Influence of small lateral variations of a soft surficial layer on seismic ground motion

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We investigate the effects that lateral variations in thickness of very soft surficial deposits have on seismic motions. We find that smooth geometrical irregularities can be associated with strong effects of local amplification of the surface motion and with large increase of the duration of the signals. These phenomena can be invoked to explain the pronounced spatial variability of damages observed in Mexico City. The theoretical study indicates that the amplitude and duration of the motion can change drastically at two close locations. The map of observed damages shows that the maximum destruction occurred in zones where the surficial deposits exhibit lateral variations in thickness.

INTRODUCTION

The huge damages suffered by Mexico City during the 1985 Michoacán earthquakes are surprising if one considers the large epicentral distance of the event (350–400 km). Two of the most striking aspects of the damages are, first, that most of the heavy damages (including collapses) concern buildings of 8–12 storeys, suggesting a predominant period of the shaking of about 2 sec, and second, the very different amplitudes of the motion at different locations in the city. Because most of the damage occurred in the zone covered by soft lacustrine deposits, we are led to identify this surficial layer as a predominant cause of strong amplification of ground motion.

The distribution of damage and strong-motion records suggest that the amplitudes and duration of the ground motion changed rapidly from one location to another. This is illustrated by the records obtained at the two stations Central de Abastos Frigorífico, CDAF, and Central de Abastos Oficina, CDAO[8]. These two stations are located 0.8 km apart. The depth of alluvium is about 45 m beneath CDAF and about 57 m under CDAO[11]. These two records show strong differences of amplitude and duration the period range between 2 and 4 seconds (Fig. 1). Both stations are located far from the edge of the valley. Then, only local heterogeneity can be invoked to explain their large discrepancy. It is the aim of this work to investigate theoretically if this hypothesis is suited, given the known features of the structure and mechanical characteristics of Mexico City basin, to explain damage distribution.

SOIL CONDITIONS IN MEXICO CITY

For a long time soil conditions in Mexico City have been studied by Mexican engineers[10]. Following Suárez *et al.*[12], we shall consider a simplified overview of the structure beneath the city. This can be regarded as a deep

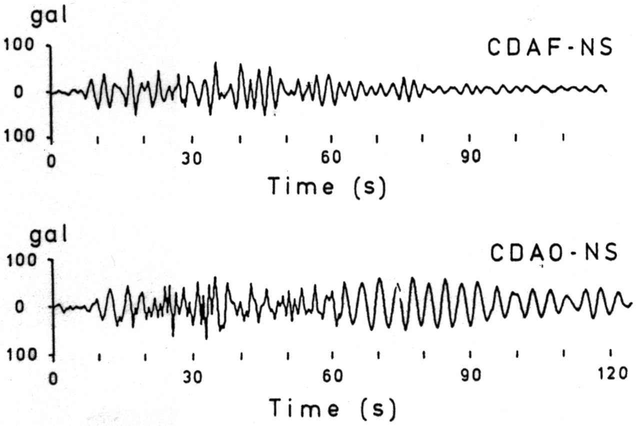

Fig. 1 NS component of the acceleration records at stations CDAO and CDAF in Mexico City during the September 19, 1985 Michoacán earthquake; after Kobayashi et al.[7]

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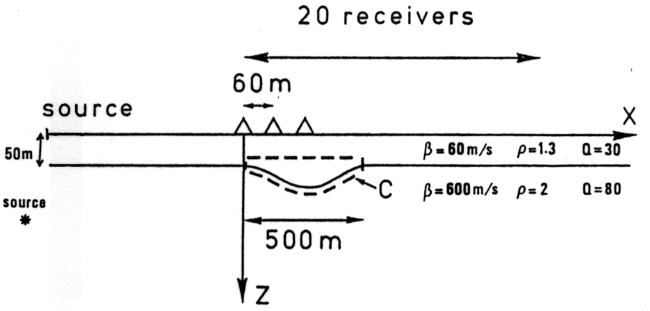

Fig. 2 Geometry of the problem. C indicates the boundary along which the numerical treatment is applied. Material properties shown for each layer are: β=shear wave velocity (m/s), ρ=mass density (g/cc), and Q=quality factor which includes the effects of attenuation

basin (the pre-Chichinautzin layer) covered by very soft clay. The depth of the pre-Chichinautzin layer ranges between 100 m at the foot of the Chapultepec and Peñón hills and more than 700 m in the southeastern part of the city. The velocity of shear waves in this layer ranges around 600 m/sec. The clay layer is 30 to 60 m thick with small-scale variations probably due to water erosion. The shear velocity in this layer lies between 30 and 70 m/sec. Presence of interbedded layers of volcanic materials strongly complicates this scheme. Moreover, the surficial deposits exhibit strong attenuation.

In order to address the problem of the spatial variability of the amplitude and duration of strong ground motion, we will limit our investigation to the effect of lateral variation of thickness of a surficial layer of very low velocity. In the case of Mexico City, the extent of the basin (more than 10 km) and the very low velocity of the upper layer (less than 60 m/sec) indicate that a surface wave guided in this layer cannot be involved in two- or three-dimensional effects of global resonance of the valley, as pointed out by Ohta *et al.*[9] Nevertheless, guided waves can be trapped in the deep basin and thus can be associated with lateral focusing phenomena[1]. In this study we will consider those waves which propagate close to the horizontal direction as an input motion on the very surficial structure studied.

COMPUTATION METHOD

The configuration of interest is shown in Fig. 2. Lateral variations consist of a smooth cosine-shaped change of depth of the interface between a half-space whose characteristics are chosen to represent the deep basin beneath Mexico City, and a surficial layer corresponding to the clay layer. The incident field is given by the radiation of a SH-source at a distance of 5000 m and a depth of 300 m. This is a rough representation of the scattered and guided waves in the deep basin.

The numerical simulation uses a boundary method associated with the discrete wavenumber decomposition of the wavefields[2,5]. This technique consists of representing the actual model as a reference flat layered medium with a local irregularity, identified by contour C in Fig. 2. The solution must satisfy the wave equation for two-dimensional antiplane shear motion, and the conditions of continuity of displacement and traction along the boundary C:

$$u^{(1)}=u^{(2)},$$

$$\mu^{(1)}\left[n_x\frac{\partial u^{(1)}}{\partial x}+n_z\frac{\partial u^{(1)}}{\partial z}\right]=\mu^{(2)}\left[n_x\frac{\partial u^{(2)}}{\partial x}+n_z\frac{\partial u^{(2)}}{\partial z}\right]$$

where superscripts 1 and 2 refer, respectively, to the inner and outer media, and $n(n_x, n_z)$ denotes the unit vector normal to the boundary. Total fields are decomposed into incident and scattered fields in the form:

$$u^{(1)}=u^{i}+u_C^{(1)},$$
$$u^{(2)}=u_C^{(2)},$$

where u^{i} is the incident displacement. The scattered fields are associated with the radiation of two distributions of sources $F^{(1)}$ and $F^{(2)}$ along C and acting, respectively, in media (1) and (2). The local strengths of these distributions have to be chosen such that the boundary conditions be satisfied along C. The scattered field at any point is given in the form

$$u^{(j)}(\bar{x})=\int_C F^{(j)}(\bar{\eta})G^{(j)}(\bar{\eta},\bar{x})\,d\bar{\eta},$$

where $G^{(j)}$ is Green's function for medium (j). Therefore, $G^{(1)}$ is Green's function of the layered half-space, while $G^{(2)}$ should be simply Green's function of the homogeneous space. These Green's functions are computed by the discrete wavenumber method of decomposition[3] associated with the reflection-transmission matrix method[6].

We represent the irregular boundary by an equally spaced array of points in a zone where forces are applied and boundary conditions are matched. The interval is chosen such that the distance between two points, measured along the boundary, is shorter than one-fourth of the shortest wavelength at each frequency. Green's functions are computed with a corresponding spatial resolution (i.e., they are expressed as truncated series). We then build a linear system of equations from the boundary conditions whose unknowns are the strength of the distribution at each point, and the system is solved numerically. This technique allows us to compute synthetic seismograms including all types of waves (reflected, refracted, multiple, etc.) in complex media[4].

NUMERICAL RESULTS

Figure 3(a) presents the results obtained for a flat interface using a reference model in which the alluvium is 50 m thick. The synthetic seismograms are computed at a series of 20 receivers on the free-surface at an equal interval of 60 m as shown in Fig. 2. This configuration will be used in the following computations. The source time function is the derivative of a pulse of 3 sec of half duration. The first cycle of the synthetics shown in Fig. 3(a) gives an idea about its waveform. Calculations include frequencies up to 1 Hz. The synthetics show a clear effect of partial resonance of the surficial layer which leads to a long monochromatic coda. Because of the strong velocity contrast between the half-space and the upper layer, constructive interference thus occurs

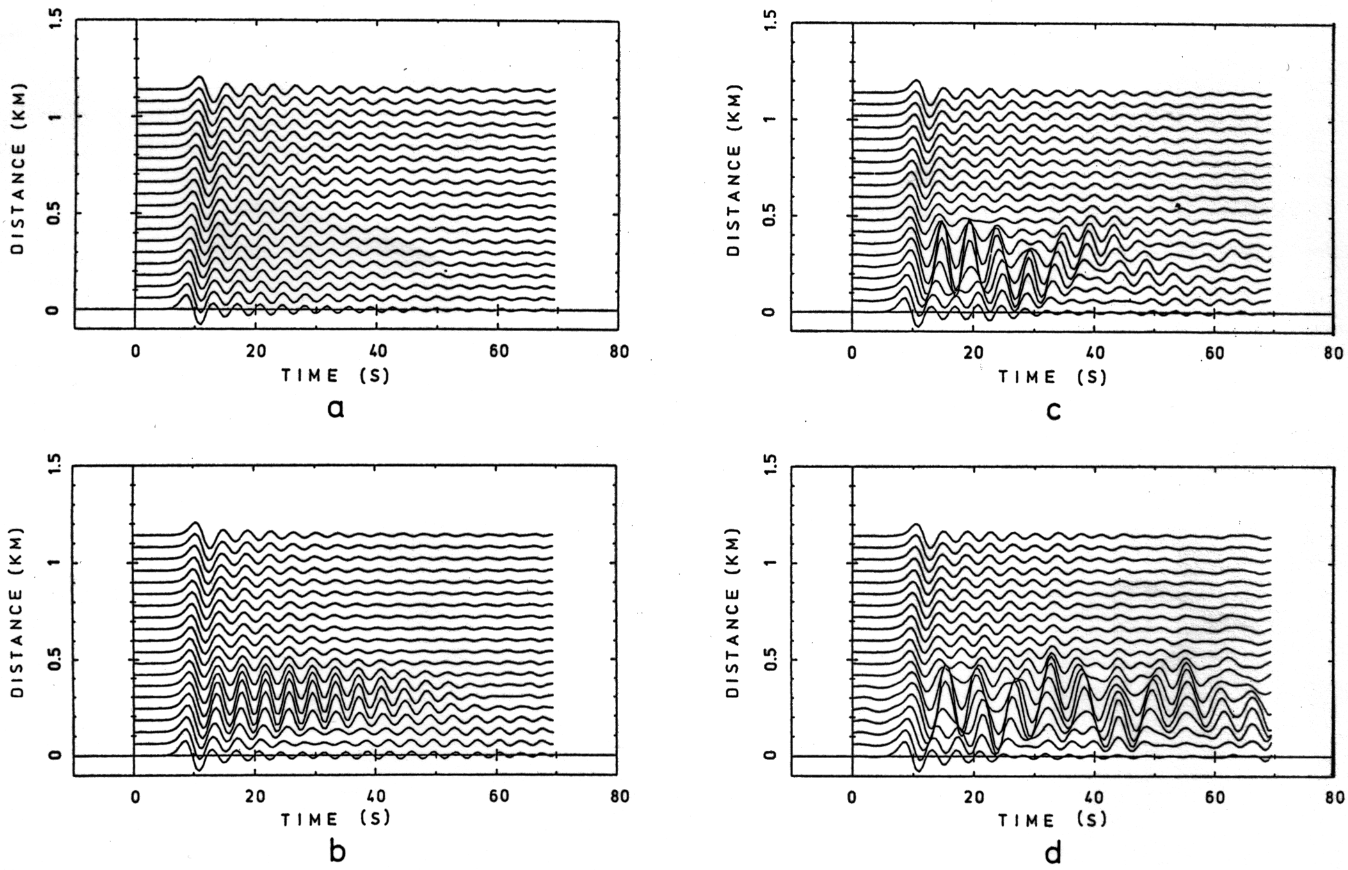

Fig. 3(a) Synthetic seismograms obtained in a flat layered reference model (50 m thick alluvium layer). (b) Synthetics obtained in presence of a thickening of 10 m of maximum amplitude and 500 m of lateral extent. (c) The maximum amplitude of the thickening is now 30 m. (d) Finally, the maximum thickening of the surficial layer is 50 m

between multiple reflections of waves whose trajectories are nearly vertical. The critical angle for a downgoing wave on this interface is 5.74°.

Whatever depth the input wave field may be at, the wave phenomena in the upper layer will involve nearly vertical propagation in a small range of incident angles, which therefore will be very sensitive to any variations of slope of the interface. This is illustrated by results in Fig. 3(b). Here we consider the presence of a local smooth increase of alluvium with 10 m of maximum thickness and 500 m of lateral extent. The maximum slope of the interface is 3.4° with respect to the horizontal. This gentle slope suffices to cause a clear focusing of the energy associated with amplification and increase of signal duration. The maximum effect occurs in the central part of the basin with a maximum strength at points above the part of the irregularity farthest from the source. Relative amplification due to the presence of the irregularity increases with time up to 50 sec. The amplification of the time domain amplitude is 3.1 at 20 sec and 4.5 at 30 sec. The effect of the irregularity is strictly limited to the receivers just above it.

We now consider the case of 30 m increase of the thickness of the surficial layer. Synthetics are presented in Fig. 3(c). The amplification is now large with respect to the flat layered case: 6 around 20 sec, where the maximum amplitudes occur. A striking feature of the synthetics is the criss-cross pattern indicating lateral propagation. This is more pronounced when we consider a thickness variation of 50 m (Fig. 3(d)). The signal duration then exceeds the 70 sec of our time window. The apparent period of the motion is larger above the irregularity. On the other hand, for receivers outside of the irregular zone, the effect of the irregularity is weak. A detailed analysis of the amplitude allows us to identify the shadow zone due to the bump with the weakening of the first arrival at receivers just behind the irregular zone.

Finally, consider the case of a local decrease of the alluvium thickness. We use a reference model in which the alluvium is 80 m thick. The irregularity consists of a bump of 20 m amplitude and 500 m of lateral extent. Results are presented in Fig. 4. The irregularity results in a local weakening corresponding to the geometrical shadow zone. The apparent period of the signal at the centre of the irregular zone is shortened. In this case we can identify a perturbation that propagates outside of the irregular zone; this is the fundamental Love-wave mode, excited by the waves refracted on the right side of the bump. Because of the strong attenuation this wave rapidly disappears.

CONCLUSIONS

These computations show that, in conditions similar to those encountered in Mexico City (i.e., a very soft cover), the effect of small, smooth variations of the surficial structure can produce striking effects. Numerical simulations show that the amplitude and duration of the signal can change rapidly from one point to another. We can expect a change of an order of magnitude in amplitude and duration at points a few hundred meters apart, as shown by the comparison of Figs 3(d) and 4(b),

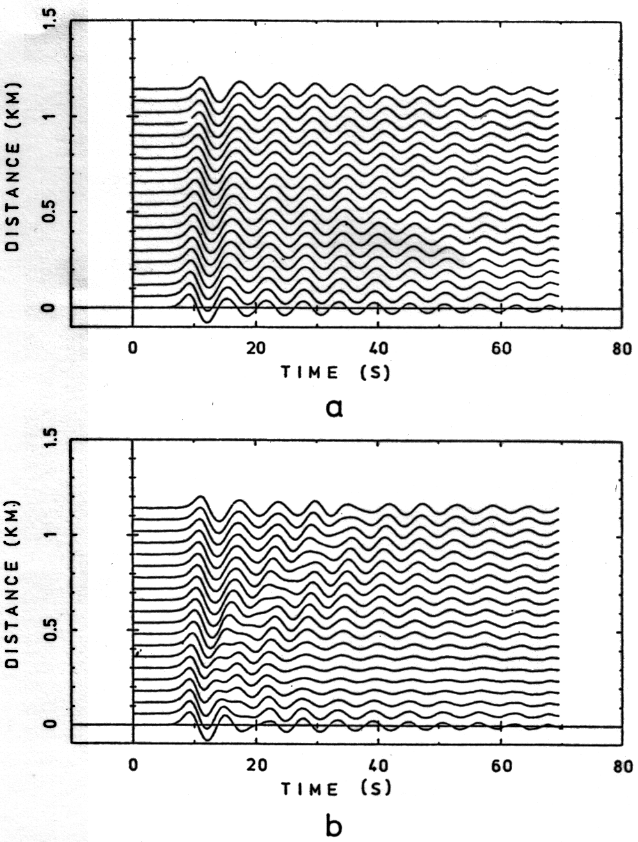

Fig 4(a) Synthetic seismograms obtained in a flat layered reference model (80 m thick alluvium layer). (b) Synthetic seismograms in presence of a 20 m reduction of thickness

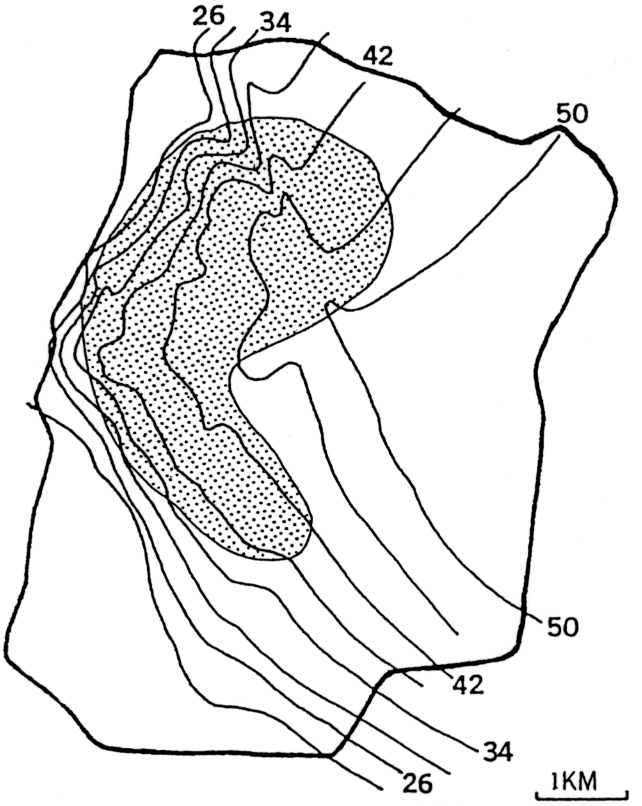

Fig. 5 Schematic map showing the thickness in meters of the clay layer in Mexico City. The shaded area represents the zone of huge damage. The heavy line marks the 'Circuito Interior', the freeway surrounding the central part of the city (after Romo and Seed, 1986)

even for periods of several seconds. This explains in part the irregular distribution of damages. The distribution probably reflects the characteristics of the boundary between alluvium and deep deposits. The zone of the heaviest damages, including numerous collapses, is the one where the thickness of the upper layer has the maximum of small-scale variations (Fig. 5), and must coincide with where the transfer of energy from the deep basin to the surficial layer is greatest. The correlation length of the damage should thus be directly related to the correlation length of the irregular boundary.

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