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ENGINEERING SEISMOLOGY:SEISMIC HAZARD AND RISK ANALYSIS:SEISMIC HAZARD ANALYSIS FROM SOIL-STRUCTURE INTERACTION TO SITE-CITY INTERACTION

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SUMMARY

Site-city interaction is studied by using a red of buildings located on the Mexico City basin. A 3D modelling provided from vibrating system analysis and seismology method have been first used, which consisted in computing the total radiated wavefield caused by the shear base force developed at the soil-structure interfaces, when the structures are excited by seismic input motion. Finite elements method is also used, in case of simple red of buildings (2D modelling), in order to compute the multi-interaction effects. The radiated wavefield is compared to the input wavefield, to estimate the modification of the urban free-field motion.

INTRODUCTION

Seismic risk is usually defined by two ways: (1) the seismic hazard, which allows to define the seismic event by its fundamental built features and its spatial distribution on the studied zone and (2) the vulnerability, defined as the response of the environment, during an earthquake. The seismic risk corresponds then to the convolution of these two aspects. We know the building response is depending on the soil stiffness in (or on) which the buildings are founded. Despite the well-known effects of surface irregularities on the seismic motion, no seismic hazard studies take into account the urban environment as factor modifying the seismic ground motion. The buildings are usually considered as part of vulnerability, i.e. they suffer the seismic input motion without affecting the ground motion. However, it seems relevant to know the effects of the potential interaction between a densely urban environment, made of buildings with different features, and the ground motion. Moreover, the soil conditions may in some case induce a more efficient radiation, keeping the wavefield diffracted from the buildings trapped into the surface layers. Effects of site conditions have long been recognised as main part of damage distribution during earthquakes (e.g. the San Francisco (1906), Kobe (1995) and Mexico (1985) earthquake). For the case of Mexico, the surface seismic ground motion has been greatly amplified due to the very soft uppermost clay layer located in the so-called “lake bed” zone.

The main goal of the study is to analyse the effects of a group of buildings on the close free-field motion, when they are forced into vibration by a realistic seismic input motion. The Mexico City configuration has been selected. First, the present knowledge (experimental or numerical) concerning this topic is reminded. A 3D model, based on the substructure method, is then used to compute the single effect of a building array, made of three building categories. Second, a 2D model (Finite Element Method) is also used which allows taking into account the multi-interaction between buildings, as well as the 2D geometrical effect of the filling.

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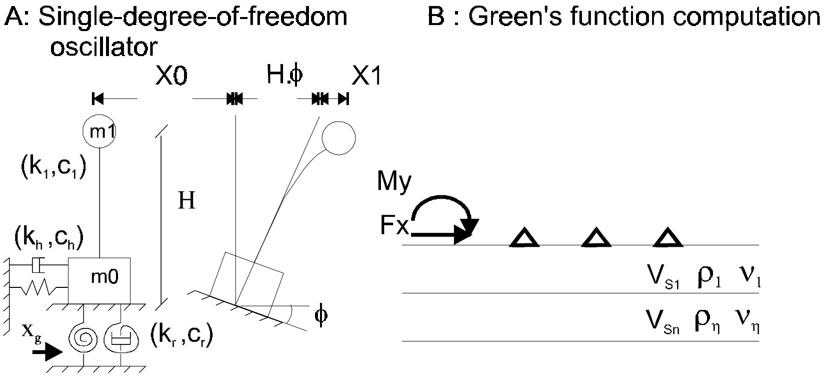

Figure 1: Modelling of the soil-structure system.

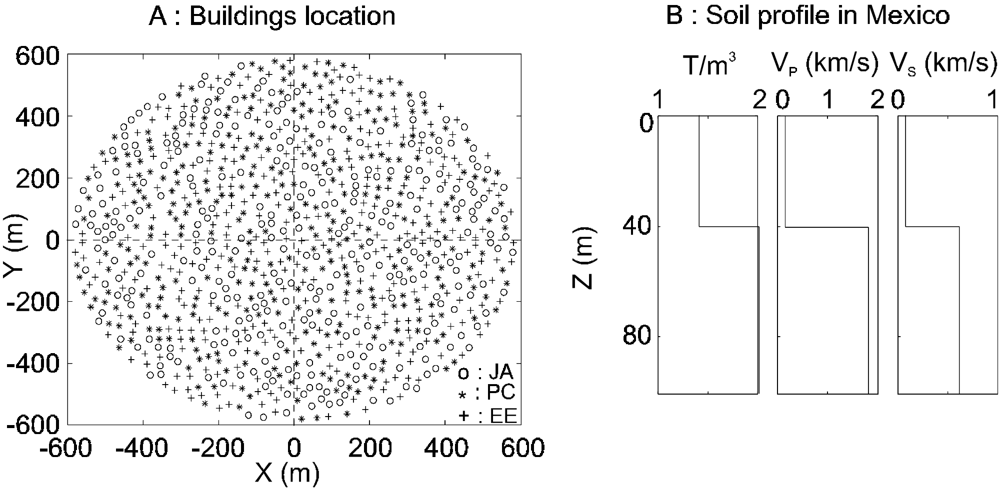

Figure 2: Site-City model

KNOWLEDGE

In 1954, Housner [1954] has shown by using simple models the effects of surface soft soil on the building response. Since, this Soil-Structure interaction effect (SSI), as well as the influence of structural and geometrical features of the building, has been confirmed by numerical studies [Novak, 1970; Bard et al., 1996] and by accelerometric data study [Bard, 1988; Bard et al., 1992; Paolucci, 1993; Stewart et al., 1999a, 1999b]. On the other hand, Jennings [1970] recorded the radiated wavefield back into the ground from a San Francisco building which was forced into vibration (Structure-soil Interaction StSI), up to a few hundred meters from the structure base. The recorded waveform was characterised by the building frequency itself. Kanamori et al. [1991] also observed the StSI effect provided by the vibration of San Francisco downtown high-rise buildings, which were excited by the shockwave produced by the re-entry into atmosphere of the Columbia space shuttle. A recent study [Erlingsson and Bodare, 1996; Erlingsson, 1999] has also reported and explained that, during a rock music concert which held in the Ullewi Stadium (Sweden), the audience started to jump in time to the music and produced violent vibrations level in the ground and the structure. This observation has been explained by the resonance phenomena between vibrating frequencies of the surface soft clay deposit layer of the ground and of the beat of the music. Moreover, the StSI wavefield has been analysed by a recent experimental study performed at the Volvi site test (Greece) [Guéguen and Bard, 1998]. It consisted in recording the surface free-field motion by a 3C-seismic temporary network during series of pull-out-tests, performed on a 1/3-scale RC-building model. The results show a monochromatic wavefield at the building frequency, a time decrease on the records corresponding to the building damping and a spatial decrease related to the geometrical damping factor of body (1/r) and surface ($1/r^{1/2}$) waves, at near and far field respectively.

Recent 2D [Wirgin and Bard, 1996] and 3D [Bard et al., 1996] modelling studies allowed to compute the wavefield radiated from seismically excited buildings, in case of soil configuration close to those of the lake-bed zone of Mexico city, so-called Soil-Structure-Soil Interaction (SSSI) effects. The ground motion computed at the surface of the uppermost soft clay layer show long-duration signals, in comparison with free-field motion computed without buildings, and characterised by beatings. These studies also confirmed the aggravating configuration when buildings and soil frequencies are close: it is the Site-Structure Interaction (SiSI) effect. These particularities have been observed at Mexico City, during the Guerrero-Michoacan earthquake (1985). Although most models account for the large amplitude of the ground response at resonant frequencies, none of them can reproduce the long-time and beating signal [Chavez-Garcia, 1991]. High coupling between SiSI provided from the totality of buildings and ground motion amplification due to site effects of the Mexico basin (3D-site effects) might explain the modifications of the seismic motion observed in the densely urban area of Mexico City: it is therefore a “group” effect that we will call in the following “Site-City Interaction (SCI)”.

MODELLING

Multi-degree of freedom system (MDOF)

Principle

This first analysis consists in modelling the structure as an equivalent vibrating system characterised by a stiffness-damping couple (k_1,c_1), with a mass m_1, resting on the soil through a square footing with a mass m_0 (Fig. 1a). Derived from the classical equation of motion, the motion of the MDOF system submitted to the input seismic motion (x_g) is computed. The induced shear force and rocking moment are then computed at the soil-base interface, which are associated to surface point seismic sources. The induced wavefield radiated back into the stratified half-space is computed at several surface receiver points by using Green’s functions computed with the modified Discrete Wave Number technique [Hisada, 1994, 1995]. This modelling has been used and validated by comparing numerical results to experimental data obtained during a field experiment performed at the Volvi (Greece) Euro-Seistest site [Guéguen and Bard, 1998].

Theory

Deduced from the equation of motion, the three motions of the MDOF system are obtained as follows (Fig 1a):

$$\begin{Bmatrix} X_1 \\ X_0 \\ \phi \end{Bmatrix}(\omega) = -\bar{p}\,x_g(\omega)\,\omega^2\left[\bar{\bar{K}}_t - \bar{\bar{M}}\omega^2\right]^{-1} \tag{1}$$

where X_1, X_0 and ϕ are the structural distortion, the horizontal translation and the footing rocking, respectively, for a harmonic input motion x_g having an angular frequency ω, p the mass vector $\{m_1 \;\; m_0 \;\; 0\}^T$ and M and K_t the mass and impedance matrix, respectively, as following:

$$\bar{\bar{M}} = \begin{bmatrix} m_1 & m_1 & H.m_1 \\ 0 & m_0 & 0 \\ 0 & 0 & J_0 \end{bmatrix} \qquad \bar{\bar{K}}_t = \bar{\bar{K}} + i\omega\bar{\bar{C}} = \begin{bmatrix} K_1 & 0 & 0 \\ -K_1 & K_h & K_{hr} \\ -H.K_1 & K_{rh} & K_r \end{bmatrix} \tag{2}$$

J_0 is the centroidal inertia moment of the footing, K_1 the structure impedance defined by its angular frequency ω_1, its static stiffness k_1 and its damping ξ_1, so that $K_1 = k_1 + i\omega c_1$ ($k_1 = \omega_1^2 m_1$; $c_1 = 2\omega_1 m_1 \xi_1$) and K_i the soil-structure impedance functions for the horizontal translation ($k_h + i\omega c_h$), rocking ($k_r + i\omega c_r$) and coupled horizontal displacement-rocking ($K_{hr} = K_{rh} = k_{hr} + i\omega c_{hr}$). The impedance functions are provided by Sieffert and Cevaer [1992] bringing together impedance functions of surface footings published in the relevant literature. The forces applied on the soil at the soil-foundation interface are derived from the footing motion according to the complex formulation of impedance functions:

$$\begin{Bmatrix} Fx \\ My \end{Bmatrix}(\omega) = \begin{bmatrix} K_h & K_{hr} \\ K_{rh} & K_r \end{bmatrix}\begin{Bmatrix} X_0 \\ \phi \end{Bmatrix}(\omega) \tag{3}$$

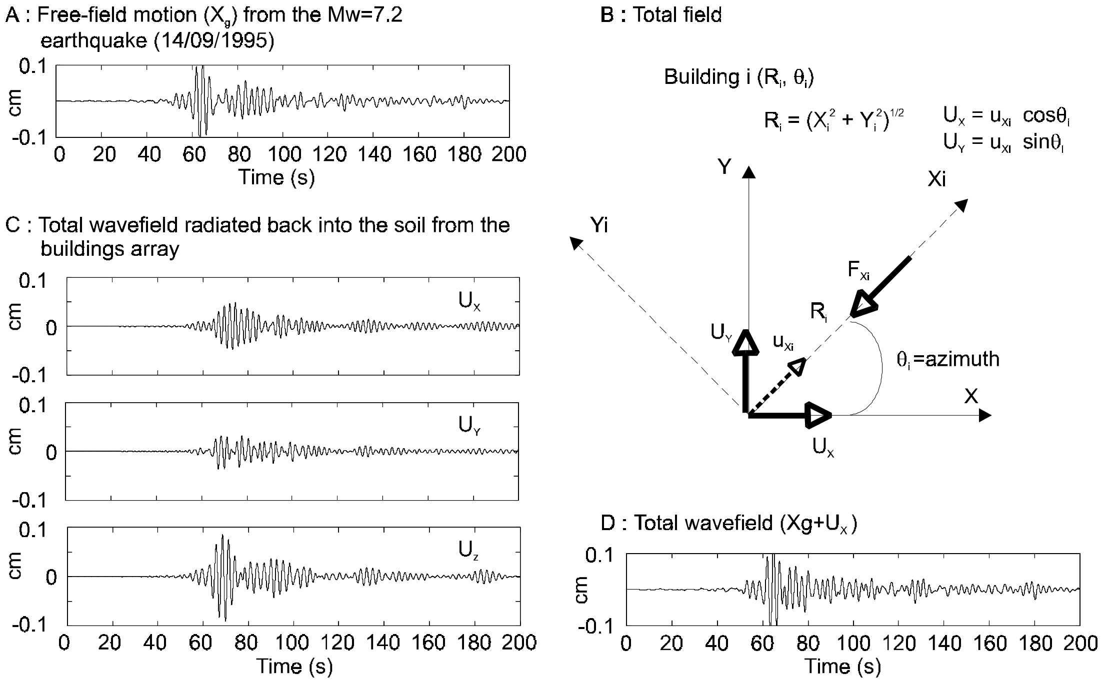

Figure 3: Input seismic motion and radiated wavefield from the building array

where Fx(ω) and My(ω) are the shear base force and the rocking moment, respectively (Fig. 1b), which induce an additional surface soil motion, computed by Green's functions [Hisada, 1994; 1995].

Using this modelling, recent studies [Guéguen, 1995; Bard et al., 1996] have shown the soil stiffness effect on the building response, the higher energy radiated back into the soil due to the force than due to the moment, in case of embedded footing, and the effect of resonance between building and soil frequencies for keeping high energy of the radiated wavefield within a hundred meters from building base. In this study, and in order to simplify the modelling of the building red and to get rid oneself of impedance functions using, we consider only the effect of the shear base force and the building response is computed as for a fixed-base structure, by the following formulation:

$$X_1(\omega) = -x_g(\omega)\omega^2\left[K_1 - m_1\omega^2\right]^{-1} \tag{4}$$

As previously shown [Guéguen, 1995; Bard et al., 1996], considering the soil-structure system as an equivalent fixed-base structure does not modify the building response, and consequently the diffracted wavefield, except for the fundamental frequency of the system. Even if the soil-structure interface is considered as a continuous contact along the footing length 2L and because of the distribution of Fx(ω), uniformly spreading along the footing length as smaller horizontal point forces, does not influence the wavefield characteristics at long distances, Fx(ω) is considered as an one point horizontal surface force, applied at the centre of the interface.

Results

A 950 buildings array, hasardly distributed on the 1200mx1200m surface disk, has been considered (Fig. 2a). Each building position has been referenced following its distance from the array centre and its azimuth with respect of the X-axis. Three kinds of structures (Tab. 1) have been selected in the Mexico housing stock, resting on the Mexico basin profile (Fig 2b).

Table 1: Buildings characteristics

Name	*JA*	*PC*	*EE*
2B,2L,H (m)	20,40,33	32,40,41	20,50,32
D (m)	5	17	5
m_1 (kg)	5.4 10^6	2.0 10^7	1.2 10^7
T_1 (s) - ξ_1	2.8 - 4%	2.9 - 4.5%	1.5 - 4%

These soil-structure systems have been seismically excited by the NS-component of the 14/09/95 (Mw=7.2) event, recorded at the Cup4 station, considered as Mexico survey reference. Therefore, the component is convolved by the theoretical soil column response to obtain the surface seismic motion, applied at the building base (Fig. 3a). The total wavefield radiated back into the soil from the building array is obtained by adding at the array centre the single building contributions (Fig. 3c). The shear base force induces a displacement field on the vertical component, as well as on the horizontal component (u_{xi}) in each building i reference (Xi, Yi) (Fig. 3b), parallel to the x_{gi} direction. The entire building array contribution exhibits a monochromatic wavefield which resemble to long duration records with beatings obtained in Mexico City during the 1985 and later events. The considered building array corresponds to a normal urban density, which provides an important radiated wavefield (around 100% of the seismic input motion, on the U_X component). By stacking the incident motion to the radiated wavefield (Fig. 3d), the free-field motion is clearly modified. This result is in conformity with those expected because of very soft thin filling (V_S=65m/s; H=40m). From an energetic point of view, the required energy allowing the vibration of the entire filling is close to those produced by the building array. Then, the effect of building array would be smaller in case of thicker layer.

Finite element method modelling

Principle

The CESAR-LCPC [Humbert, 1989] finite element code has been use for computing the 2D soil-city model response by direct time integration. The model is submitted to a dynamic input motion. A recent study [Guéguen et al., 1999b] validated this method used to model and study the wave propagation as well as the soil-structure interaction, for an isolated structure resting on stratified half-space. Each structure is modelled by linear triangular elements, with undamped homogeneous elastic features. The size of mesh elements have to be chosen to limit numerical damping and dispersion [Semblat, 1998]. In order to model the 2D-basin effect, and for avoiding artificial reflections at the boundaries of the model, a rectangular filling has been considered, surmounted an half-space supposed as infinitely stiff (i.e. high elastic modulus).

Results

Three kinds of buildings have been selected with homogeneous elastic features (density ρ_2, Poisson modulus ν_2 and Young modulus E_2, Tab. 2), resting on 600mx40m basin, made of uppermost layer of the Mexico basin (Fig. 4b). The input motion corresponds to a horizontal displacement applied at the basin base, time-dependent following a Gaussian function (Fig. 4a). The filling response computed at the surface by Fast Fourier Transform (FFT), without buildings (Fig. 4c, left), clearly exhibits the resonance frequency f_0=0.4Hz, which corresponds to the theoretical response of the soil layer ($f_0=V_S/4H$). The response of each kind of structure, performed by FFT of the horizontal displacement computed at the building top, depending on whether the structure is isolated or surrounded by other buildings (Fig. 4d). The total effect of the buildings array clearly appears on the figure 4c (right), where the horizontal displacement computed in time at the filling top is depending on the position of considered point. Therefore, the free-field motion is directly dependent on the urban environment: this is the so-called Site-City Interaction.

Table 2: Finite element modelling of buildings

Name	*B1*	*B2*	*B3*
2L,H (m)	40,60	20,40	30,30
D (m)	30	10	10
ρ_2 (kg/m^3)	300	300	300
ν_2	0.4	0.4	0.4
E_2 (10^8 Pa)	1.3	1.3	1.3

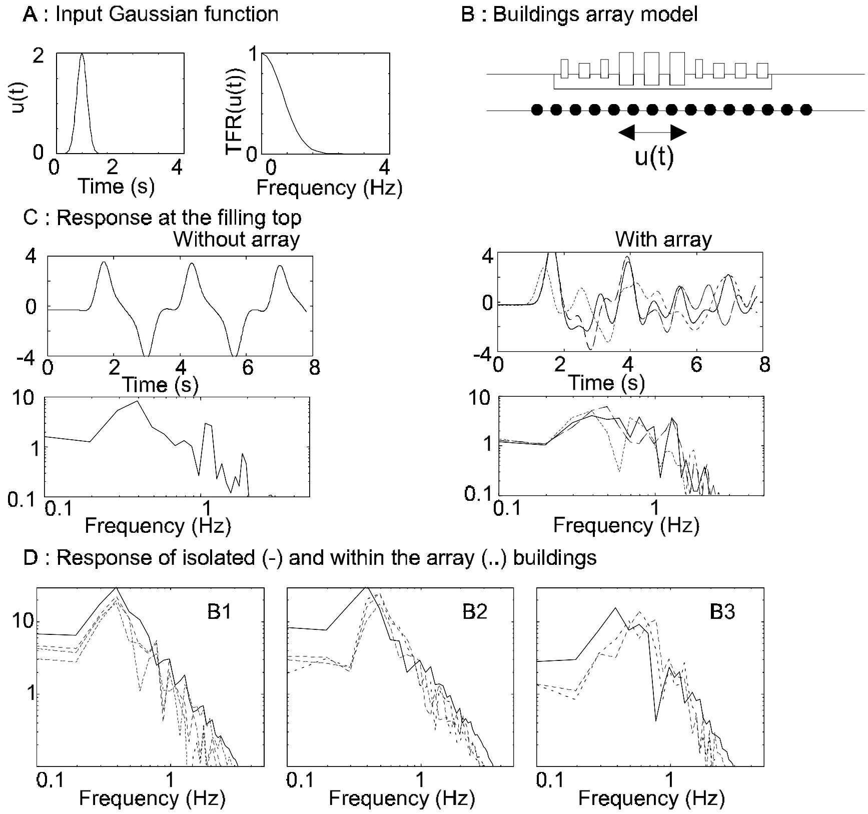

Figure 4: Finite element modelling results

CONCLUSION

This study allows us to confirm the potential effects produced by the city on the ground motion when buildings are forced into vibration by seismic input motion, under favourable conditions. We also note the interaction effect between structures, due to the surrounding building effects. The Mexico configuration (thin soft filling with high dense urban area) is one of the most favourable configurations to produce the Site-City interaction phenomena. Energy considerations show that the (*Kinematic energy in the soil layer/ Kinematic energy in the building stock*) ratio is large but Mexico is not the only case where such a phenomenon may occur (e.g. Nice in France). Thus, the city has to be also considered as part of seismic hazard and not only as vulnerability component in future seismic risk studies.

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