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STUDIES OF SITE RESPONSE AND SOIL-STRUCTURE INTERACTION EFFECTS IN A TALL BUILDING IN MEXICO CITY

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ABSTRACT

In the wider framework of the analysis of the seismic response of an instrumented building in Mexico City, some salient aspects of the site response and soil-structure interaction effects have been studied by the interpretation of several earthquake recordings, with magnitude varying from ~5.2 up to 7.4 and peak ground accelerations at free-field sites in Mexico City up to ~0.05g. The analyses have been focused especially on the interpretation of the peak amplitude reduction of spectral ratios between surface and intermediate depth borehole recordings and on the influence of surface waves on ground motion. SSI effects have been also analysed, showing a moderate reduction of the fundamental period of the interacting system and evidence of kinematic effects on the high-frequency range of the basement response.

KEYWORDS

Building instrumentation; 1D soil response; spectral ratios; surface waves; soil-structure interaction effects.

INTRODUCTION

Among the dozen, or so, buildings in Mexico City presently instrumented to record their seismic response, only three are equipped with an array of sensors capable of providing a sufficiently detailed picture of such response. One of those, the Jalapa building (JAL), has been instrumented in a joint project between the Institute of Engineering of the National University of Mexico and the Technical University (Politecnico) of Milan, Italy, which lasted from 1990 to 1994. The analysis and interpretation of some significant earthquake recordings of the JAL accelerometer array (still in operation) are illustrated herein for the aspects related to site response and SSI interaction, while a companion paper, also presented at this Conference, is mainly devoted to the seismic instrumentation aspects (Meli *et al*, 1996). We refer to the latter for a more detailed description of the accelerometer array itself, which has the configuration schematically represented in Fig. 1.

After the great earthquake of 1985, extensive studies on local wave propagation supported by a wealth of high-quality data of weak and moderate events, including a few from borehole arrays, have fostered substantial progress in understanding the unique characteristics of seismic ground motion on the soft clays of the lake-bed zone of the Valley of Mexico (e.g. Ordaz and Faccioli, 1994, Chávez-García *et al.*, 1994). Explaining the enormous duration of motion which occurs jointly with extreme amplification in narrow frequency bands on the lake-bed, crucially calls into play the wave contents and duration of the incident signal (i. e. outside the lake-bed zone), and possibly also the influence of 2D or even 3D effects both within the surface clay layer and in the surrounding geological structure (Singh and Ordaz, 1993). The most recent interpretations see the great duration of motion as the result of guided surface waves slowly propagating within deep and relatively soft layers of the Valley of Mexico, whose natural frequency should be close to that of the surface layers (Chávez-García *et al.*, 1994).

To understand the seismic excitation to the JAL building it is desirable to check the extent to which the local borehole and free-field recordings support the standard assumption of 1D vertical wave propagation. This is not completely obvious, considering the strong reduction in peak surface amplification observed at accelerometer G when W1 (located within the clay layer, see Fig. 1) is taken as the reference underground receiver, rather than W2 (located at the top of the stiffer deposits underlying the clay). A second aspect, specific to the JAL site is the possible influence of the nearby, fairly large and rigid underground inclusion represented by the Insurgentes underground station.

The second part of this study is devoted to the characterisation of SSI response of the JAL building., as regards both dynamic and kinematic interaction aspects. For the inertial interaction, the observed transfer functions are compared with those obtained using elementary dynamic models of the superstructure.

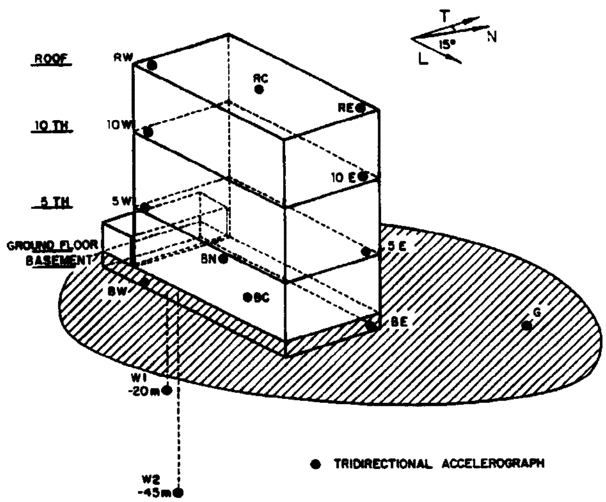


Fig. 1. Overview of the building instrumentation

THE 1D SEISMIC RESPONSE

One-dimensional (1D) models for the study of the seismic response of the lake-bed zone in the Valley of Mexico have been widely used (e. g. Sánchez-Sesma *et al.*, 1988; Singh *et al.*, 1988; Ordaz *et al.*, 1992; Singh and Ordaz, 1993; Ordaz and Faccioli, 1994). Besides their simplicity, this is due to the fact that the clay deposits where the largest amplification of seismic motions occur have a small thickness (from 10 to 80 m) compared with their lateral extension (30-40 km) (Seed *et al.*, 1988). The reliability of the 1D model has been well confirmed by the observed correlation of the dominant periods of vibration of the soil with its local thickness (Singh *et al.*, 1988). The ground motion recordings used herein were obtained during three 1993 earthquakes, the first two of them occurring on May 14 (M_W5.2), and another on October 24 (M_W6.6). Also included is the September 14, 1995 earthquake (M_W 7.4). The epicenters of all these events are located about 300 km South of Mexico City, in the so called seismic gap of the subduction zone on the coast of Guerrero.

Since the response of the Mexico City clay remains elastic up to high shear strain levels (Ordaz and Faccioli, 1994), a 1D linear viscoelastic model of the soil profile was used to analyse the response at the JAL site, with the properties indicated in Tab. 1. The S-wave velocities v_s have been estimated from SCT measurements (see Meli *et al.*, 1996), slightly adjusted to match the lowest resonant frequency of the soil, while the internal damping values were taken from laboratory tests performed on soil samples from neighboring sites. An average unit weight of clay soils of 13 kN/m^3 was used. The mechanical properties of the clay tend to improve with depth, changing significantly at about 45 m from surface , where the so called deep deposits are encountered. This depth is in fact typical of the area of the lake-bed zone where the JAL building is located.

Tab. 1 Soil profile used for 1D analyses. v_s denotes the S-wave velocity ,while ξ is the internal damping of the soil.

layer n.	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*bedrock*
Depth (m)	4.4	6.6	9.1	12	14	18	24.5	26	29	31.5	35	40	45	
v_s (m/s)	100	35	44	48	87	51	60	130	87	173	139	242	346	600
ξ (%)	0.5	3.5	2	2	2	2	2	1	1	0.5	0.5	0.5	0.5	0.15

The theoretical transfer functions provided by the 1D model have been compared with the observed spectral ratios between the surface (point G in Fig. 1) and the borehole points at 20 and 45 m depth, respectively (points W1 and W2 in Fig. 1). The comparison is shown in Fig. 2 for the NS components of motion of the 1995 event. No significant differences exist with the records of the other events.

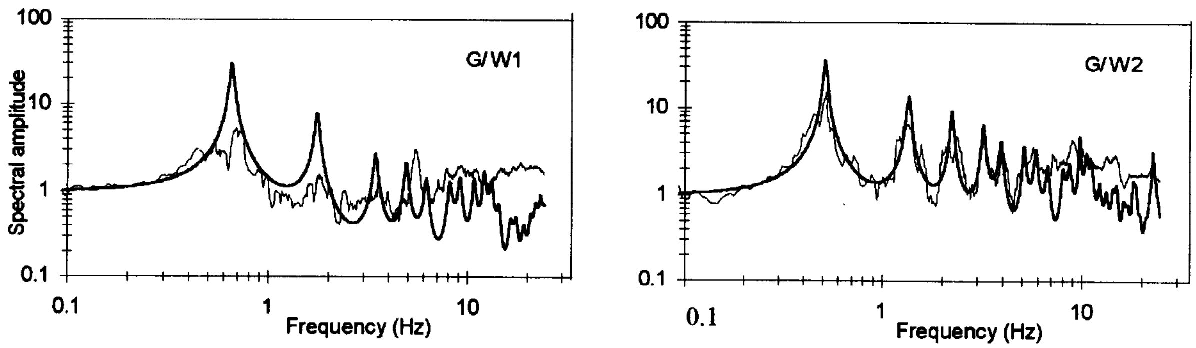
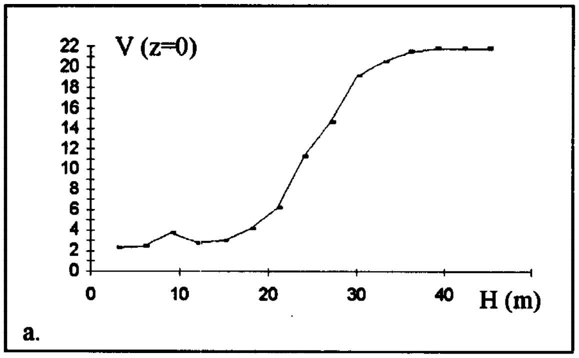


Fig. 2. Comparison between theoretical 1D transfer functions (thick line) and observed (smoothed) spectral ratios (thin line). The latter are taken between the surface NS components of motion and those recorded at borehole points W1 (20m) and W2 (45 m). during the September 14 1995 earthquake.

Concerning the G/W2 spectral ratios, the 1D model seems to capture the main features of the seismic response in a satisfactory way. Note in particular the good matching for the higher resonant modes. This also shows that the free-field recordings at the JAL site are not affected by the presence of neighboring structures, such as the large (~40 m diameter) underground inclusion represented by the Insurgentes subway station.
As to the G/W1 spectral ratios, they are affected by a strong reduction in the peak amplitude of the lowest modes of vibration. The same feature was observed by other authors for other borehole points at intermediate depth (10 to 25 m) for several recordings in Mexico City. The amplitude reduction was attributed to local 2D or 3D effects, such as destructive interference between the 1D response and the lateral propagation of surface waves (Ordaz *et al.*, 1992).

To explain the amplification reduction, we performed additional analyses on the trend of the absolute value V(z,f) of displacement amplitude with depth and frequency, and on the influence of noise. For an incident harmonic wave of unit amplitude, Fig. 3 displays the dependence of the absolute value of displacement at the top (z=0) and at the bottom (z=H) of the soil profile on the height H of the profile itself. The curves of Fig. 3 are calculated with the theoretical 1D algorithm using the same reference soil profile of Table 1 and starting with the top layer alone. The deeper layers are progressively included one by one , and the frequency of excitation is changed as each new layer is added so that it always coincides with the fundamental frequency of the current profile. Note that the ratio V(z=0)/V(z=H) of the values shown in Fig. 3 determines the amplitude of the analytical 1D transfer function.

Based on the type of evidence presented in Fig. 3, we investigated the effects of adding random noise to the signals. In Fig. 4 are shown two comparisons between the theoretical 1D transfer functions of Fig. 2 and the G/W1 and G/W2 spectral ratios obtained by propagating from 45 m depth up to the surface a double impulse signal of finite duration. The same synthetic white noise was subsequently added to the propagated waveforms. The white noise level has been chosen so as to have a ratio of about 0.025 with respect to the



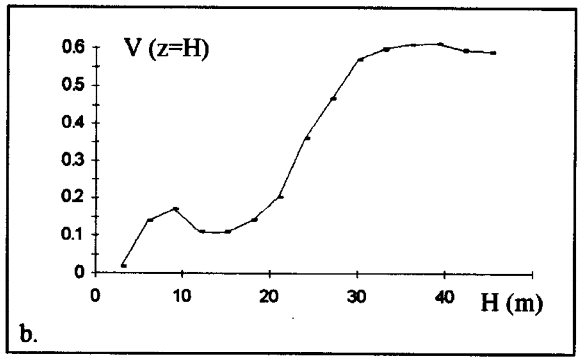
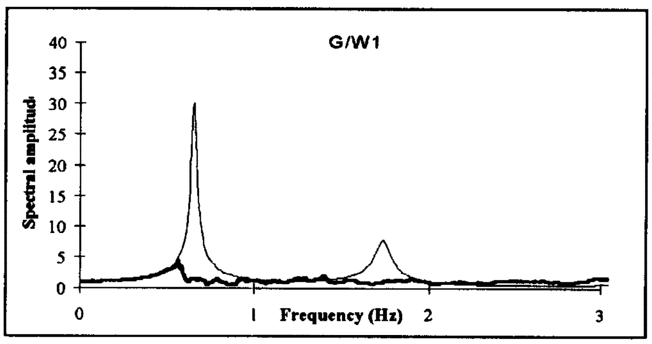


Fig. 3 Absolute value of displacement at top (a) and bottom (b) of the soil profile with thickness H for its first mode of vibration .

peak of the signal at the surface. The spectrum of the double impulse has enough energy to excite just the first mode of vibration of the soil profile. As shown in Fig. 4, the simulated G/W1 transfer function exhibits the same peak amplitude reduction as the observed ones in Fig. 2, while the spectral ratios in the absence of noise match fairly well the theoretical functions.

These analyses suggest that the peak amplitude reduction of the transfer functions at intermediate depths in the clay deposits should be due to the presence of noise. This happens because the amplitude of the motions measured at top (surface) and bottom (depth) of a certain soil profile vibrating at its resonant frequency decreases with the thickness of the deposit. This decrease makes the influence of noise critical for a depth range below a certain limit, in which the amplitudes become very small (such as below about 20 m in Fig. 3b).



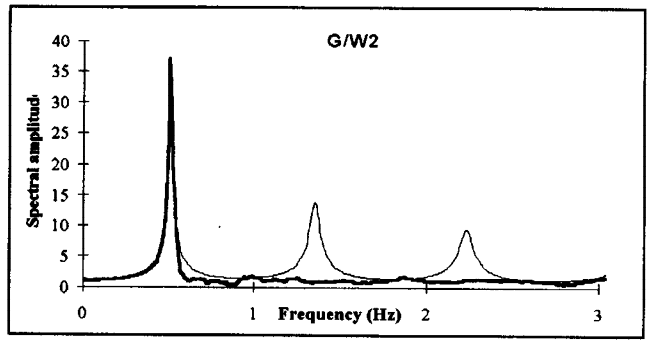


Fig. 4 Comparison between theoretical 1D transfer functions (thin line) and simulated transfer functions in the presence of noise (thick line), obtained from the propagation of a double impulse signal.

ANALYSIS OF SURFACE WAVES

The presence of surface waves in the Valley of Mexico has been long investigated to justify some features of the observed surface motions impossible to explain with the 1D theory (Singh *et al.*, 1988; Singh and Ordaz, 1993; Chávez-García *et al*, 1994). A long-period wave with 10 to 12 s, interpreted as a Rayleigh wave, was identified for the 1985 Michoacán earthquake (Campillo *et al.*, 1989; Ordaz *et al.*, 1989) and the 1989 Guerrero earthquake (Pérez-Rocha *et al*, 1991; Sánchez-Sesma *et al*, 1993; Gómez-Bernal and Saragoni, 1995), and was interpreted as a path effect propagating South-North from the Coast of Guerrero. The long period arrival is particularly evident in the vertical components of the displacement time history, whose characteristics remain almost identical in all the recordings obtained in and around Mexico City. Gómez-Bernal and Saragoni (1995) identified in the 1989 recordings Rayleigh wave arrivals of 5 to 6 s before the longer period ones, and ripples of 2 to 3 s in the coda.

In order to identify wave types and ground motion characteristics for the JAL site, the displacements obtained by double integration of the accelerations of the four considered events have been analysed. The displacement time histories at the surface (G) and at 45 m depth (W2) are displayed in Fig. 5 for all components of motion, for the September 1995 event (M_w 7.4). The displacements have been computed from the acceleration traces after highpass filtering at 0.07 Hz. The waveforms of the W2 signal and of the vertical component of the G signal suggest the presence of surface waves, including a long period Rayleigh phase, especially in the vertical traces between 50 and 70 s. The vertical components are almost identical in the two waveforms, indicating that this component is not influenced by the local soil amplification, and thus provides a good representation of the incident wave-field. The surface horizontal components of motion are strongly affected by local site effects, showing a large amplification with respect to borehole signals and a sharp resonance at the fundamental period of vibration of the soil profile (2 s). Only the coda of these two traces show evidence of surface waves. The signals at 20 m depth (not shown) are very similar to those at 45 m, except for a slightly larger amplitude. The displacement traces of all the events considered show similar features.

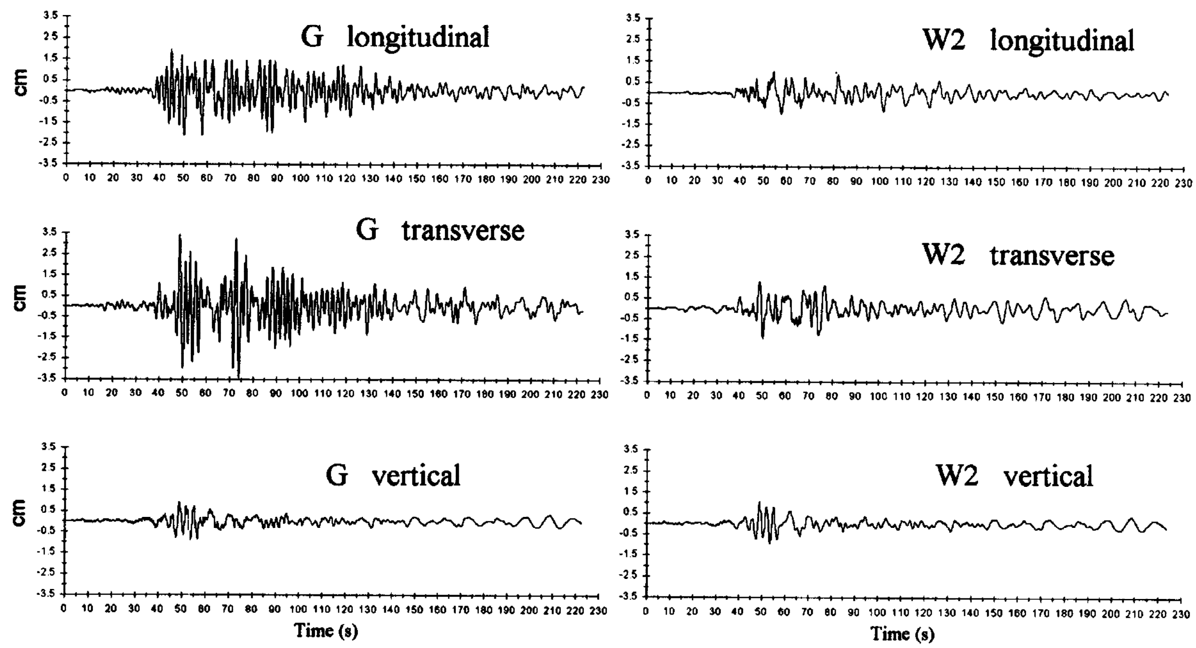


Fig. 5. Displacement components of motion for the Sept. 14 1995 earthquake recorded at free-field (G) and at 45 m depth (W2) at the JAL site. The transverse components refer to the NS direction, while the longitudinal ones to the EW direction.

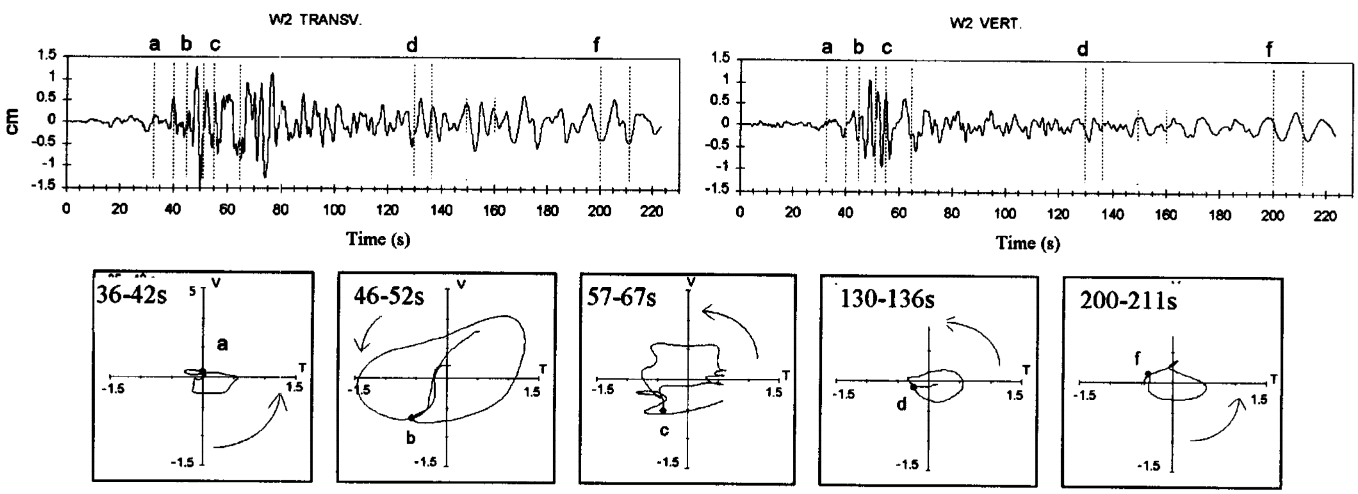


Fig. 6. Displacement components and particle motion trajectories in different time windows in the vertical-transverse (NS) plane for the Sept. 14, 1995, event, at 45 m depth (W2).

The identification of surface waves has been done by plotting the orbits of displacement in the vertical plane oriented NS. In Fig. 6 the transverse and vertical components of motion at 45 m depth are presented, together with the particle motion within the time windows indicated. All the hodograms show retrograde elliptical motion typical of Rayleigh waves propagating from S to N; the periods are about 5 s for the arrivals denoted as a (35 s), b (46.5 s) and d (130 s) and about 10 s for the other arrivals, namely c (57 s) and e (200 s). The particle motions for the 20 m depth W1 point (not shown) exhibit the same arrivals. These arrivals have been identified also in the horizontal components of the surface records by a narrow band-pass filtering (0.07-0.4 Hz), out of the range of the local site amplification. Finally, it is worth noting that the displacement traces as well as the particle motion orbits of the lower magnitude events of May 14, 1993, also provide evidence of Rayleigh wave arrivals, although characterized by lower amplitudes and shorter periods. In Fig. 7 the main surface wave arrivals for the W2 signals recorded during one of these events are shown; in order of decreasing period these are denoted as c (8 s period), a and d (4 s) and b, e and f (2-3 s).

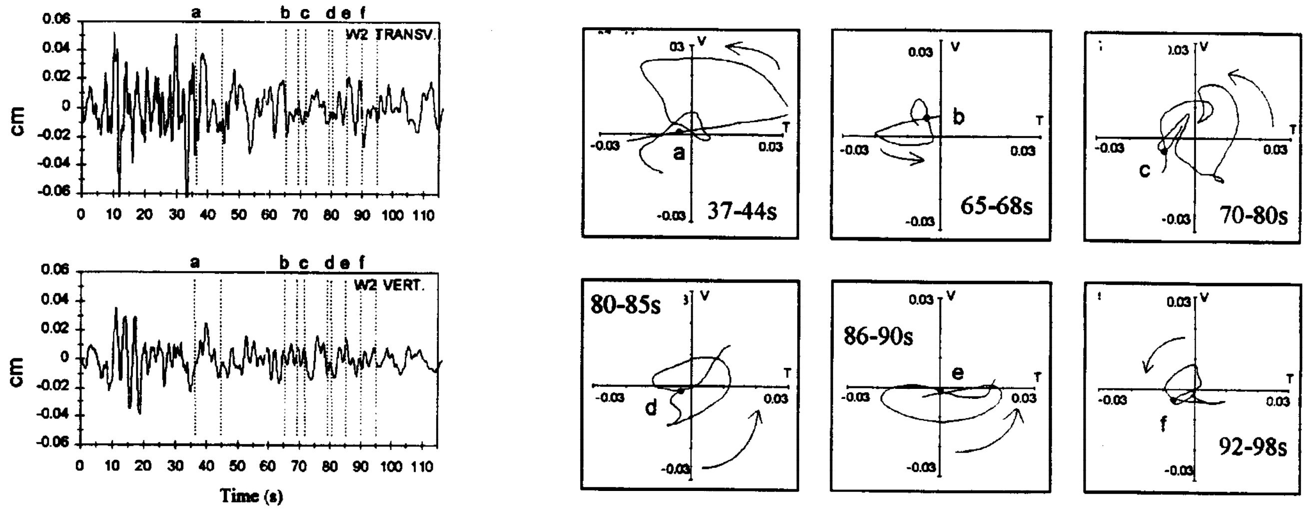


Fig. 7. Displacement components and particle motion trajectories in the vertical-transverse (NS) plane for the May 14 1993 event with M_w 5.4, recorded at 45 m depth (W2).

INERTIAL AND KINEMATIC SSI EFFECTS FROM EARTHQUAKE RECORDS

As well known, a typical effect of the inertial SSI interaction is to conceal the fundamental frequency (f_r) of a structure founded on rigid soil; the fundamental frequency (f_i) of the soil-structure interacting system is generally smaller than f_r, depending on the relative stiffness of the soil and the foundation. For the very soft soil conditions of Mexico City, strong SSI effects are expected, leading to values of f_i close to the fundamental frequency of the soil ($f_s \cong 0.5$ Hz) even for relatively rigid structures. A more detailed analysis of these effects and the evaluation of the dynamic impedances of the JAL building pile group is presented by Paolucci (1993). The evaluation of SSI effects from the recorded motion was carried out in a simplified way, considering the 3 degrees of freedom (dof) model illustrated in Fig. 8.

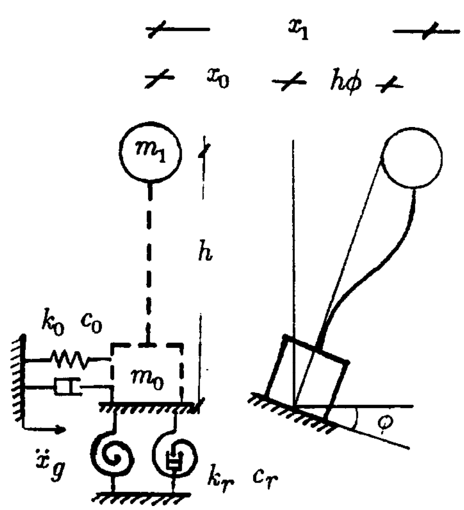


Fig. 8. Three degrees of freedom model.

Referring to the notations of Fig. 8, let $x_1^t = x_1 + x_g$ be the total motion of the structure at the roof level, and $x_0^t = x_0 + x_g$ that of the basement. For the 3 dof model, it can be easily shown that the response function

$$\psi = \frac{x_1^t}{x_0^t + h\phi} \tag{1}$$

has a fundamental frequency $\omega^2 = k_1 / m_1$, which coincides with the fundamental frequency of the fixed-base structure, and is independent of the interaction coefficients. Based on this simple model of the building, the spectral ratios x_1^t/x_g and $x_1^t/(x_0^t+h\phi)$, evaluated from earthquake records, provide a rough estimation of f_i and f_r respectively, as shown in Fig. 9 for the events of May 14 and Oct. 24 1993, and Sept. 14, 1996. The SSI effects significantly reduce the fundamental frequency of the system, varying from ~10% for the transverse (T) component up to 25% for the longitudinal one (L); in this direction the building is stiffer, so that SSI effects are more pronounced. Also, this figure clearly indicates the influence of non-linear effects on the structural behaviour, leading to a substantial reduction (~25%) of the fundamental frequency of the system in both directions. These effects are described more in detail in the paper by Murià-Vila and Gonzales (1996) on the same building.

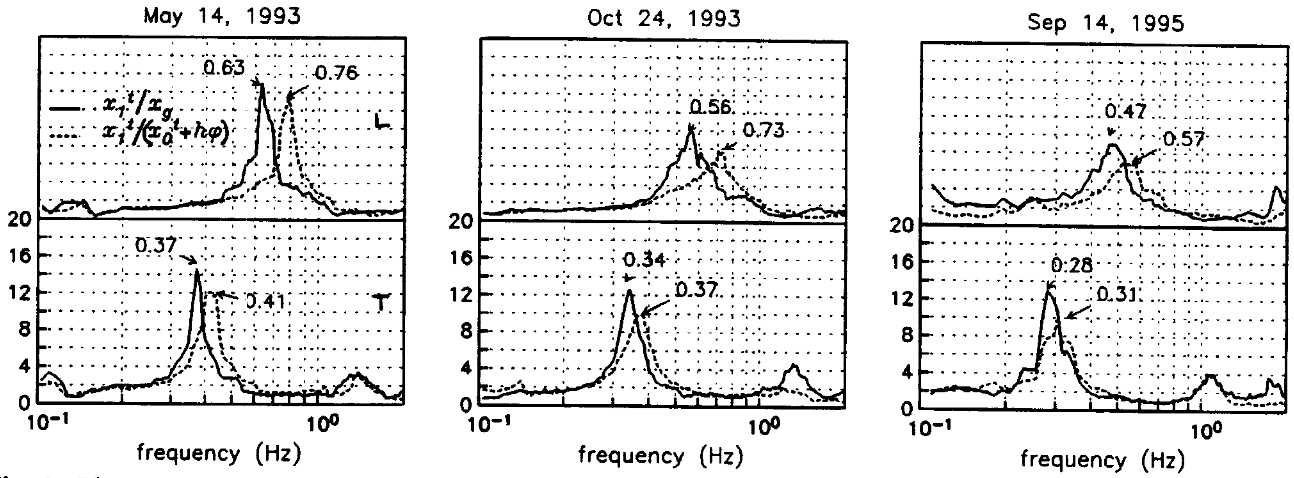


Fig. 9. Observed spectral ratios between the total motion at the roof and the free-field motion (continuos line) compared with the observed response function given by (1) (dashed line). The frequencies corresponding to the peak values are indicated. Upper side: L motion; lower side: T motion.

Contrary to the inertial SSI effects, which typically occur for frequencies close to the fundamental frequency of the system, the kinematic SSI effects tend to act on the high-frequency range of the excitation, due to the diffraction of the incoming wave-field in the presence of the building and the foundation. As shown by Fan *et al.* (1991), the kinematic response of a pile group is strongly dependent on the soil profile, with a dimensionless cut-off frequency $a_0 = \omega d/v_s$ (ω being the circular frequency, d the pile diameter, vs the average shear wave velocity in the layer) varying from 0.05 for a strongly inhomogeneous layer, up to 0.2-0.3 for a homogeneous one. In the case of the JAL building a value $a_0 \cong 0.07$-0.08 was found (Fig. 10), in good agreement with these indications.

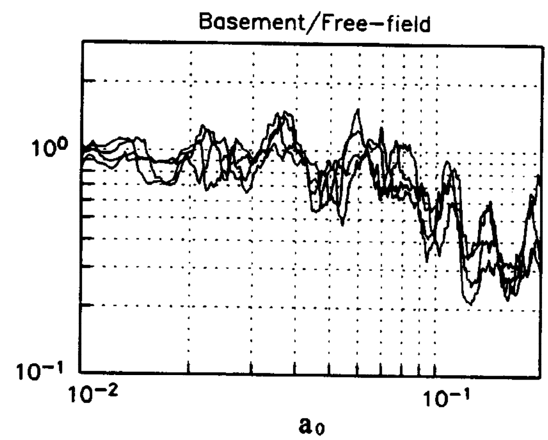


Fig. 10. Observed spectral ratios between the motion at the basement and at the free-field site.

CONCLUSIONS

A detailed analysis of the site response at the JAL site has been carried out, to investigate two salient aspects, namely the peak amplitude reduction of the spectral ratios between surface and intermediate depth borehole recordings and the influence of surface waves on ground motion. A possible explanation of the spectral peak reduction has been given in terms of the effect of noise, which becomes critical at depths where the amplitude of motion at the fundamental frequency of the soil drops to very small values. Surface waves were found to be present since the early phases of the waveforms incident at the base of the clay layers, with rather strong modulating ripples of ~2-3 s period. The latter may be the result of the waveguide phenomena occurring in the deeper, soft layers of the Valley of Mexico, while the longer period waves are attributed to path effects.

Both kinematic and inertial SSI effects have been investigated in a simplified way. A reduction of the fundamental frequency of the interacting system has been observed, varying from ~10% in the T direction, up to ~25% in the stiffer L direction. Kinematic effects on the response of the basement appear only in the frequency range typical of foundations on large pile groups in inhomogeneous soil conditions.

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