ECEE2026
18th European Conference on Earthquake Engineering

Assessing Seismic Interactions at Small and Large Scales: SSI, SSSI, SFSI, SCI and SFCI

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Abstract

The interactions between seismic waves, geological structures and constructions may be assessed at the local scale (Soil-Structure Interaction) or at the global scale (Site-City Interaction). At the local scale, impedance functions may be sufficient to account for the interactions. For strong motions, macroelement formulations may also be considered. At the global scale, surface wave generation and double resonance effect have to be considered. Interactions between alluvial deposits and building network is also a key issue. The combination of incident, amplified and radiated wavefields governs the global interactions. The local and global scales may also be accounted for simultaneously. The local structures may be described in great details (e.g. deep foundations) and the global interactions assessed through homogenization methods. The global Site-Foundation-City Interaction is strongly influenced by the features of the deep foundations. The final objectives are either to assess the urban seismic hazard more accurately or to incorporate such interactions in the seismic design of structures or building blocks.

Keywords: Soil-Structure Interaction, Site-City Interaction, Site-Foundation-City Interaction.

1- SEISMIC INTERACTIONS AT A GLANCE

Seismic events generate waves radiated from the fault and propagating in deep geological structures first [1]. Such body waves interact with the surficial layers to convert part of the seismic energy into surface waves (Rayleigh, Love, Stoneley). They also interact with human constructions such as tunnels, pipelines, bridges, dams, buildings, foundations [2-8]. In terms of seismic design, dynamic Soil-Structure Interaction (SSI) is known to strongly influence the structural response. At much larger scales, Seismic Site Effects (SSE) characterize the interaction between seismic waves and alluvial basins. Such interactions may also incorporate the waves radiated by structures at the free surface [3,6]. The so-called Site-City Interaction combines all these effects at the global scale. The main objective of this paper is to make the link between the local interaction (SSI) and the global interaction (SCI) by also accounting for the detailed structural features.

2- LOCAL INTERACTIONS (SSI)

The local interaction between the soil and a structure may be accounted for in different ways [9], see Fig.1.

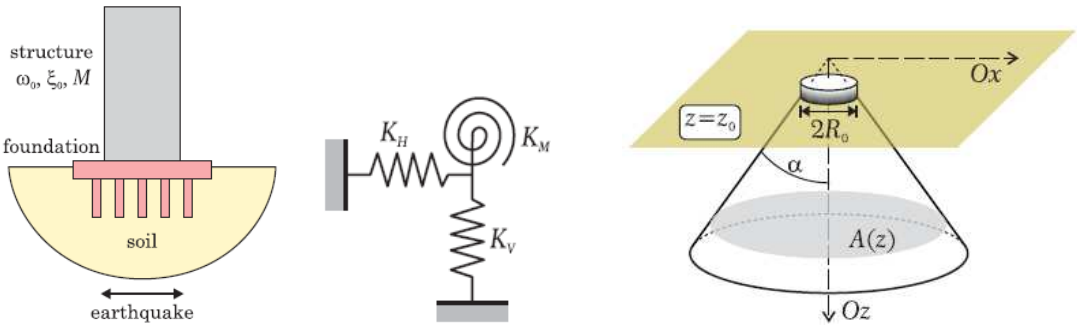


Figure 1 – Complex soil-structure configuration (left), impedance function assessment (middle), cone model description (right) [1,9].

As shown in Fig.1, the interaction between the soil and a complex structure-foundation system (left) may be investigated through impedance functions (middle) or cone models (right) to account for wave radiation at infinity. When compared to fixed base structural response, there are two main features of local Soil-Structure Interaction: softening of the soil-base connection and energy dissipation into the soil (either through wave radiation or material wave attenuation). In the case of strong motions, macro-element approaches help to consider the local nonlinearities around the foundation. Since the pioneering works are very old [9], SSI is nowadays well incorporated in seismic design procedures. The influence of wave radiation at the scale of several structures is less considered and will be detailed hereafter.

3- SURFACE WAVES AND INTERMEDIATE INTERACTIONS (SSSI)

The seismic waves propagated in various geological/geotechnical structures lead to significant amplification and duration lengthening [10-12]. The velocity contrast between the soil layers is a key parameter but the alluvial basin geometry also plays a crucial role [11]. In alluvial basins, surface waves may be generated at the basin edges strengthening the amplification process and possibly interacting with structural vibration. It is possible to characterize such surface waves from the so-called Normalized Inner Product in the time-frequency domain [13]. As shown in Fig.2 for two different geological sections in Rome (Fosso di Vallerano), the time-frequency plots (top) characterize the time windows and frequency bands leading to the largest amount of surface waves in the total wavefield [14]. The geometry of the geological profile strongly influences the generation of surface waves. Such surface waves may interact with the vibrations radiated from structures at the free surface.

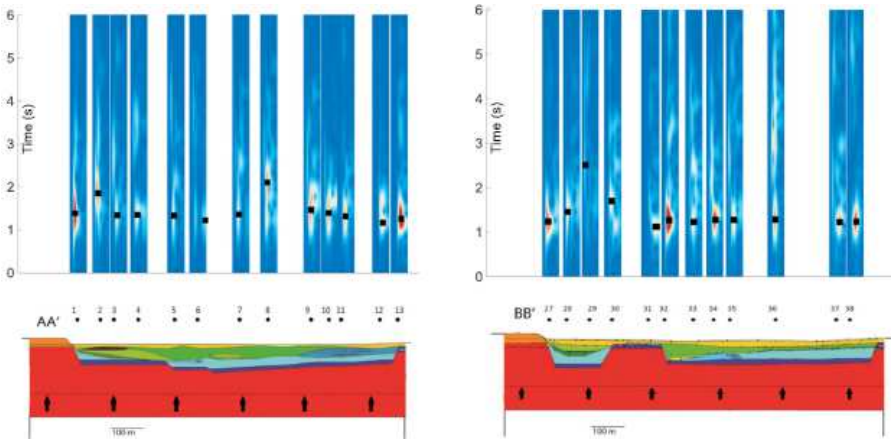


Figure 2 – Time-frequency transforms of vertical components of extracted Rayleigh waves on two different cross sections in Rome (Fosso di Vallerano valley [14]).

In Fig.3, the wavefield radiated by a structure vibrating at the free surface is computed. It simulates experiments performed at the Volvi EuroSeisTest site [1,15]. Due to the soil layering, the vibrations radiated by the structure were observed tens of meters away due to waves trapping in the surficial layers. It may thus lead to strong interactions between the surface waves generated at the basin edges and that radiated from the structure. We may also observe structure-soil-structure interaction for specific soil layerings [15].

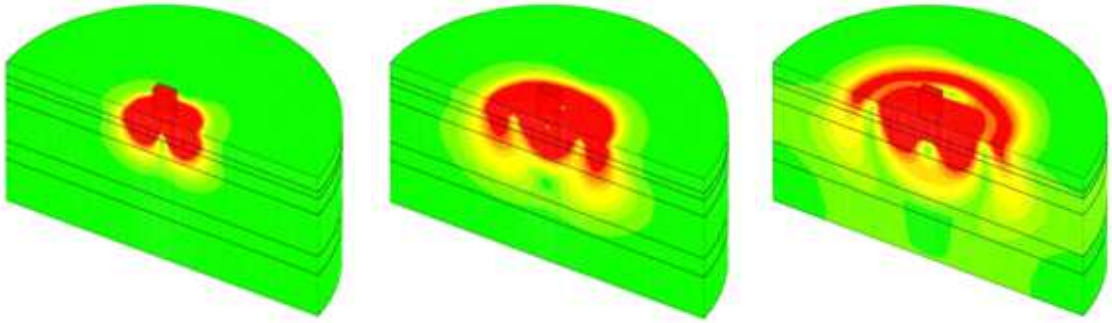


Figure 3 -: Wavefield radiated by a single structure in the Volvi EuroSeisTest site [1,15].

4- GLOBAL INTERACTIONS (SCI)

When considering a large buildings' network at the global scale, the interactions between basin-edge generated surface waves and vibrations radiated by the numerous structures become complex. Numerous studies have investigated such configurations either on the experimental side or the numerical side [15-25]. After the pioneering theoretical work of Wong & Trifunac [16] and Luco & Contesse [17], various observations were processed for the Volvi European test site [15] or in the built environment of Mexico city [18-20]. Simplified configurations were also investigated in order to assess complex site-city effects at the global scale [21-23].

Kham et al. [24] characterized the Site-City Interaction (SCI) at the scale of a large building network for horizontal soil layering: influence of the urban density, soil-structure double resonance effect, group effect, boundary effects, radiated wavefield, etc. Semblat et al. [25] assessed Site-City Interaction in an irregular alluvial basin. As shown in Fig.4 (left), the influence of the urban density is found to be very large. SCI is also influenced by the coincidence between the fundamental frequency of the alluvial filling and the eigenfrequency of the buildings. In Fig.4 (right), the eigenfrequency of each individual building is 1 Hz which is close to that of the deepest part of the basin. As shown on the plot, the perturbations due to the buildings vibrations are then radiated leftward in the deepest part whereas no energy is radiated rightward to the shallowest part. The surface waves radiated leftward are reflected on the left basin edge. Part of the energy is also reflected at the city left boundary.

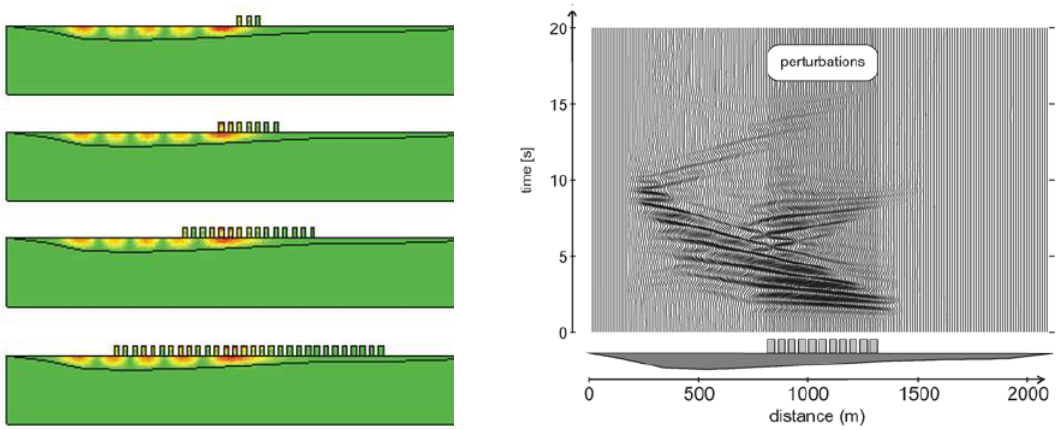


Figure 4 - Site-City Interaction for various building densities (left) ; Wavefield perturbations induced by 33 buildings with a fundamental frequency of 1 Hz and seismic Ricker excitation at 0.8 Hz (right) [25]**.**

In the case of an irregular city, Semblat et al. [25] evidenced the heterogeneous radiated wavefield (Fig.5, left). The tallest buildings on the left hand side (f_b=1Hz) radiate more energy that the smaller buildings on the right (f_b=2Hz). The urban density being less on the right hand side of the city, it also leads to less radiated waves. The energy ratios are given in Fig.5 (right): the perturbations are found to be much larger on the left hand side (energy ratio up to 60%) and for excitations close to f_b=1Hz.

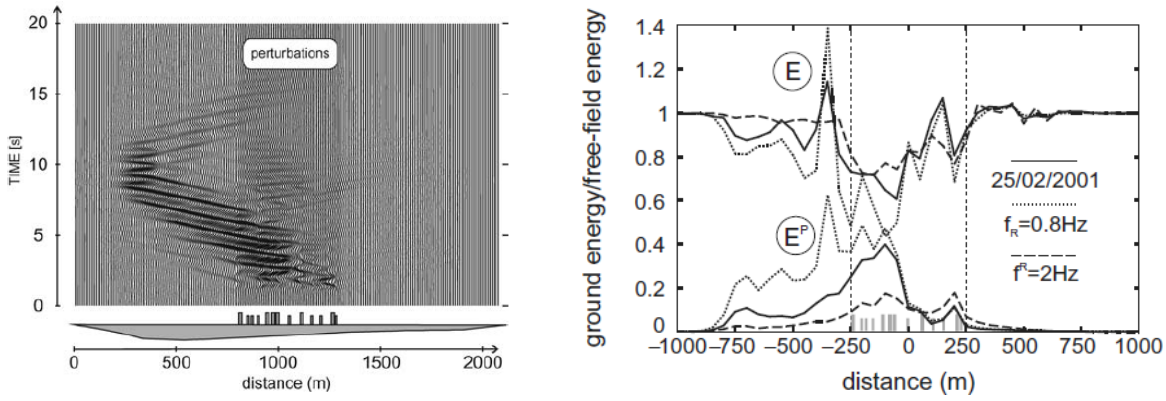


Figure 5 - Left: Urban ground motion perturbations induced by the irregular city for f_R=0.8 Hz; Right: Ground-motion energy along the basin for the irregular city under a Ricker wavelet (f_R=0.8 and 2 Hz) and the Nice 2001 earthquake [25].

In the work by Varone et al. [26], the city of Rome was considered at different urban development stages. As shown in Fig.6 (left), the perturbations of the seismic ground motion at an early urban development stage are mainly radiated leftward in the vicinity of the structure. For a more recent stage (Fig.6, right), the interactions between the site and the tall buildings are huge and the amplitude at the buildings' location is found to be much less. The impact on the vertical and horizontal components shows a significant discrepancy for the tallest building. The structure to structure interactions are also obvious on these plots.

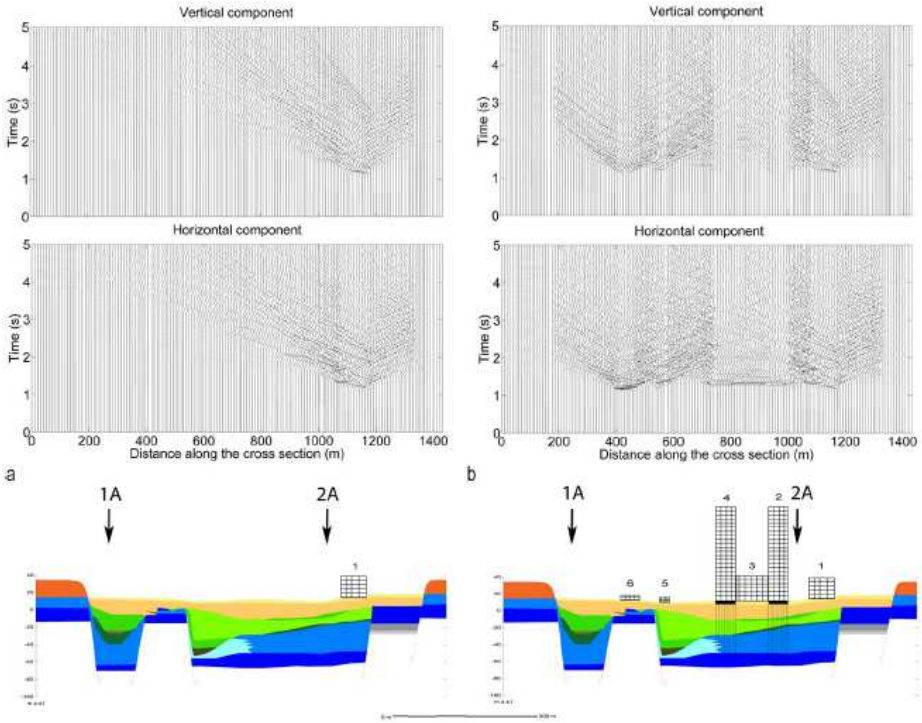


Figure 6 – Perturbations of the seismic ground motion in Rome at two different urban development stages: early stage (left, recent stage (right); vertical (top) and horizontal (middle) motion components [26]

5- MULTISCALE INTERACTIONS (SFCI)

In the previous sections, we detailed the local and intermediate interactions (SSI, SSSI) at the scale of one or several structures. At the larger scale of an alluvial basin, surface waves and global interactions have to be considered (i.e. Site City Interaction). If we combine a detailed description at the local scale and the global interactions at the basin scale, we may consider multiscale interactions. For such an objective, homogenization approaches were recently proposed to deal with a large building network in a wide alluvial deposit [27-28].

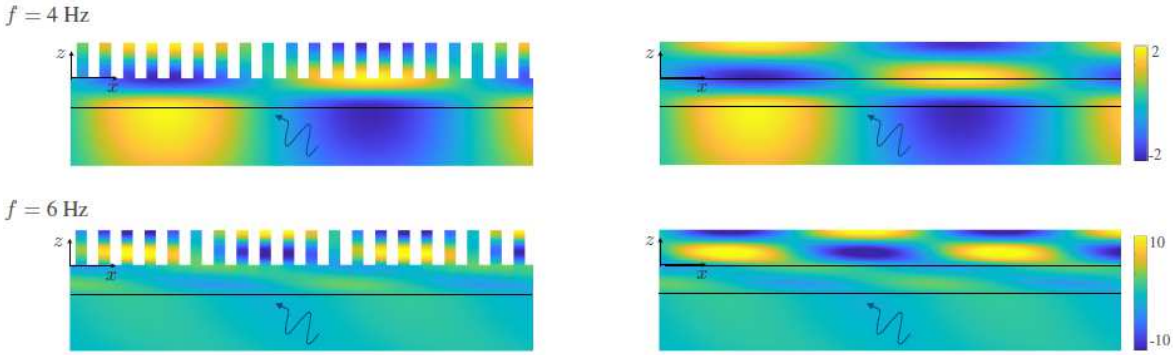


Figure 7 – Comparisons of the seismic responses of a building network simulated by a multimodal approach (left) and homogenized solutions (right) for an incident wave at 45° impinging on a city atop a soil composed of bedrock overlain by a sedimentary layer (h_C=30 m, φ_C=0.5, and h_L=25 m) at frequencies 4 Hz (top) and 6 Hz (bottom) [27].

As shown in Fig.7, the discrete building network (height h_C=30 m, urban density φ_C=0.5) is modeled in all its details (left) or as an equivalent homogeneous anisotropic layer (right) at the top of the alluvial layer (h_L=25 m) [27]. The buildings are founded on deep piles (h_F) and the deep foundations are also homogenized with the surficial sedimentary layer. The seismic response is computed for an incident wave (45°) at two different frequencies 4 Hz (top) and 6 Hz (bottom). As shown in Fig.7, the computed wavefield is the same in the bedrock and in the surficial layer for both models. The seismic motion in the buildings is found to be very close even if it is discontinuous for the discrete model (left) and continuous in the equivalent anisotropic homogenized layer (right). The homogenization approach is then found to be reliable to assess the seismic motion in a discrete building network [27].

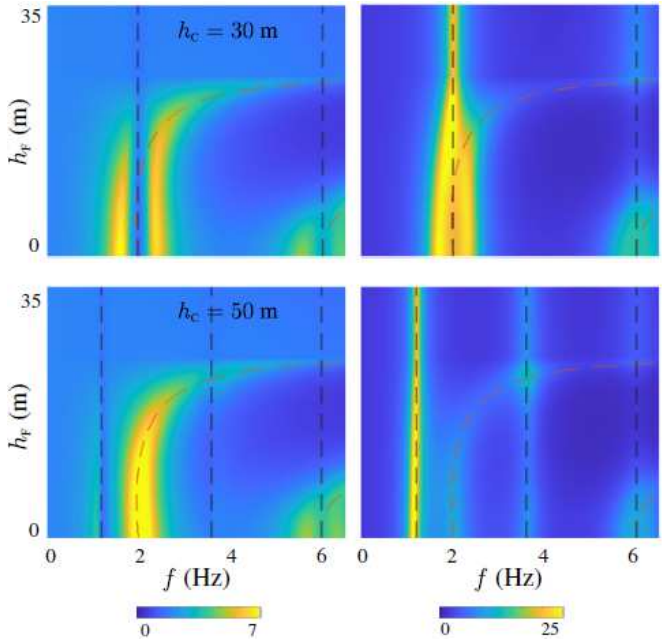


Figure 8 - Variations of $|u_{bot}|$ (left) and $|u_{top}|$ (right) as functions of frequency f and foundation depth h_F (with φ_F=0.15), for different building heights h_C (with φ_F=0.5). The vertical black-dashed lines indicate the resonance frequencies of the fixed-base buildings and the red-dashed lines indicate the sedimentary-layer resonance for h_L=25 m [27].

When introducing the deep foundations (Fig.8), we may assess their influence on the bottom $|u_{bot}|$ (left) and top $|u_{top}|$ (right) displacements wrt frequency f and foundation depth h_F [27]. The city density is chosen as φ_C=0.5 and the building height is either h_C=30m (top) or h_C=50m (bottom). The black dashed lines indicate the resonance frequencies of the fixed-base building and the red dashed line the fundamental frequency of the alluvial layer.

When the building frequency coincides with the fundamental frequency of the alluvial layer (top) the bottom displacement is very small (left) and the top displacement is very large (right). When both frequencies are different, the bottom displacement is larger and increases with the foundation depth (bottom left) whereas the top displacement is large in a very narrow frequency band (bottom right).

The Site-City Interaction is finally compared to the Site-Foundation-City Interaction in Fig.8. The top graphs correspond to Site-City Interaction (i.e. no deep foundations) for two different urban densities φ_C=0.1 and φ_C=0.5. The bottom displacement is plotted on the left-hand side showing a strong decrease of the amplitude with a double frequency peak effect. The top displacement is plotted on the right hand side showing a similar amplitude reduction.

On the bottom part of Fig.8, Site-Foundation-City Interaction is assessed. The bottom and top displacements are plotted for a foundation depth h_F=20m and two different foundation densities φ_F=0.015 (middle) and φ_F=0.15 (bottom). For the first value (middle), the displacement amplitudes are reduced and the double peak effect is much less. For the largest value (bottom), the amplitude reduction is even larger and the effect of the urban density is significantly reduced. As discussed in details in [27], the influence of deep foundations may be very large and Site-City Interaction may be significantly modified by incorporating such effects. The complexity of Site-Foundation-City Interaction for various urban configurations and complex alluvial fillings still has to be assessed and categorized.

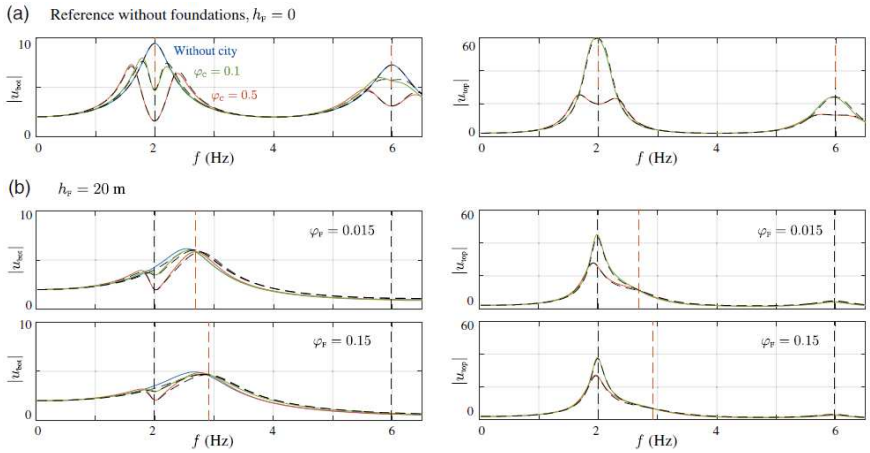


Figure 9 - Effect of foundation density: Displacement amplitudes $|u_{bot}|$ (left) and $|u_{top}|$ (right) as functions of frequency. (a) Reference without foundations and (b) with foundations of depth h_F=20 m. Multimodal simulations for h_C=0 (blue lines) and for h_C=30 m (green lines for φ_C=0.1 and red lines for φ_C=0.5). The results for foundation densities φ_F=0.015 and φ_F=0.15 show that foundation density significantly reduces resonance amplification [27].

6- FUTURE WORK

In this paper, SSI, SSSI, SCI and SFCI are assessed for weak motions and deep foundations. The optimization of the urban configuration may be analyzed as a metamaterial allowing the reduction of the seismic wavefield (e.g. 'metawedge' configuration [28]). The influence of strong motions should also be considered in order to account for the nonlinearities in the soil, in the structure and in the foundations. In saturated soils, pore pressure may also significantly influence the interactions [29].
Various homogenization approaches may also be considered for a detailed description of the structural behavior [3,30]. Recent numerical methods may also be implemented to compute the seismic and radiated wavefields (fast multipole or H-matrices accelerated BEM [12,31]). Instead of deep piles, rigid inclusions could also be modeled [32] in order to assess the changes in the SFCI. Finally, Structural Health Monitoring (SHM) may be generalized to "City Health Monitoring (CHM)" to characterize the effect of the global interactions on the behavior and potential damaging of a building network.

7- CONCLUSIONS

The effect of SSI is widely accepted nowadays [9]. The influence of basin edge generated surface waves and vibrations radiated by several structures have recently been accounted for [1-8, 10-20]. Waves radiated by traffic or construction works have also been investigated in the recent years [33-35]. At the scale of an entire city, the interactions are controlled by the coincidence of the fundamental frequencies of the alluvial filling and that of the structures [21-26]. The urban density and homogeneity are important governing parameters. Finally the multiscale analysis (i.e. homogenization) of Site-Foundation-City Interaction shows that deep foundations strongly change the effects of Site-City Interaction [27]. By stiffening the surficial layers, the deep foundations reduce the modification of the urban wavefield. Experimental data are also needed to validate these numerical results (e.g. in situ observations [18-20], centrifuge experiments [2]).

8- ACKNOWLEDGMENT

The author would like to thank all the colleagues and former students without whom some of the results would not have been reached: P.Y. Bard, S. Chaillat, F. Cuira, P. Dangla, S. Félix, C. Franco, P. Guéguen, M. Kham, L. Lenti, S. Martino, A. Maurel, K. Meza-Fajardo, A.S. Papageorgiou, J. Perez Herreros, K. Pham, M.P. Santisi d'Avila, Y. Shen, C. Varone.

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