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Effect of Built Environment on "Free-Field" Motion for Very Soft, Urbanized Sites

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Effect of Built Environment on "Free-Field" Motion for Very Soft, Urbanized Sites

Paper No. 7.04

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SYNOPSIS: A preliminary numerical investigation is presented on the long distance effects of soil-structure interaction for important buildings located on soft soils. A simple 2D model is considered, with homogeneous rectangular buildings resting on a single, horizontal, soft layer overlying a much stiffer half-space, impinged by SH waves. Computations are made for different parameter sets, in order to analyse the respective effects of the main parameters: clay layer thickness and frequency, building size, and spacing between buildings. For realistic building properties, wave diffraction related with soil-structure interaction is shown to alter the "free-field" surface motion up to distances of at least 1 km from the next building: duration as well as amplitude are significantly increased at some frequencies, while they may be reduced at other frequencies.

INTRODUCTION

The effects of surface geology on damage level and ground motion characteristics have been recognized for a very long time. However, one of the recent, most typical examples of such effects, i.e., the observations made in the Mexico City basin, and in particular the anomalously long duration of lake-bed accelerograms recorded during the Guerrero-Michoacan event (and since then during moderate-size events), have not yet received fully satisfactory explanations, despite the numerous studies and models proposed. At the end of their critical appraisal of most of these studies, Chàvez-Garcià and Bard (1994) conclude that, although most models account for both the spatial variability of ground response and its rather large amplitude at resonance frequencies, none can produce sharp enough resonance peaks to result in sufficiently long duration signals, at least for realistic damping values in the clay layer.

A remarkable feature of all these studies is that they take no account of the urban environment above the clay layer: the problem of ground response is always disconnected from that of the resonant response of buildings. However, it is known, on one hand, that the natural frequencies of any man-made structure are influenced by soil-structure interaction, especially on soft soils. And, on the other hand, it has already been noticed that *1)* the presence of structures at the surface of an otherwise homogeneous half-space can significantly modify the ground motion at distances at least one order of magnitude larger than the structure foundations (Trifunac, 1972; Wong _et al._, 1977), and *2)* irregularities at the free surface of a soft layer / bedrock medium, can modify the dispersive characteristics of Love (and Rayleigh) waves, and therefore modify the values of the characteristic frequencies associated with these modes (Wirgin, 1988).

Moreover, just as it was shown by Hill and Levander (1984), Levander and Hill (1985) and Chàvez-Garcià and Bard (1989), that irregularities in a sediment - bedrock interface enable a significant coupling of energy between body and surface waves, one can demonstrate a similar effect due to irregularities of the free surface (Wirgin, 1989; Chàvez-Garcià and Bard, 1990). It is therefore reasonable to expect noticeable changes in ground motion duration due to the presence of buildings that may be viewed as large surface irregularities.

Such expectations 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 soil-structure interaction mechanism (so-called "residual free vibration").

It therefore seems clear that, for the particular case of Mexico City, investigations should be performed on the effects of the presence of many high rise buildings, on the "free-field" ground motion, since the proximity of the natural frequencies of some buildings and of the clay layer may lead to a significant coupling. This is the object of the present contribution, which is indeed only a preliminary study simply aimed at determining whether or not such coupling may be significant.

DESCRIPTION OF THE MODEL

A city such as Mexico City is an assembly of blocks densely occupied by buildings of various sizes. Since we are interested here only in a *qualitative* appraisal of the possible effects of buildings, we *idealize* the complex, 3D reality by a periodic assembly of parallel, 2D blocks with a rectangular cross-section (i.e., similar to walls), of width *w* and height *b*, while the spatial period of the structure is *d* (Figure 1).

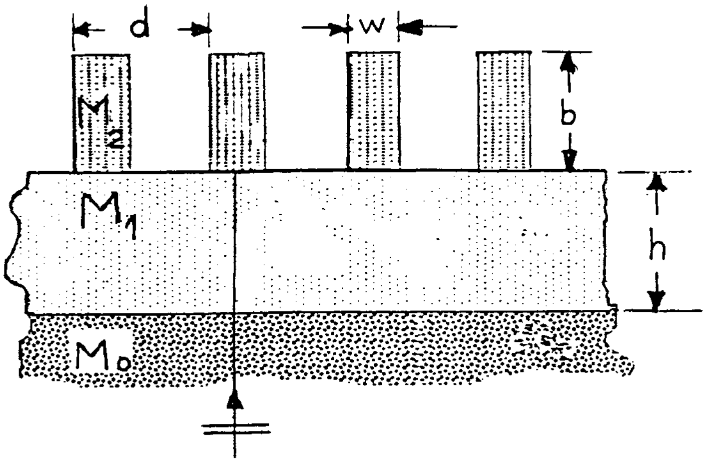

Figure 1: *Section view of the idealized city site*

Each such block, considered to be in welded contact with the ground, is assumed to be filled with an isotropic, elastic material (medium M2) whose characteristics represent the homogeneized properties of a building. The underground structure is also idealized as a horizontally layered half-space, with one surficial layer (M1) having a thickness h and the characteristics of the lacustrine clay, and an underlying substratum (M0) corresponding to the deep, stiffer sediments in Mexico City. For sake of simplicity, we consider here only the response of such a system to vertically incident plane SH waves (antiplane motion).

The numerical solution is obtained by the procedure described in Wirgin (1988): the field in each block is represented by a complete set of functions satisfying the free surface conditions on top and side walls, while the field in the stratified half-space is described by plane wave expansions. Continuity conditions at the boundary between M2 and M1 lead to a set of linear equations whose unknowns are the coefficients of the block functions, from which the amplitudes of the plane waves in the clay layer are computed.

By turning off the driving term (i.e., looking for normal modes in the absence of any excitation), one recovers the classical Love modes when the building height b vanishes. Inversely, when the thickness of the soft layer vanishes, one finds the so-called "Cutler" modes, well-known in electromagnetics (Borgnis and Papas, 1958). The wavefield in the ground, when both the clay layer and the surface buildings are present, may thus be viewed as a - coupled - superposition of vertically bouncing body waves and hybrid "Love-Cutler" surface modes.

RESULTS

The computations were made with the mechanical parameters listed in Table 1, and the geometrical parameters listed in Table 2. The "homogeneized" properties of the building are in good agreement with actual observations, since, for instance, the fundamental fixed base frequency of the building ($f_0 = \beta_2 / 4b$) matches well the formulae derived by Bard et al. (1992), from a comprehensive set of strong motion data ($f_0 = 25 / b$ for steel buildings).

The various models considered here allow to have an idea of the respective effects of building height, building mass, soft layer thickness, and of the spacing between buildings. One may also notice that a realistic value of damping was considered for the clay layer (1.667%). The motion was computed at various points: building top, building base, and six ground surface sites, equispaced from building base ($x = w/2 = 15$ *m*) to half distance between buildings ($x = d/2 = 50$ *to* 1000 *m*). Given the building dimensions, sites located more than 500 m from the building would certainly be considered, in usual practice, as "free-field" sites.

Table 1: Mechanical parameters of the models

Unit i	Density ρ_i (kg/m^3)	S velocity β_i (m/s)	Quality factor Q_i
Substratum (0)	2000.	600.	infinite
Clay (1)	1300.	60.	30.
Building (2) (a)	1300.	100.	100.
(b)	325.	100.	100.

Table 2: Geometrical parameters of the models

Models	Building			Clay
i	Height b (m)	Width w (m)	Spacing d (m)	Thickness h
1	50.	30.	2000.	0.
2	50.	30.	2000.	10.
3	50.	30.	2000.	50.
4	0.	30.	2000.	50.
5	5.	30.	2000.	50.
6	50.	30.	1000.	50.
7	50.	30.	400.	50.
8	50.	30.	100.	50.

Figure 2 depicts the Fourier transfer function of the motion at building top and at the farthest distance from building (*x = d/2*), for three different clay thicknesses (models a1, a2 and a3). The effect of soil-structure interaction is obvious for the building response, for which it induces a reduction of the fundamental frequency (from 0.5 Hz for rigid base to 0.223 Hz when *h = 50 m*) and a slight increase in amplitude. But it is also very significant at "free-field" site when the natural period of the ground is comparable to the natural period of buildings, i.e. for model 3: the 1D response of the clay layer is perturbed by ripples, which are characteristic of interferences between the direct body waves composing the actual free-field, and the "hybrid" Cutler/Love surface waves diffracted from the buildings. When the layer is thin, its fundamental frequency is much larger than building frequency, SSI remain very weak; but when the layer is thick enough to have a natural frequency comparable to the building frequency, then SSI becomes very significant and has consequences on both building and ground motion.

Figure 3 illustrates the influence of building height on both the ground and building responses (x = d/2 and building top, respectively). The building up of the interferences at distant ground surface appears very clearly for increasing building height, in relation with an increasing excitation of the "hybrid" Cutler/Love modes due to increasing irregularities.

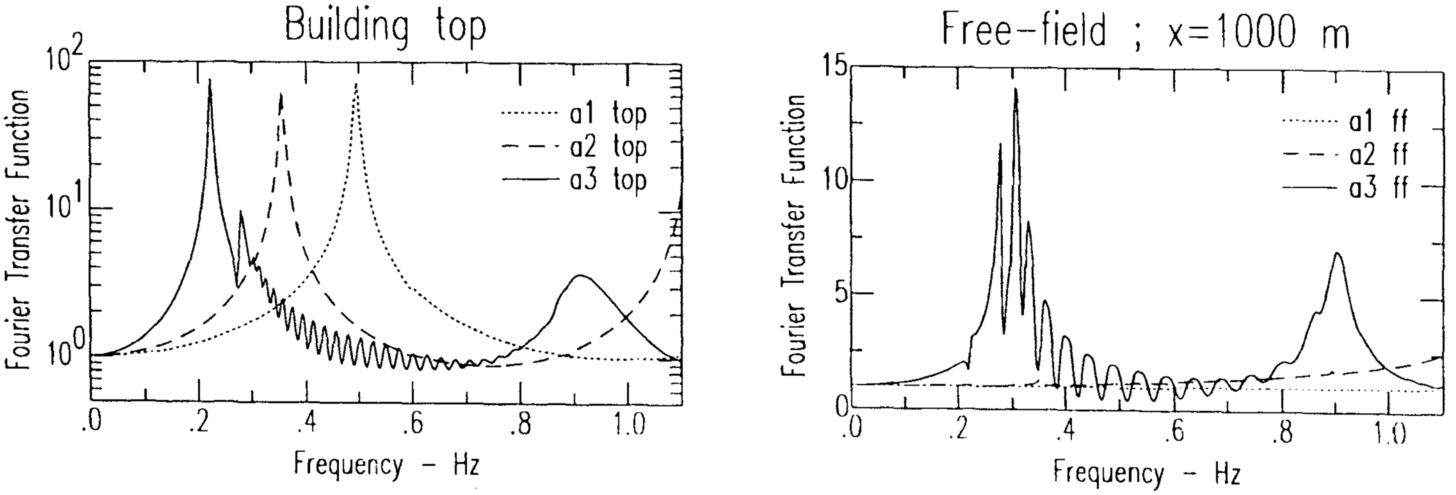

Figure 2 : *Fourier transfer functions at sites 1 (Building top) and 7 ("free-field", i.e., 1000 m away from buil-ding), for models a1, a2 and a3 (See Tables 1 and 2).*

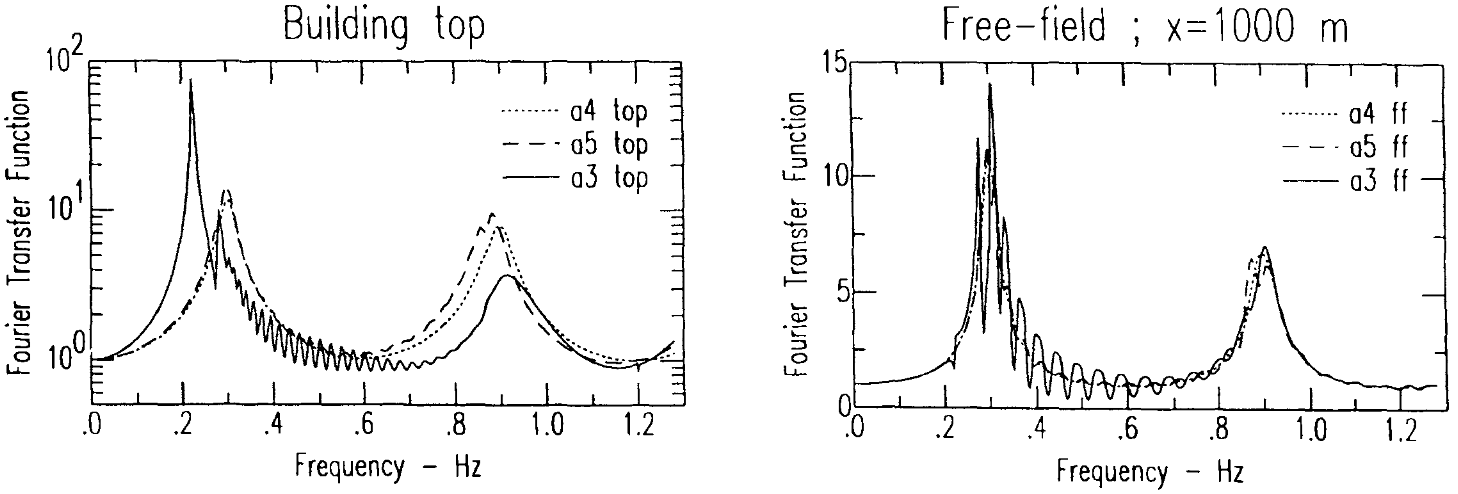

Figure 3 : *Fourier transfer functions at building top and "free-field"site (i.e., 1000 m away from building), for models a4, a5 and a3 (See Tables 1 and 2).*

Since the value of building density in Figures 2 and 3 (model a in Table 1) is too large, computations were also performed with a much lower, more realistic value (model b in Table 1). The resulting motions for model b3 at the 6 surface sites are displayed in Figure 4 for the frequency domain (Fourier transfer functions) and in Figure 5 for the time domain, where they are also compared with corresponding results for model a3. One clearly sees that, although the building mass is much lower, the effects of soil-structure interaction are significant up to distances of at least 1 km. Synthetic seismograms in Figure 5 confirm that the basic effects of buildings are to diffract waves back into the earth, that propagate as guided waves in the clay layer, with an ampitude, in the present case, reaching about 40% of the exact free-field amplitude. The comparison between models a3 and b3 also shows that building mass is not a crucial parameter in this interaction phenomenon, as far as ground motion is concerned: the amplitude of the diffracted waves is comparable in both cases (although building motions do differ significantly). These waves result in a significant increase in motion duration, as depicted by the comparison with the "reference synthetic" also shown on top of Figure 5, and corresponding to a single clay layer without buildings. Also noticeable in Figure 5 is the beating shape of synthetics, which - qualitatively - resembles the observations made in Mexico City since 1985 (Sànchez-Sesma <u>et al.</u>, 1993; Singh and Ordaz, 1993; Arciniega <u>et al.</u>, 1993), and which is related, in the frequency domain to the existence of sharp resonance peaks with narrow separation (splitting phenomenon).

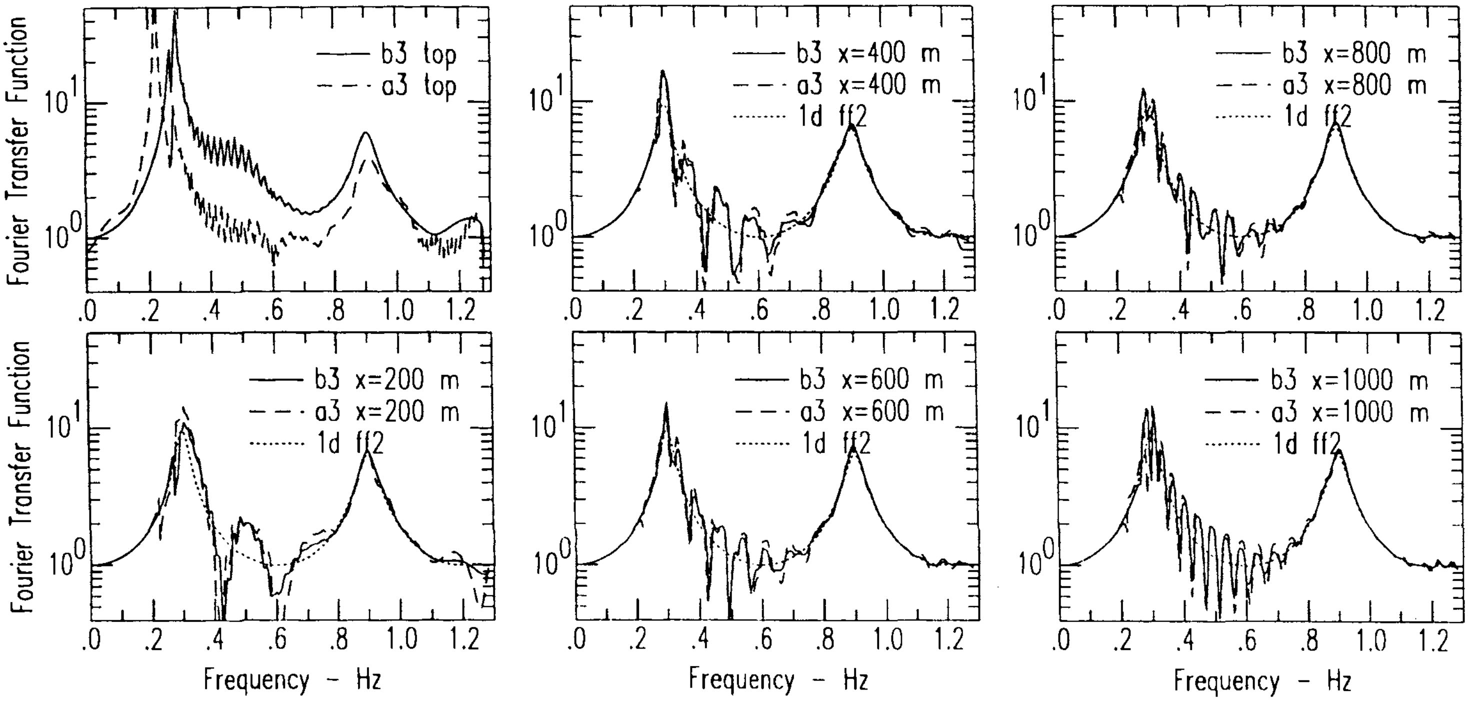

Figure 4 : *Fourier transfer functions at building top and various surface sites, from x=200 m to x=1000 m, for models b3 (solid line) and a3 (dashed line). Surface responses are also with the 1D response of a single clay layer (dotted line).*

The above results illustrate the possible effects for almost isolated buildings (d = 2 km). Reducing the building periodicity has strong effects on building motion and on ground motion as well, as illustrated in Figures 6 and 7. For instance, the structure-soil-structure interaction is shown to be very significant for very close buildings (d = 100 m), since roof motion decreases sharply (a factor of 3) at the fundamental frequency, while the first higher harmonics has a much lower frequency (from .9 Hz for d = 2 km to .45 Hz when d = 100 m), and a significantly higher amplitude. There also appears some frequency bands with large attenuation effects (around .6 Hz).

Simultaneously, the increased coupling between soil and structures for closely spaced buildings results in the splitting of the single layer fundamental resonance peak into several peaks (Figure 7); for a very high density of tall buildings (d = 100 m), this may even completely hide the soil frequency, since the whole system is now interacting and has its own natural frequencies: the "free-surface" response at .3 Hz varies from above 10 for true free-field sites to much less than 1 for d = 100 m, while it varies in the other way at .2 Hz and .45 Hz.

Although Figures 6 and 7 only display examples of results for oversimplified models, it allows to draw the following conclusions, at least for the particular class of building and soft layer characteristics that are considered here:

- when the building periodicity is large (here, more than about 400 m), the structure-to-structure interaction remains negligible, but the interferences between "free-field" body waves (vertically bouncing S waves) and the surface waves diffracted from building base significantly affect the ground motion (up to distances of at least 1 km), introducing ripples in the Foruier transfer functions and late phases in the time domain signals.
- when the buildings are close to one another (typically, less than a few hundred meters, i.e., for densely urbanized soft sites), the strong coupling between soil and surface structures gives rise to strong structure-soil-structure interaction (SSSI) phenomena, modifying not only the

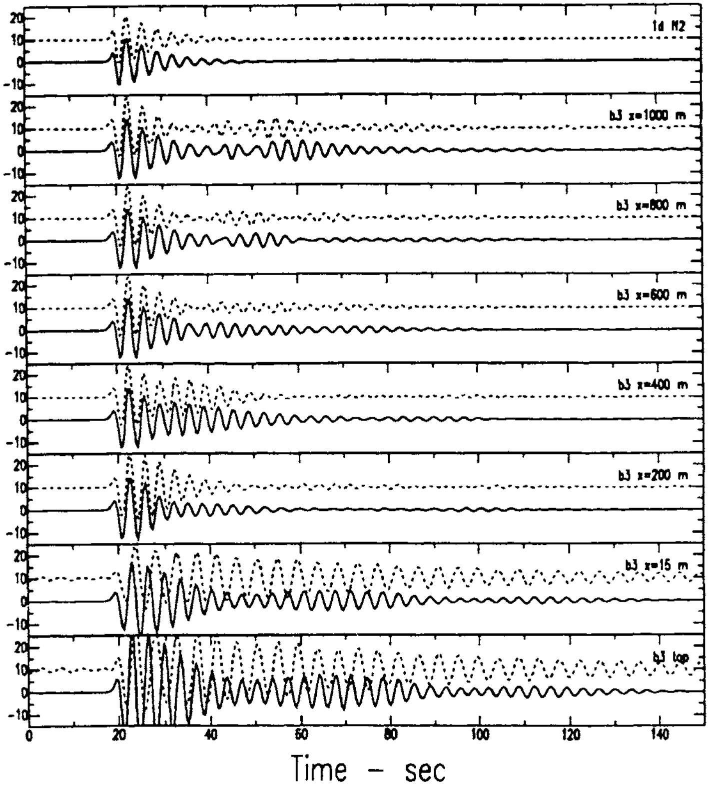

Figure 5 : *Synthetic seismograms at building top (bottom trace) and 6 surface sites (from x=15 m to x = 1 km) for model b3. The input signal is a Rickerwavelet having a characteristic frequency fp = 0.28 Hz. (Also compared with the 1D response of a single clay layer shown on top, and with the synthetics obtained with models a3, shown in dotted lines).*

amplitude of building motion, but also their frequencies; and it also completely modifies the characteristics of ground motion, altering the whole spectrum, including the location of the fundamental frequency. The notion of "free-field" station then becomes very uneasy to define...

DISCUSSION AND CONCLUSIONS

Soil structure interaction and soil amplification have both been known and recognized as important for a long time. The present results simply correspond to some specific cases, such as Mexico City, where they are strongly coupled: the existence of tall buildings on very soft soils gives rise to a strong soil-structure interaction, and the resulting waves diffracted from the building back into the soil are trapped and guided in the surface layer because of the very high impedance contrast with the stiffer substratum.

There is no doubt that the results presented here are only partial. They correspond to a very idealized, very simplified model of the Mexico City urban site: only the antiplane motion of a 2D periodic assembly of blocks was considered, without any consideration either of the possible lateral variations in the geological structure (clay layer, underlying sediments, basin shape,...), nor of the inplane motion, nor finally of the 3D nature of buildings. While the latter certainly diminishes the importance of the guided waves diffracted at the building / soil interface (simply because of the geometrical spreading of surface waves, which does not exist in 2D models), the two former would probably - in our mind - enhance them: on the one hand, lateral irregularities generally induce a better trapping of energy in surfical layers; and on the other hand, soil-structure interaction is much more efficient for rocking (corresponding to inplane motion) than for translational motion (corresponding to antiplane motion), while the results of Levander and Hill (1985) compared to those of Hill and Levander (1984) also suggest that the effect of irregularities is larger for in plane motion than for antiplane motion. And there exist clear evidences from instrumental data recorded in buildings that rocking motion may be very significant (Bard et al., 1992). From another point of view, the actual building distribution in any city (even North American cities...) is far from being periodic; the diffraction effects at the soil-structure interface will however exist for

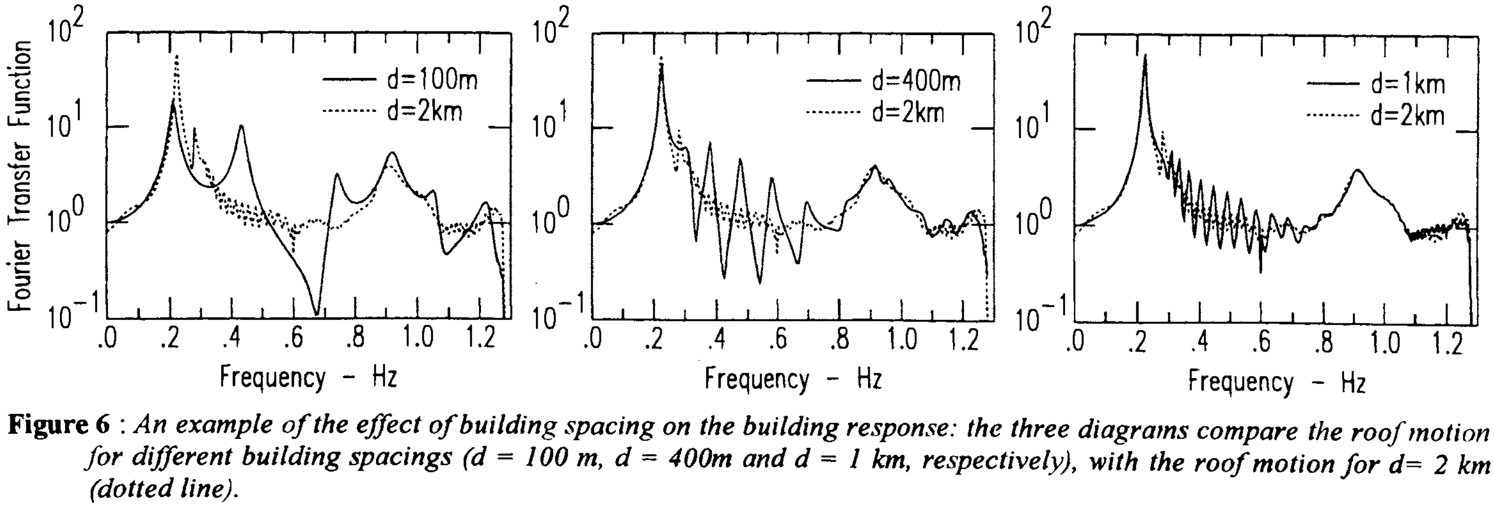

Figure 6 : *An example of the effect of building spacing on the building response: the three diagrams compare the roof motion for different building spacings (d = 100 m, d = 400m and d = 1 km, respectively), with the roof motion for d= 2 km (dotted line).*

all tall buildings whose fundamental resonance period is near to that of the soil.

We therefore feel justified to conclude that 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 meters), especially for the late part of the records, and that, inversely, the construction of tall buildings on soft soils might significantly modify the distribution, amplitude and duration of ground motion up to several hundred meters from its location. Further studies are under way to substantiate these qualitative conclusions in a more quantitative way, through investigations of inplane motion with both periodic and non-periodic distributions of buildings.

ACKNOWLEDGMENTS

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REFERENCES

Arciniega, A, E. Reinoso, and M. Ordaz, 1993. Duration of strong ground motion in Mexico City valley, *Seism. Res. Letters*, **64**, 19.

Borgnis, F.E. and C.H. Papas, 1958. Electromagnetic waveguides and resonators, in *Handbuch der Physik*, Vol. **16**, S. Flugge (Editor), Spinger, Berlin, 378-384.

Bard, P.-Y., H. Afra and P. Argoul, 1992. Dynamic behaviour of buildings : experimental results from strong motion data, in *Recent advances in earthquake engineering and structural dynamics, V. Davidovici editor*, Ouest-Editions, 441-478.

Chàvez-Garcià, F.J., & P.-Y. Bard, 1989. Effect of random thickness variations on the seismic response of a soft soil layer, Application to Mexico City, *Proceedings of the 4th International Conference on Soil Dynamics and Earthquake Engineering,* Mexico City, October 23-26, 1989, 15 pages.

Chàvez-Garcià, F.J., & P.-Y. Bard, 1990. Surface ground motion modifications by the presence of a thin resistant layer. Applications to Mexico City, *Proceedings of the 9th European Conference on Earthquake Engineering*, Moscou, Septembre 1990, Vol. **4-B**, pp. 37-46.

Chàvez-Garcià, F.J., & P.-Y. Bard, 1994. Site effects in Mexico City eight years after the September 1985 Michoacan earthquakes, *Soil Dynamics and Earthquake Engineering*, **13**, 229-247

Dobry, R., I.M. Idriss and E. Ng, 1978. Duration characteristics of horizontal components of strong motion earthquake records, *Bull. seism. Soc. Am.*, **68**, 1587-1520.

Hill, N.R. and. A.R. Levander, 1984. Resonances of low-velocity layers with lateral variations, *Bull. seism. Soc. Am.*, **74**, 521-537.

Jennings, P.C., 1970. Distant motions from a building vibration test, *Bull. seism. Soc. Am.*, **60**, 2037-2043.

Kanamori, H., J. Mori, D.L. Anderson and T.H. Heaton, 1991. Seismic excitation by the space shuttle Columbia, *Nature*, **349**, 781-782.

Kawase, H, and K. Aki, 1989. A study on the response of a soft soil basin for incident S, P, and Rayleigh waves with special reference to the long duration observed in Mexico City, *Bull. seism. Soc. Am.*, **79**, 1361-1382.

Levander, A.R. and N.R. Hill, 1985. P-SV resonances in irregular low-velocity surface layers, *Bull. seism. Soc. Am.*, **75**, 847-864.

Sànchez-Sesma, F.J., L.E. Pe,rez-Rocha, and E. Reinoso, 1993. Ground motion in Mexico City during the April 25, 1989, Guerrero earthquake. *Tectonophysics*, **218**, 127-140.

Singh, S.K, and M. Ordaz, 1993. On the origin of long coda observed in the lake-bed strong- motion records of Mexico City. *Bull. seism. Soc. Am.*, **83**, 1298-1306.

Shaw, D.E., 1979. Comment on "Duration characteristics of horizontal components of strong motion earthquake records" by Dobry, R., I.M. Idriss and E. Ng, 1978, *Bull. seism. Soc. Am.*, **79**, 2125-2126.

Trifunac, M.D., 1972. Interaction of a shear wall with the soil for incident plane SH waves, *Bull. seism. Soc. Am.*, **62**, 63-83.

Wirgin, A., 1988. Love waves in a slab with rough boundaries, in *Recent Developments in Surface Acoustic Waves*, D.F. Parker and G.A. Maugin (Editors), Springer series on Wave Phenomena, Berlin, 145-155.

Wirgin, A., 1989. Amplification résonante du tremblement d'une chaîne de montagnes cylindriques soumise à une onde SH, *C. R. Acad. Sci. Paris II*, **311**, 651-655.

Wong, H.L., M.D. Trifunac and B. Westermo, 1977. Effects of surface and subsurface irregularities on the amplitudes of monochromatic waves, *Bull. seism. Soc. Am.*, **67**, 353-368.

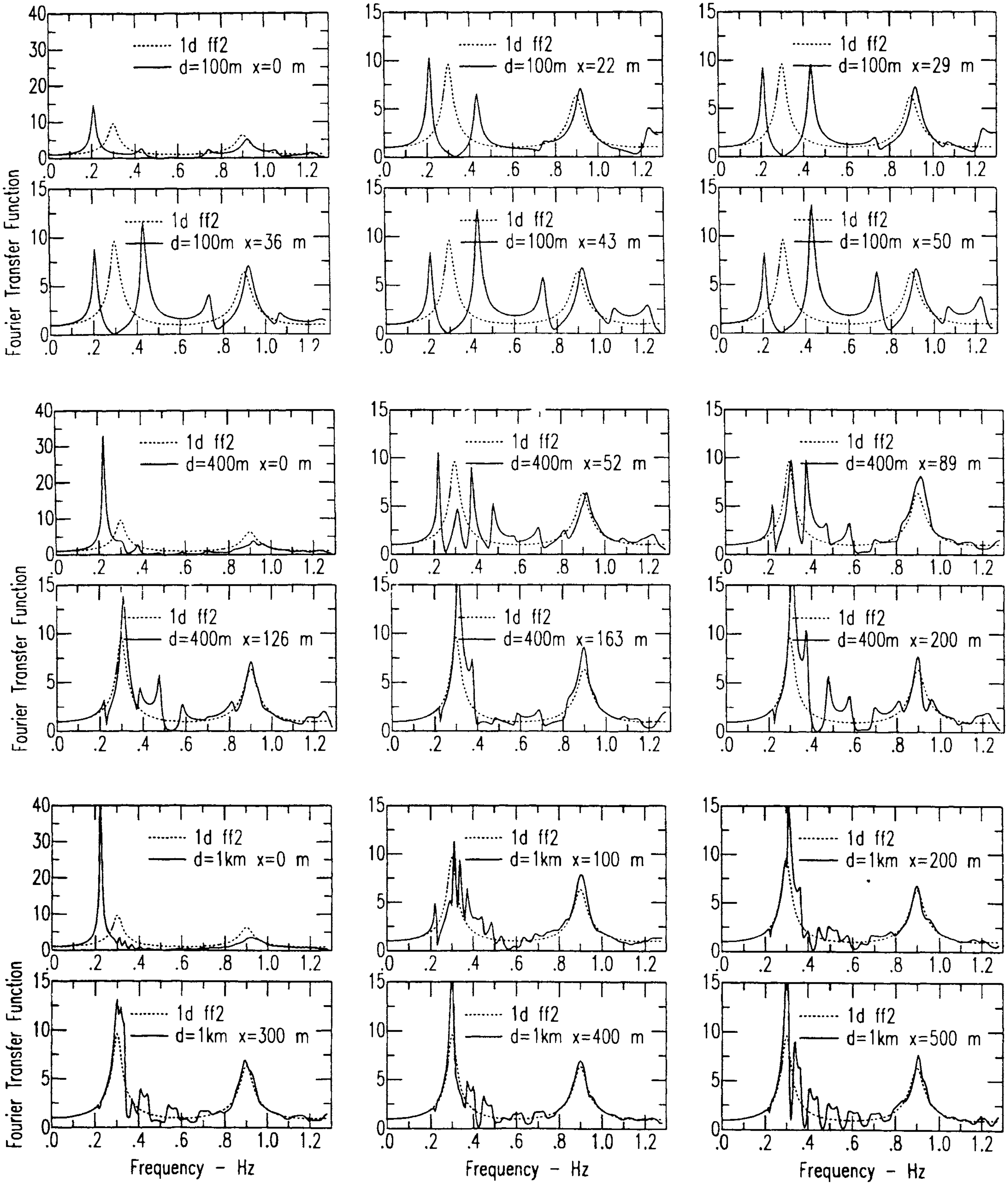

Figure 7 : *An example of the effect of building spacing on the surface motion. For three different building spacings (d = 100 m, d = 400m and d = 1 km, respectively), the Fourier transfer functions of motion are displayed for 6 surface sites, located from building base to half-way between buildings, and compared with the 1D free-field response of the surface layer without buildings (dotted line)*