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Paper No. 1838. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

A note on the seismic wavefield radiated from large building structures into soft soils

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ABSTRACT :

The effects of soil-structure interaction *on ground motion* are investigated through simple though realistic numerical simulations. The model consist of a single SDOF building resting at the surface of a horizontally stratified half-space. Building motion, base forces and moments are estimated through foundation impedance functions, and the 3D wavefield radiated back into the stratified half-space is computed with discrete wavenumber technique. Results obtained for simple configurations do confirm the possibility of significant modifications of the "free-field" motion up to distance of a few hundred meters from large size buildings resting on very soft soils; the origin of these modifications is shown to be principally the SSI induced rocking motion of buildings, which is larger for embedded foundations (deep pile foundations were not considered).

KEYWORDS :

Soft soils - Soil-structure-interaction - Free-field - Impedance functions - Discrete-wavenumber method -

INTRODUCTION

Seismologists have learnt very early not to install sensors near to trees because of the feedback effects of wind-induced tree movement on ground motion. Civil engineers have known for several decades the possible effects of soil-structure interaction on building motion, especially for soft soils. Yet, the issue of the "genuine free-field character" of ground motion recorded in heavily urbanized cities (many such records do exist...) has received till now only very little attention, and has never been addressed in a quantitative, systematic way.

If such effects are to be significant, the "best" case for their appearance certainly corresponds to large-size structures resting on very soft soils. Preliminary investigations with such structures have been presented in a previous paper (Bard and Wirgin, 1995) with an oversimplified 2D, SH model. Their main conclusions arethat, for tall buildings resting on very soft soils (i.e., for cases comparable to the Mexico City situation), the wave diffraction phenomena related with soil-structure interaction, combined with the trapping of surface waves in the topmost soft layer, could result in very significant modifications in the "free-field" motion up to distances of several hundred meters from the closest building: duration as well as amplitude are significantly increased at some frequencies, resulting in some cases (corresponding to very dense urbanization) in drastic changes in the ground "natural" frequency. However, the model used in these preliminary investigations was too simple, and it was felt necessary to proceed with a more realistic model. It is the aim of the present paper to present such a new model, together with a few quantitative results for realistic cases.

DESCRIPTION OF THE MODEL

Let us consider the configuration displayed in Figure 1, consisting of a single building, represented as a SDOF oscillator, resting on a horizontally stratified half-space. The problem may be separated in two main steps : the first one is intended to compute the base shear force S(f) and rocking moment M(f), and the second one to compute the wavefield radiated in the half-space by these near-surface forces.

Derivation of surface forces

The first step is solved using the "classical" formulation of soil-structure interaction problems. Let f_l, ζ_l, and m_l denote, respectively the fixed-base natural frequency, damping, and mass of the building, and m_0 denote the foundation mass. Let also x denote the relative displacement of the center of mass of building (located at height h) with respect to its foundation, ϕ the rocking angle, x_0 the relative displacement of the foundation with respect to the soil, and x_g the (imposed) free-field ground motion. For a harmonic input motion having an angular frequency ω, the interaction between soil and structure may be desribed with frequency-dependent, complex impedance functions, specified as $(K_h + i\,\omega C_h)$ for the translational interaction, $(K_r + i\,\omega C_r)$ for the rocking interaction, and $(K_{hr} + i\,\omega C_{hr})$ for the coupling term. These parameters obey the following matrix equation:

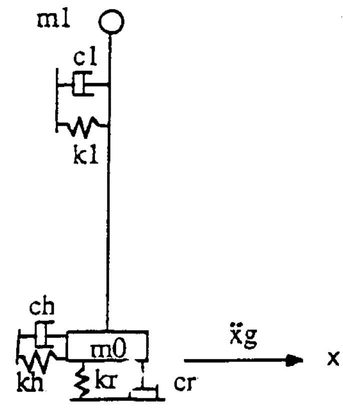

Figure 1 : *Building model including SSI.*

$$[\underline{\mathbf{K'}} - \underline{\mathbf{M}}\,\omega^2]\,\underline{\mathbf{X}} = -\,\omega^2\,\underline{\mathbf{P}}\,x_g \qquad (1)$$

where $\underline{\mathbf{K'}}$ is the generalized (damped) stiffness matrix, $\underline{\mathbf{M}}$ the generalized mass matrix, $\underline{\mathbf{X}}$ the unknown vector and $\underline{\mathbf{P}}$ the excitation vector, given by the following expressions:

$$\underline{\mathbf{X}} = \begin{bmatrix} x \\ x_0 \\ \phi \end{bmatrix} \qquad \underline{\mathbf{P}} = \begin{bmatrix} m_l \\ m_0 \\ 0 \end{bmatrix}$$

$$\underline{\mathbf{K'}} = \begin{bmatrix} k_l + i\,\omega\,c_l & 0 & 0 \\ -(k_l + i\,\omega\,c_l) & K_h + i\,\omega\,C_h & K_{hr} + i\,\omega\,C_{hr} \\ -(k_l + i\,\omega\,c_l) & K_{hr} + i\,\omega\,C_{hr} & K_r + i\,\omega\,C_r \end{bmatrix} \qquad \underline{\mathbf{M}} = \begin{bmatrix} m_l & m_l & h.\,m_l \\ 0 & m_0 & 0 \\ 0 & 0 & J \end{bmatrix}$$

The impedance coefficients (terms $K_{ij} + i\,\omega C_{ij}$), are frequency-dependent terms, which depend on the shape (circular, rectangular, ...) and dimensions of the foundation, its embedment D, and the elastic properties of the soil (shear modulus μ, and Poisson ratio ν). In the present case, we considered only simple cases, for which the values of these impedance functions could be found in the literature, most often in a graphical way. We therefore digitalized the curves provided in Sieffert and Cevaer (1992), where these functions are given as a product of the static stiffness values by a correction term depending on the dimensionless frequency.

Once the system (1) is solved, the forces applied on the soil (at the soil-foundation interface) are derived from the foundation relative motion (x_0 and ϕ) according to the following relations:

$$\begin{bmatrix} S \\ M \end{bmatrix} = \begin{bmatrix} K_h + i\,\omega\,C_h & K_{hr} + i\,\omega\,C_{hr} \\ K_{hr} + i\,\omega\,C_{hr} & K_r + i\,\omega\,C_r \end{bmatrix} \begin{bmatrix} x_0 \\ \phi \end{bmatrix}$$

When the "input" motion x_g is taken equal to 1 whatever the frequency (which corresponds to a pdeudo-Dirac displacement pulse), the horizontal force S and rocking moment M (as well as the motions x, x_0 and ϕ) can be plotted as a function of frequency : these curves are called transfer functions in the following.

Radiated wavefield

There are several methods allowing to compute the wavefield generated by surficial sources in a layered 3D half-space. The discrete wavenumber technique (Bouchon, 1981; Coutant, 1989) has been used here in its slightly modified, axisymmetric version already used in Lachet and Bard (1994) to account for near-surface point sources.

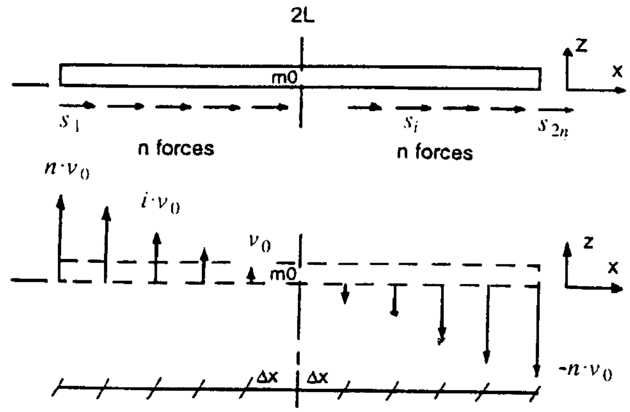

Figure 2 : *Model for the computation of the radiated wavefield, due to the base shear force (top), and the rocking moment (bottom)*

In the present case however, the sources are indeed spread along the whole foundation soil-interface. This source extension was taken into account as illustrated in Figure 2. The total horizontal force S(f) was represented by 2n smaller horizontal point forces $s(x_i, f)$ distributed uniformly along the foundation length 2L (i.e., with $x_i = \pm i\ L/n$, and $s(x_i,f) = S(f) / 2n$). The rocking moment M(f) was represented by n couples of vertical forces $v(x_i,f)$ with linearly increasing amplitudes as a function of x_i (see Figure 2b) : $v(x_i,f) = i\ v_0(f)$. This linear dependence was (arbitrarily) chosen as a first order approximation of an elastic, rigid foundation rocking motion (with the vertical force directly proportional to the rocking-induced vertical motion). Under such conditions, $v_0(f)$ is very simply related to M(f):

$$M(f) = \Sigma\ 2x_i\ .\ v(x_i,f) = \Sigma\ 2\ (i\ L/n\ )\ (\ i v_0(f)) = 2.\ L/n\ .v_0(f).\ \Sigma\ i^2, \quad \text{so that} \quad v_0(f) = M(f)\ /\ [(n+1)L].$$

The computations presented below were all performed with a n value of 5: with L=20 m, the inter-source spacing was therefore 4 m, much smaller than the shortest wavelength (around 30 m at 2 Hz for a shear wave velocity of 65 m/s).

The surface motion associated with these surficial sources was computed at five different sites, located, respectively, at 50, 100, 200, 500 and 1000 m from the foundation center. As in the previous section, this surface motion may be computed both for an input displacement pulse, or for any realistic input motion.

Parameters for numerical computations

This kind of model includes many different parameters : building and foundation masses, building fixed-base stiffness and damping, foundation geometry, and soil profiles (density, velocities and damping). The results presented here were obtained with the parameters listed in Tables I and II. The building and foundation characteristics are those of the Jalapa building, located in Mexico City, as described in Paolucci (1993). The soil parameters were also chosen close to those of the Mexico city clay (Table II).

Building			**Foundation**		
Mass	m_1 (kg)	5.97. 10^6	mass	m_0 (kg.)	1.18 10^6
Height (mass center)	h (m)	31.40	Inertial moment	J (kg. m²)	6.54 10^8
Fixed-base frequency	f_1 (Hz)	0.79	Length	2L (m)	40
Damping	ζ_1	0.04	Width	2B (m)	20

Table I : *Building and foundation characteristics*

	Volumic mass ρ (kg/m3)	Vs (m/s)	Vp (m/s)	Poisson ratio ν	Qs	Qp
Clay	1 400	65	135	0.35	25	50
Substratum	2 000	600	1800	0.44	50	100

Table II : *Soil characteristics*

The value of the Poisson coefficient for the clay layer is certainly not realistic (it reaches much higher values in Mexico City, very close to 0.5). The reason for such a low value is simply related to the non-existence of tabulated impedance functions for high Poisson ration values. Another important soil parameter needs to be specified: the clay layer thickness. Several computations were performed with different values in the range 0 - 100 m, for a sensitivity analysis.

Although the Jalapa building is indeed founded on deep friction piles, we considered here only surficial foundations, for which impedance functions are more easily available. Because of our previous model where buildings were located directly at the soil surface, we considered here both cases of surface foundations (no embedment) and of an embedment ratio (D/B) of 1.33 : the objective is to estimate whether the embedment increases or decreases the radiated wavefield.

For sake of simplicity, the results presented here were computed only along the x axis and for an input motion also polarized along the same direction. The method, however, allows any kind of polarization.

RESULTS

Base forces

The first investigations were devoted to the frequency dependence of base forces for various foundation and soil configurations. When the soil consists of a homogeneous elastic half-space, the natural frequency of the whole system is obviously decreasing with decreasing shear wave velocity in the soil. For the example building considered here, these variations are found significant only when the soil shear wave velocity is smaller than 200 m/s. Simultaneously, as illustrated in Figure 3, the base rocking moment M and shear force S also decrease, although the "SSI" motions x_0 and ϕ do increase with decreasing Vs. For Vs = 65 m/s, the rocking motion $h\phi$ accounts for approximately 25 % to 50 % of the total building motion, depending on whether the foundation is embedded or surficial

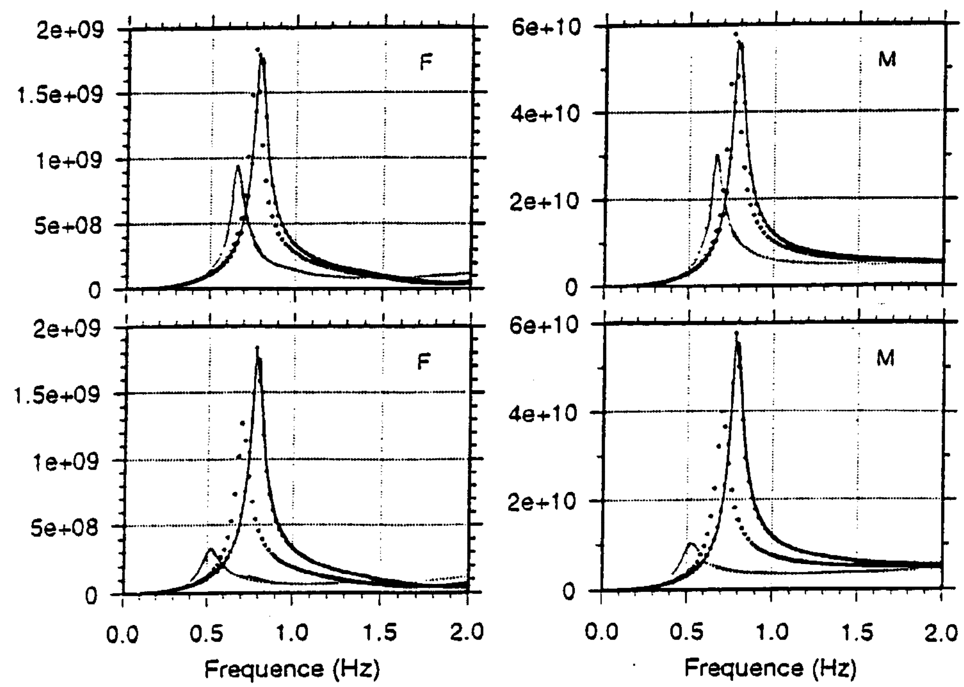

Figure 3 : *Transfer function for the base shear force and rocking moment, in the two cases of a rectangular embedded foundation (D/B = 1.33, top), and of a rectangular surface foundation (bottom). The different curves correspond to different values of the shear wave velocity in the half space: 65 m/s (thin line), 135 m/s (dots), and above 400 m/s (other symbols).*

Another interesting result concerns the effect of foundation embedment: a systematic increase of the peak moment M and shear force S is observed when the embedment increases from 0 to 4B/3 (i.e., here,13 m). For instance, for a homogeneous half-space with a S wave velocity of 65 m/s (i.e., a very thick clay layer), S and M are multiplied by a factor 3 at the fundamental frequency. Similar observations were obtained also for circular foundations of varying radius. This is mainly due to the larger stiffness of embedded foundations, which results in a smaller fundamental frequency decrease, and therefore in a smaller decrease of base forces.

Radiated motion

The main goal is to know whether the radiated motion is very small compared the free-field motion, or not. In that aim, we first compared the respective effects of the base shear force S(f) and of the rocking moment M(f). For the "basic" configuration of an rectangular foundation embedded at 13 m within a very soft half-space, Figure 4 displays the horizontal, longitudinal (x) motion induced by the rocking and shear forces, respectively, at distances from 100 m to 1 km from building base. The rocking motion thus appears the most efficient in radiating energy back into the soil, since the associated motion is 2.5 times larger at 100 m and about 10 times larger at 1 km. Other computations (not shown here) with other configurations systematically led to the same conclusions: the following results therefore focus on the perturbations to free-field motion due to the SSI induced rocking moment.

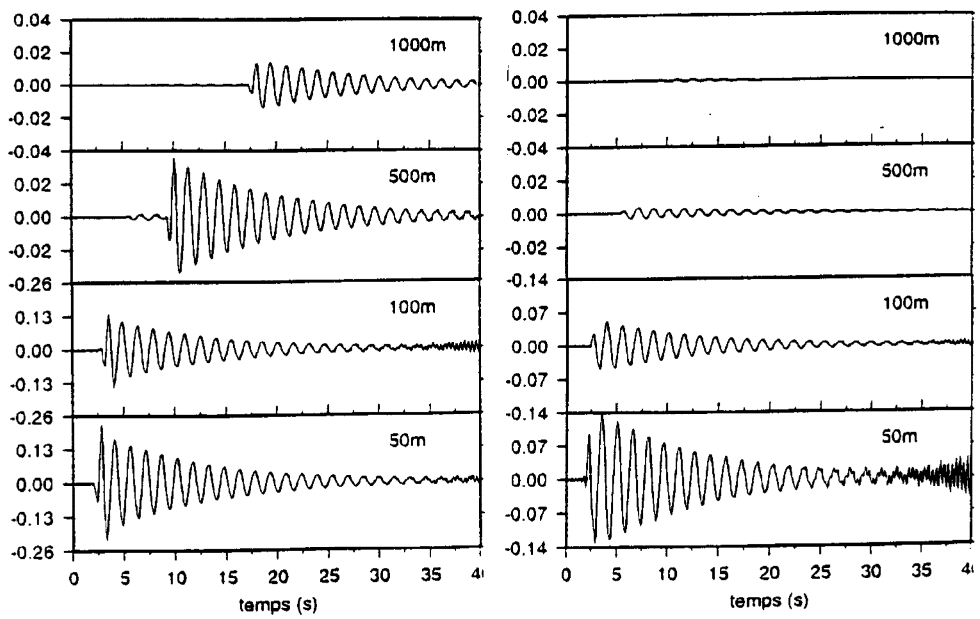

Figure 4 : *Comparison between the radiated motion due to rocking moment (left) and longitudinal shear force (right), in the case of a rectangular foundation embedded (D=13 m) in a soft clay layer. The traces are surface displacement traces generated by a displacement single pulse at building base.*

We then computed the building response and the associated radiated wavefield for a realistic input motion at the surface of a soft clay deposit. Since the surface response is highly dependent on the thickness of the clay layer, we considered three different clay thickness values, 25, 50 and 75 m, corresponding to different values of the fundamental soil frequency (0.65, 0.325 and 0.217 Hz, respectively), and convolved the corresponding transfer functions (illustrated in Figure 5) with the EW acceleration trace recorded at Tacubaya station during the April 25, 1989 Guerrero event (Ms = 6.9, see Sanchez-Sesma *et al.*, 1993), to obtain the forcing motion x_g. The resulting free-field and building motion are displayed in Figure 6, together with the radiated motion due to the building rocking, at distances of 50 and 500 m from building base. These plots call two main comments. On one hand, there is a very close relationship between the radiated motion and the building motion: they have very similar waveforms and frequency contents. On the other hand, the radiation "efficiency" is closely related to the coincidence between building frequency and soil natural frequency: for the first case, the (interacting) building frequency (0.66 Hz, see Figure 3) is the same as the soil natural frequency; in the third case, it is the same at the first soil harmonics; in the second one, it falls exactly in between the fundamental and first harmonics. The radiated motion is clearly the largest for the first case, and the smallest for the second one.

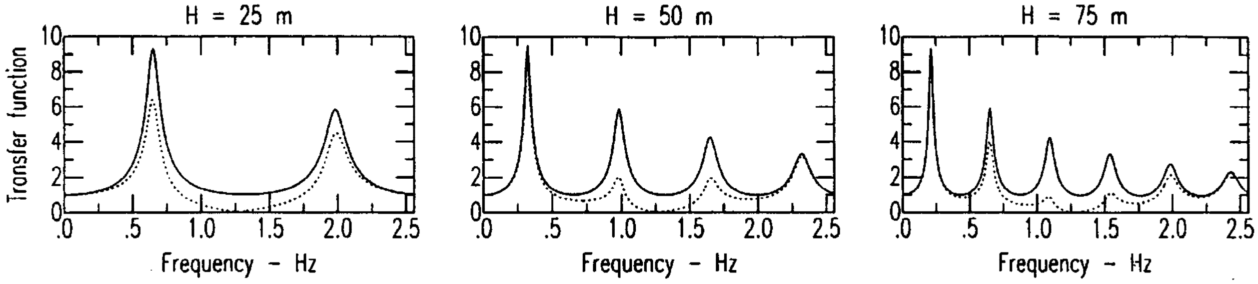

Figure 5 : *Soil transfer functions corresponding to three different clay thicknesses (H=25m, top; H=50 m, middle ; H=75 m, bottom). The solid lines correspond to surface motion while dotted lines correspond to motion at foundation base (z = 13 m).*

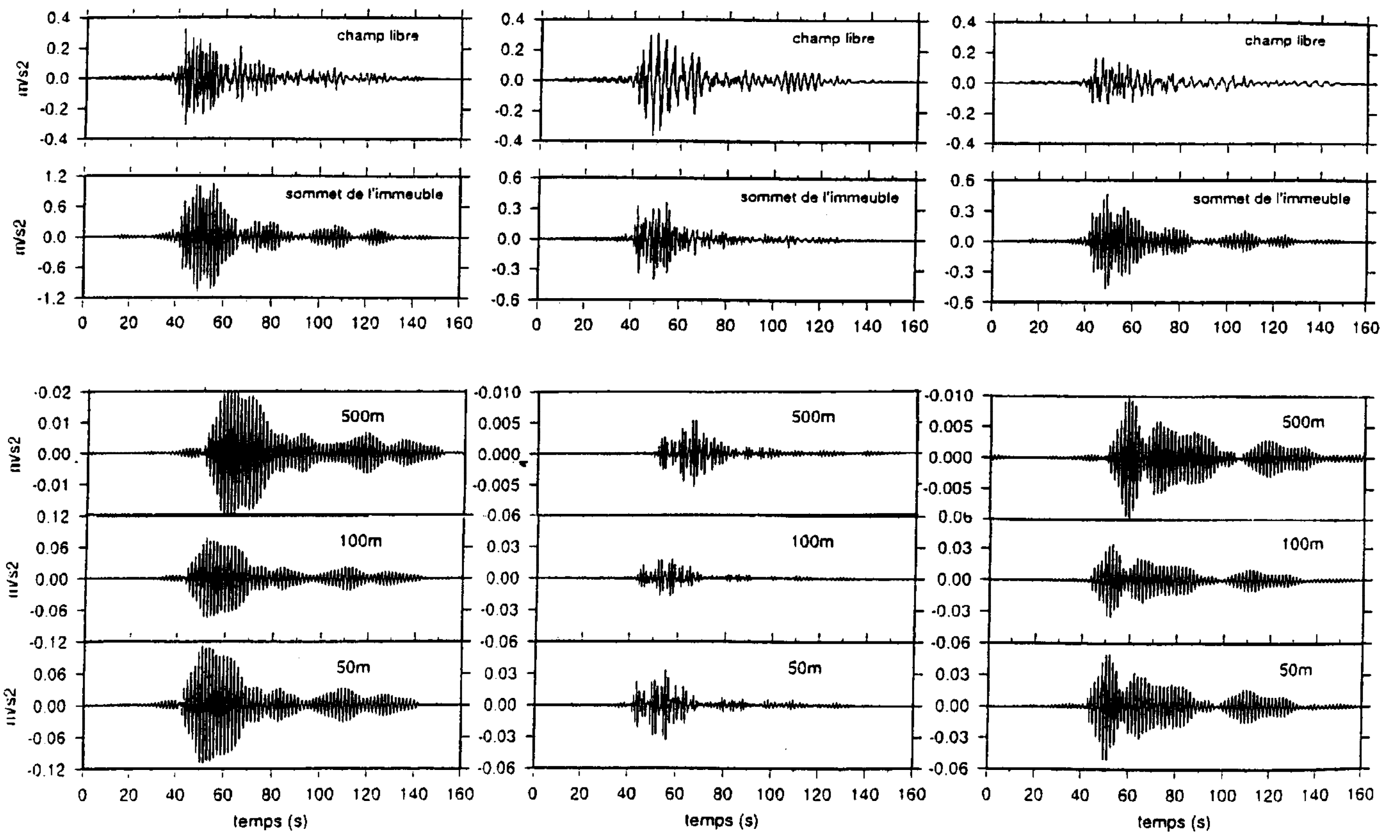

Figure 6 : *Surface motion radiated by the rocking moment in the three cases displayed in Figure 5, again in the case of an embedded (D=13 m) rectangular foundation. The top traces are the surface free-field accelerations, which would occur in the absence of any surface building. The second from top traces are the building response (longitudinal acceleration, center of mass). The bottom traces represent the surface acceleration induced by the rocking moment of the building, at various distances from building base.*

These results also present two more remarkable features. In the first ("worst") case, the peak acceleration due to radiated motion reaches 31 %, 23 %, 12 %, 6 % and 3 % of the free-field peak acceleration, for distances of 50, 100, 200, 500 and 1 000 m, respectively. These values are very significant, and comparable, at close distances, to values obtained in the 2D SH model presented in Bard and Wirgin (1995): the very strong interferences they predicted in the case of small inter-building spacing, are therefore likely to occur also in the 3D, much more realistic case. From another viewpoint, it is worth noticing that the radiated motion presents, in cases 1 (H = 25 m) and 3 (H = 75 m) some kind of beating phenomena, often observed in Mexico City, and which are due in the present case to the proximity of soil and building frequencies.

DISCUSSION AND CONCLUSIONS

The previous model used in Bard and Wirgin (1995) had three main drawbacks. Its 2D character lead to an overestimation of the long-distance effects because of the zero geometrical spreading of surface waves in 2D media. Consideration of antiplane motion only allowed to account only for translational soil-structure interaction, while the most important one is the rocking one, corresponding to inplane motion. And building base had to be specified at soil surface, which prevented to consider any foundation embedment, which is, however, almost always required in case of large structures on soft soils. The "new" model presented above, despite its relative simplicity, allows to overcome these three limitations, and is therefore much more realistic.

It still presents, however, some shortcomings: for instance, it can only account for already known impedance functions, which restricted our computations to a limited class of foundations (in particular, the imortant case of deep pile foundations, which considerably limit the rocking motion, could not be addressed). This limitation may, however, be rather easily overcome, at least partly, with the help of simple cone models as proposed by Wolf (1994). More importantly, our model is valid only in the linear range. This may be considered as a serious limitation, since strains developped at the soil-foundation interface may reach large values. However, our aim in this presentation remains essentially a qualitative one, much more than a quantitative one: we still want to answer the question: may such SSI effects significantly affect the *ground motion* ? Would the answer be *no* in the elastic range, then there will be no need for any further non-linear check, since non-linear dissipation mechanisms will certainly diminish the efficiency of wave radiation from the foundation.

Despite these limitations, this model lead, in our opinion, to significant and interesting results. The radiated wavefield has - as expected - a very low amplitude when the soil stiffness is large (Vs > 300 m/s), while it becomes significant on layered soft soils when the building frequency is close to the soil natural frequency. In such cases, the rocking moment is shown to radiate more energy along the surface than the base shear force, and embedded foundations to induce a more efficient radiation than surface foundations (because of their larger stiffness). For realistic configurations representative of the Mexico city case (i.e., 10 and more story buildings founded on very soft clay), the induced motion is found to reach up to one third of the actual free-field motion within a hundred meters from building base. In addition the obtained waveforms exhibit characteristic monochromatic wavetrains which resemble some of the late sections of long duration records obtained in Mexico city during the 1985 and later events.

As already emphasized in Bard and Wirgin (1995), these theoretical results are supported by the observations reported in Jennings (1970) and Kanamori *et al.* (1991), who recorded on distant seismographs (up to distances of a few kilometers) the vibrations induced in some Los Angeles buildings by roof actuators (Jennings, 1970) and shock waves associated with the reentry into the atmosphere of the Columbia space shuttle (Kanamori *et al.*, 1991). In addition, it has also been reported by Dobry *et al.* (1978) that the motion both of a building and of the relatively soft ground in its vicinity had a long duration, and Shaw (1979) attributed it to a sort of SSI mechanism (so-called "residual free vibration"). There also exist clear evidences from instrumental data recorded in buildings that rocking motion may be very significant (Bard *et al.*, 1992).

There is no doubt that the results presented here are still partial. Further studies are certainly needed to validate them with adequate instrumental recordings on one hand, and on the other to perform a more systematic sensitivity analysis, to account for other foundation types, and to estimate the effects of a heterogeneous, randomy distributed building stock. These new results, however, confirm our previous findings and indicate that, in a few cases at least, soil-structure interaction may induce a strong interrelation between the built environment and the surface ground motion, with two main practical consequences : a) the interpretation of "free-field" strong motion recordings in densely urbanized sites such as Mexico City should include the possible effects of buildings located in the "neighbourhood" (i.e., within a few hundred meters), especially for the late part of the records; and b) the design of ground motion for soft sites in highly urbanized areas should not be based only on seismological and geotechnical considerations, but should also pay some attention to the possibility of strong structure - soil - structure interaction with the surrounding buildings.

ACKNOWLEDGMENTS

These investigations have performed with financial support from the "Progamme National sur les Risques Naturels" of the "Institut National des Sciences de l'Univers".

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