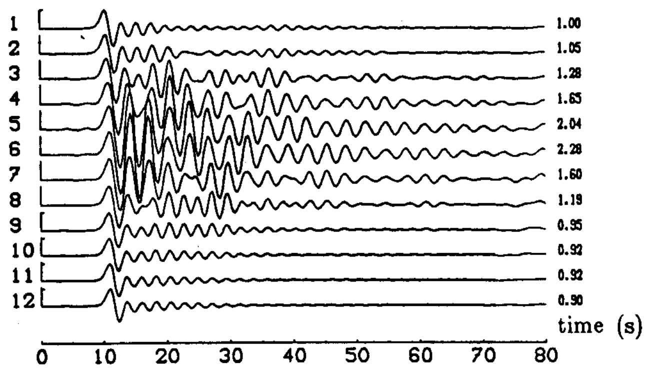


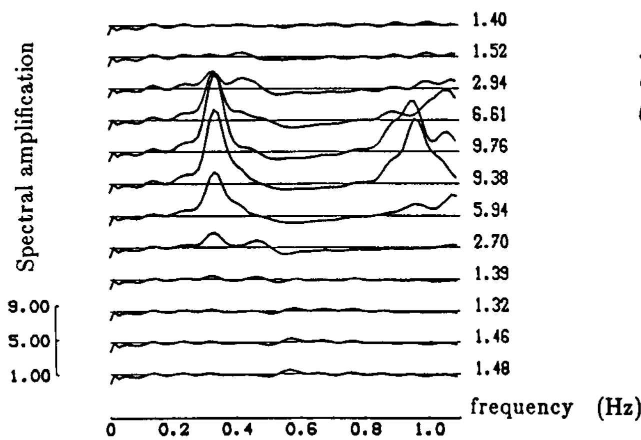
Figure 12 : *Small-scale effects of a large, localized increase in the clay layer thickness, and comparison between the results given by 2D (solid line) and 1D (dashed line) models. Similar to Figure 11, but for Dh = 30 m and l = 500 m.*



(a) Synthetic seismograms computed for a flat clay layer, at the same 12 surface sites as in Figure 12.



(b) Synthetic seismograms, at the same 12 sites, obtained when the clay pocket is taken into account.



(c) Spectral ratios of signals shown in (b) with respect to the corresponding signals shown in (a).

Figure 13 : *Small-scale effects of a large, localized tickness increase in the clay layer. The "pocket" model is the same as in Figure 12, but the incident wavefield is now a SH point source located 5 km apart form the pocket, at a 300 m depth.*

V. Summary and conclusions

The large-scale and small-scale amplification effects in the Mexico City valley, related to both the surficial clay layer and the underlying thick sediments, have been investigated with 2D models and compared with the results of simple 1D models, both models considering only a linear behavior.

The geometrical characteristics of the large-scale models were chosen so as to be grossly representative of the cross-sections linking the three major basment outcrops in Mexico City: Chapultepec, Peñon and Estrella (or at least of their current estimation...). The lacustrine clay unit was modelled as a thin (h=40 m), perfectly horizontal layer; the deep sediments - basement interface was modelled as a parabolic arc, having a maximum thickness of 500 m. The lack of information as to the mechanical characteristics of these deep sediments was tentatively overcome by the consideration of two "extreme" velocity laws. The small-scale models consider local (*i.e.* over distances of about 500 m) increases in the thickness of an otherwise flat clay layer, overlying a half-space having the mechanical characteristics of the deep sediments. The computations were made with Thomson-Haskell, Aki-Larner and discrete wavenumber methods. As partial conclusions and discussions have been exposed at the end of each main section, we will mention here only the main outcomes of this investigation.

The deep sediments have been shown to be responsible, on their own, for an amplification ranging between 3 and 7, a significant part of which (about 30%) is due to 2D effects in case of a vertical velocity gradient. This result is consistent with the relative amplification around 0.5 Hz at CU stations with respect to Tacubaya. The amplitude of these deep sediments effects emphasize the need for experimental surveys of both their geometrical and mechanical characteristics, so as to better constrain the models: the results obtained in the present study indicate that the prior aim of such surveys should be, at least in a first stage, to estimate the maximum thickness (is it limited to a few hundred meters, or does it reach 1, or even 2 km ?), and their velocity law (what is their velocity just beneath the lacustrine clay unit, and how steep is the vertical gradient ?). The total response in the central part of the valley has been shown, however, to depend only weakly on the sediments velocity law.

The amplification due to the clay layer is much larger (around 10 in an average), and the corresponding 2D effects have very peculiar characteristics. On the one hand, the local surface waves generated on any lateral heterogeneity have very low group velocities (below 20 m/s) and, even in case of rather low damping (2 %), they are rapidly vanishing (over distances shorter than 1 km): the motion at a given surface site is therefore affected only by lateral heterogeneities lying within a radius smaller than 1 km. On the other hand, these *local* 2D effects may be extremely large, either on the edges of the lake-bed zone (they induce a deamplification with respect to 1D predictions on the very edges, and an overamplification characterized by a duration increase at somewhat more inward sites), or over localized thicker areas (where local surface waves are trapped in, resulting in an overamplification reaching up to 100 %).

None of the 2D models considered in this study could provide, however, a satisfactory explanation for the very long duration observed at CDAO station. We think the correct explanation is connected with the simultaneous rapid changes in clay *and* sediments thickness in the Central de Abastos area (see Figure 1), but modelling it requires (i) a more detailed information about the actual subsoil structure in this area, and (ii) more sophisticated models together with a large computational time.

The main engineering consequences of these results are twofold: (i) microzoning studies in Mexico City should take into account the effects of deep sediments (the computed amplification changes by about 80 % whether they are accounted for or not), and (ii) as the surface motion in the lake-bed zone is extremely sensitive to local heterogeneities, 1D models are probably inappropriate in many parts of Mexico City. Nevertheless, as it will be extremely difficult and expensive to obtain a reliable, very detailed mapping of the whole Mexico City's subsoil, we think that, in the present situation, the practical utility for microzoning purposes of deterministic 2D (3D) models such as those used in the present study, is limited to a qualitative investigation of the various possible effects, and to a quantitative estimation of their lower and upper bounds. This is, however, a challenging aim.

Acknowledgements

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