Site-city interaction: Experimental and numerical approaches

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ABSTRACT

At the scale of a city, surface structures such as buildings can modify the "free-field" seismic motion and act like secondary seismic sources. A number of observations have been conducted on actual datasets; these have demonstrated that such an effect may indeed be significant. The direct consequence of this "site-city interaction" is the contamination of seismic motion in an urban setting by a secondary wave field. Both centrifugal and numerical modeling efforts tend to confirm that this phenomenon is not incidental. More specifically, results indicate that between two buildings located close to one another, interactions occur that modify not only the soil movement but also the response of structures subjected to the movement. At the scale of a city, this phenomenon will become even more pronounced whenever strong coupling exists between the soil response and the response of the urban environment.

Interaction Site-Ville : approches expérimentale et numériques

RÉSUMÉ

À l'échelle d'une ville, les structures de surface telles que les bâtiments peuvent modifier le mouvement sismique en « champ libre » et agir comme des sources sismiques secondaires. Des observations ont en particulier été réalisées sur des données réelles. Elles montrent que cet effet peut être significatif. La conséquence directe de cette « interaction site-ville » est la pollution du mouvement sismique en milieu urbain par un champ d'onde secondaire. Des modélisations en centrifugeuse et numériques tendent à confirmer que ce phénomène n'est pas anecdotique. En particulier, ces résultats montrent qu'entre deux bâtiments proches des interactions existent, modifiant le mouvement du sol mais aussi la réponse des structures impliquées. À l'échelle d'une ville, ce phénomène sera d'autant plus marqué lorsqu'un fort couplage existe entre la réponse du sol et la réponse du milieu urbain.

INTRODUCTION

For many years, structural engineers and geotechnical engineers have known that the soil-structure interaction (SSI) is capable of drastically modifying the behavior of a structure when it has been built on a soft soil. The seismology community recognizes the imprudence of installing seismological stations near trees or tall buildings, both of which can alter the seismic signal. Over the last few decades, it has also become clearly apparent that surface heterogeneities could exert a significant influence on the seismic signal. These effects, referred to as site effects (SE), are generally strongest in the presence of soft soils. Given this observation, it is entirely legitimate to ask how a building built on soft soil and subjected to a seismic loading disturbs ground motion in the immediate vicinity. In pursuing this rationale, it might also be questioned how an urban zone composed of several buildings will disturb urban seismic motion, simply by the effect of structural vibrations on the soil.

The goal of this article is to present an overview of these results and observations, which tend to indicate the existence of this type of global interaction between all buildings in any given city and its subsoil (such an interaction will be called herein "site-city interaction", or SCI). Despite an abundance of literature on the topics of soil-structure interaction and site effects, very little attention has been paid to site-city interaction phenomena. Such an oversight could signify that this interaction is indeed negligible, although if the site-city interaction effects turn out to be significant, then the construction or demolition of a building or a group of buildings may modify the seismic risk for neighboring structures. This situation might simultaneously lead to critical design changes, especially in terms of microzoning studies and urban planning policy.

EXPERIMENTAL CAMPAIGN

In situ observations

At the beginning of the 1970's, by forcing the Millikan Library building (on the Caltech campus) to vibrate, Jennings (1970) demonstrated that structural motion could be detected by seismological stations located as far as several kilometers away. The same experiment was recently repeated by Favella (2004) and confirmed the emission of waves propagating outside the building base. A second observation is associated with the atmospheric entry of the Columbia space shuttle during its return flight to Edwards Air Force base in California (Kanamori *et al.*, 1991). Two broadband seismological stations installed in Pasadena and at the University of Southern California ("USC", in central Los Angeles) recorded a 2 or 3-second period pulse, which arrived in Pasadena 12 seconds before the shockwave and at the USC facility 3 seconds after the shockwave. Kanamori *et al.* (1991) clearly distinguished this pulse as being caused by the motion of downtown L.A. skyscrapers, which began vibrating due to the effect of the shockwave propagating in air. These authors added that the similarity of the period specific to the skyscrapers with that of the L.A. Basin transfer function served to exacerbate the coupling between buildings and soil. More recently, during the terrorist attacks on the World Trade Center, the impacts of the two airplanes were recorded by several seismological stations across New York state, at distances in the tens of kilometers (Kim *et al.*, 2001), indicating once again that structural vibrations were responsible for generating seismic wave fields propagating into the soil. Moreover, a temporary seismological experiment conducted in Grenoble (Cornou *et al.*, 2004) revealed the effect of the presence of a chimney on the seismic background noise recorded on the ground.

In these four observations however, the building excitation was artificial, yet all four have underscored the fact that cases exist where the energy of a vibrating building may be transmitted efficiently (via strong coupling) to the soil. The same kind of phenomena can occur when building vibration is caused by ground-level excitation. In this case however, direct observation proves much more difficult since soil motion in the vicinity of buildings entails a superposition of the direct seismic wave field and the field diffracted by the building; only very dense networks of seismographs allow for separating the various contributions. During an experiment carried out at the Volvi test site (Greece), seismological sensors set up adjacent to a reduced-scale concrete structure detected special waves propagating from the structure (Guéguen and Bard, 2005), which had been exposed to explosive blasts detonated nearby. These waves displayed a period identical to that of the structure, and their amplitude attenuated with distance to the structure (see **Fig. 1**). Another interesting set of observations stems from the Ullevi Stadium in Gothenburg (Sweden), which was subjected to unexpected vibrations, as reported by Erlingsson and Bodare (1996) and then Erlingsson (1999). During a rock concert held at the stadium, spectators on the field began jumping to the beat of the music (at a frequency of approx. 2 Hz). The waves emitted inside the stadium by the audience were trapped in the soil layer and in turn excited the base of the stands, which then started vibrating at a level sufficient to be felt by those seated in the stands. A comprehensive numerical study proved that the strong amplitude of these vibrations was due to: the type of clay layer, its geometry

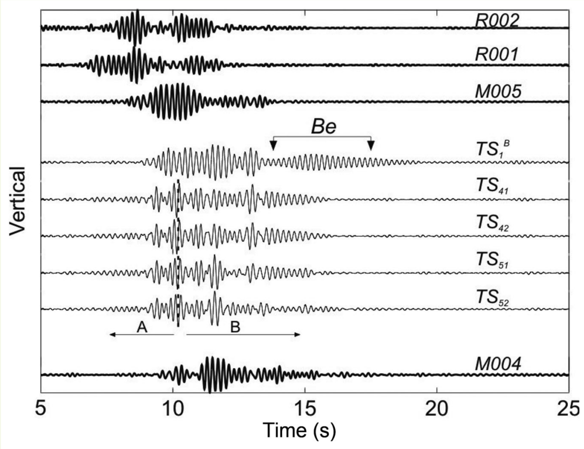


Figure 1
Recordings (vertical component) filtered around the frequency of the Volvi (Greece) test structure collected during an explosive blast detonated adjacent to the structure. The TS stations lie within the immediate vicinity of the structure. Sector A is the incident field, while sector B is contaminated by structural vibration.

(as lateral thickness variations trapped the waves more efficiently), and lastly to the overlap between beat frequency of the music and soil frequency.

Moreover, an analysis of instrumented buildings revealed another critical point: as reported in various scientific publications (Bard, 1988; Bard *et al.*, 1992; Farsi, 1996; Paolucci, 1993; Meli *et al.*, 1998; Cardenas *et al.*, 1999), buildings built on soft soils are very often set into a very strong swinging motion, basically due to the soil-structure interaction. This phenomenon has even been observed for structures built on piles. By "strong motion", let's specify that the swinging motion accounts for over 10% of the pure bending motion. In a few special cases, this proportion has reached 100%, such as the instance reported by Bard *et al.* (1992). These same authors observed swinging moments acting at ground level and capable of generating high-energy seismic waves.

In sum, although no clear-cut observation has been produced regarding the effect of the presence of structures on "free-field" soil motion during earthquakes, reported observations demonstrate that the soil-structure interaction effects may indeed be significant.

Observations in the centrifuge

› Reduced-scale centrifuge models

Reduced-scale modeling in the centrifuge offers a powerful experimental resource for studying soil dynamics; it combines the benefit of a scale reduction with the representativeness of the full scale of the phenomena under investigation. Since the mechanical properties of soils are highly correlated with their stress state, working on reduced-scale physical models raises a major difficulty: the forces induced are very weak, and the soil response differs substantially from its response in a natural soil block. The artificial gravity created inside a centrifuge makes it possible to remedy this problem: the model soil density remains constant; also, since the dimension scale factor is 1/N, an N-fold increase in gravity will reconstitute the actual stress field. Given that scale reduction enables conducting parametric studies, custom models may be built for the centrifuge. Since the 1980's, centrifuge modeling has enjoyed tremendous success in the engineering seismology discipline. These experimental campaigns are typically described in great detail at conferences dedicated to centrifuge techniques (Corte, 1988; Ko and McLean, 1991; Leung *et al.*, 1994; Kiimura *et al.*, 1998; Phillips *et al.*, 2002; Semblat and Luong, 1998). Let's not overlook however that special attention needs to be paid to the edge effects that may arise during testing, given that soil placed in a centrifuge basket has a distinctly limited volume.

› Exploration of the soil-structure interaction on simple centrifuge models

The initial objective of this research program had been to verify whether the motion of one building could be affected by the presence of another building. We thus designed an experiment using an "active" building, i.e. one loaded by a shock, and an identical passive building located a given distance from this active building. During the shock, motion was recorded at the top of both buildings, and the effect of distance between the two was analyzed based on their individual responses. The model building design was configured to reproduce a 7-storey building with a 15 m x 15 m base, which is similar to a structure analyzed by Guéguen (2000) and then Guéguen *et al.* (2002) in Mexico City. The selected reduction factor was set at 1/N = 1/100. In order to simplify the analysis, each building was designed **(Fig. 2a)** to reproduce a system with a single degree of freedom (i.e. 1 SDOF), with a composition of two sheets bearing the superstructure mass and embedded into a base. This design serves to limit vibrations to just one direction. The soil model was composed of dry, fine-grained sand (Fontainebleau sand) with a homogeneous volumic weight equal to 16.3 kN/m^3. Details of this experimental campaign are available in the publication by Chazelas *et al.* (2003).

Initially, the "active" building B1 is driven into the sand (so-called buried foundation) at the center of the soil model. The "passive" building B2 is simply set on the sand (surface foundation), successively at various distances and positions along both the radial and transverse directions of the soil block. **Figure 2b** shows the motions recorded at the top of the two buildings for a given configuration. In the absence of interaction, the active building response should remain unchanged, whereas the passive building should not exhibit any motion. Such is clearly not the case: the passive building actually moves and the active one is observed to beat, with the beats becoming more pronounced as building B2 approaches B1. In other words, the two buildings are "speaking" to one another via the soil, and the beats are characteristic of a coupling of resonance frequency values, which prove to be very similar. These observations conform with the set of full-scale experimental observations reported by Kitada *et al.* (1999), according to which the resonance frequency variations of a building depend on the presence or absence of neighboring buildings.

Two other key results were deduced from these simple centrifuge experiments, namely:

• The structure-to-structure interaction via the soil is only significant if the frequencies of the two structures are relatively close to one another. Since the building models introduced are slightly damped (1% due to their mechanical composition), a 0.3-Hz offset in their resonance frequency (at the full scale) is sufficient to cancel the interaction. Higher damping values, closer to reality (see, for example, Farsi, 1996) allow for the interaction to develop until reaching higher frequency offsets;
• The efficiency of this phenomenon remains limited. Under the experimental conditions imposed by these tests (dry sand, structural frequency values), the interaction is only visible when the distance between buildings B1 and B2 does not exceed 25 to 30 m. This value however can only be viewed as indicative: it depends to a large extent on both the soil attenuation properties and structural characteristics.

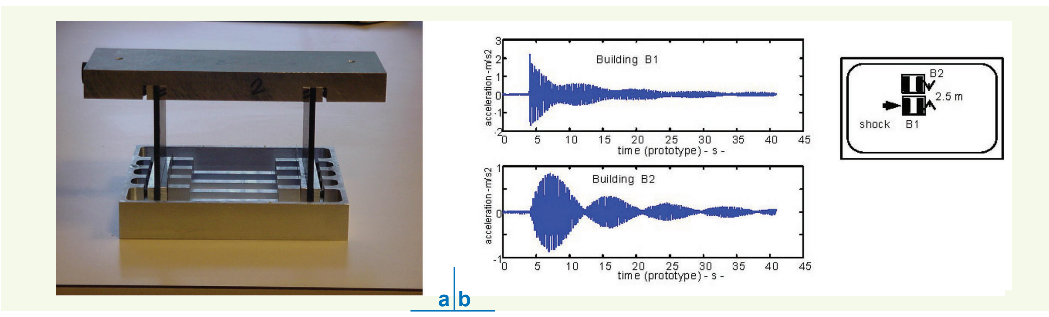


Figure 2
Centrifuge study of the interaction between two buildings
a. The selected building model
b. Motion at the top of buildings B1 and B2 vs. time during a shock on the active building B1

NUMERICAL MODELING OF THE SITE-CITY INTERACTION

The observations recorded on instrumented buildings display that buildings are capable of contaminating soil motion, as is the interaction between buildings. The modeling of these effects may be approached from two perspectives, just like the way in which seismologists addressed wave dispersion in the Earth's crust:

• The "simple" interaction may be modeled by considering each building as isolated and then summing the contributions of all of them individually;
• The "multiple" interaction includes backscattering effects, i.e. the dialogue between buildings via the soil.

The first approach is only valid in the presence of a weak interaction, while the second approach must be applied in all cases of strong interaction.

■ Simple interaction

› Model and calibration: The Volvi experimental campaign

Modeling the simple interaction consists of calculating the wave field emitted by a vibrating building. This calculation may be separated into two main steps:

a) estimating the forces generated by the soil-structure interaction around the foundation;

b) calculating the waves radiated in the soil through application of a numerical diagram used to solve the elastodynamic equation.

The first step may be executed by introducing the impedance functions found in the literature (Guéguen *et al.*, 2000, 2002), whereas the second step might rely on the discrete wave number method (Bouchon, 1981), in its modified version proposed by Hisada (1994, 1995).

This approach has been validated by an experimental study conducted at the Volvi (Greece) test site, as discussed in Guéguen *et al.* (2000). Dedicated to site effects, this test set-up also featured a 5-storey reinforced concrete structure (of the beam-column type) built at a reduced scale (1/3) (Manos *et al.*, 1995). By suddenly releasing the tension applied at the top of the structure through a cable, it becomes possible to force the structure into a vibration mode (free oscillations). The ensuing soil motion was recorded by a series of sensors positioned at various distances from the structure. These recordings were then compared with the calculation results output by the model during a two-stage process implemented and described by Guéguen *et al.* (2000, 2002). The main findings of this comparison are summarized in **Figure 3**, which shows a monochromatic signal on the soil similar to the

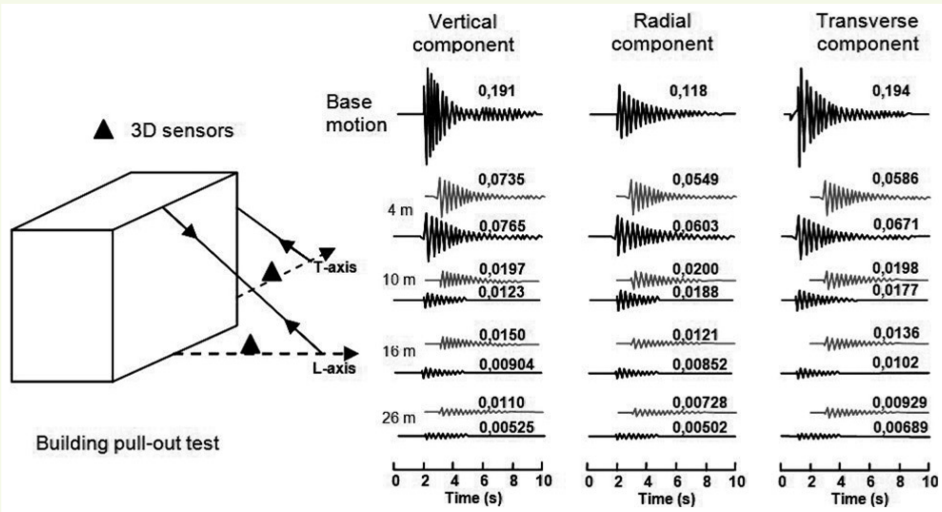


Figure 3
Soil motion both observed (bold lines) and calculated (thin lines) in the vertical, radial and transverse directions, respectively, in the case of a structural excitation in the longitudinal L and transverse T directions

free response of a damped oscillator. The frequency and damping of these signals are directly correlated with building vibration characteristics (i.e. 4.761 Hz in the radial direction T and 4.944 Hz in the longitudinal direction L). As expected, the amplitude decreases when moving further from the structure, yet non-negligible values are maintained until reaching a distance five times greater than the function dimension (approx. 5% of motion at the building base). The relatively strong similarity between calculation results and observations serves to validate the simple model.

› Mexico City application

This simple model was applied to Mexico City, Grenoble and Nice in order to evaluate the effects of the site-city interaction on free-field soil motion in a city containing many buildings. According to our simplified approach, the total wave field radiated by the buildings is solely considered as the superposition of each building's individual effects: in other words, the buildings are assumed not to interact with one another. Owing to the Mexico City Basin composition (a layer of very soft clay tens of meters thick), the present discussion will be limited to just the results obtained for Mexico City's "*Colonia Roma*" district. Further details are available in Guéguen (2000), Guéguen *et al.* (2002) and Bonnefoy-Claudet (2001) for the cities of Nice and Grenoble.

In the modeled sector, which extends roughly 500 x 500 m^2, only the 180 seven-plus-storey buildings were taken into account **(Fig. 4)**. The calculation, at a central point of the district, of the contribution from the various buildings subjected to an earthquake clearly demonstrates that the soil motion induced by the presence of buildings is comparable to the free-field motion in terms of both

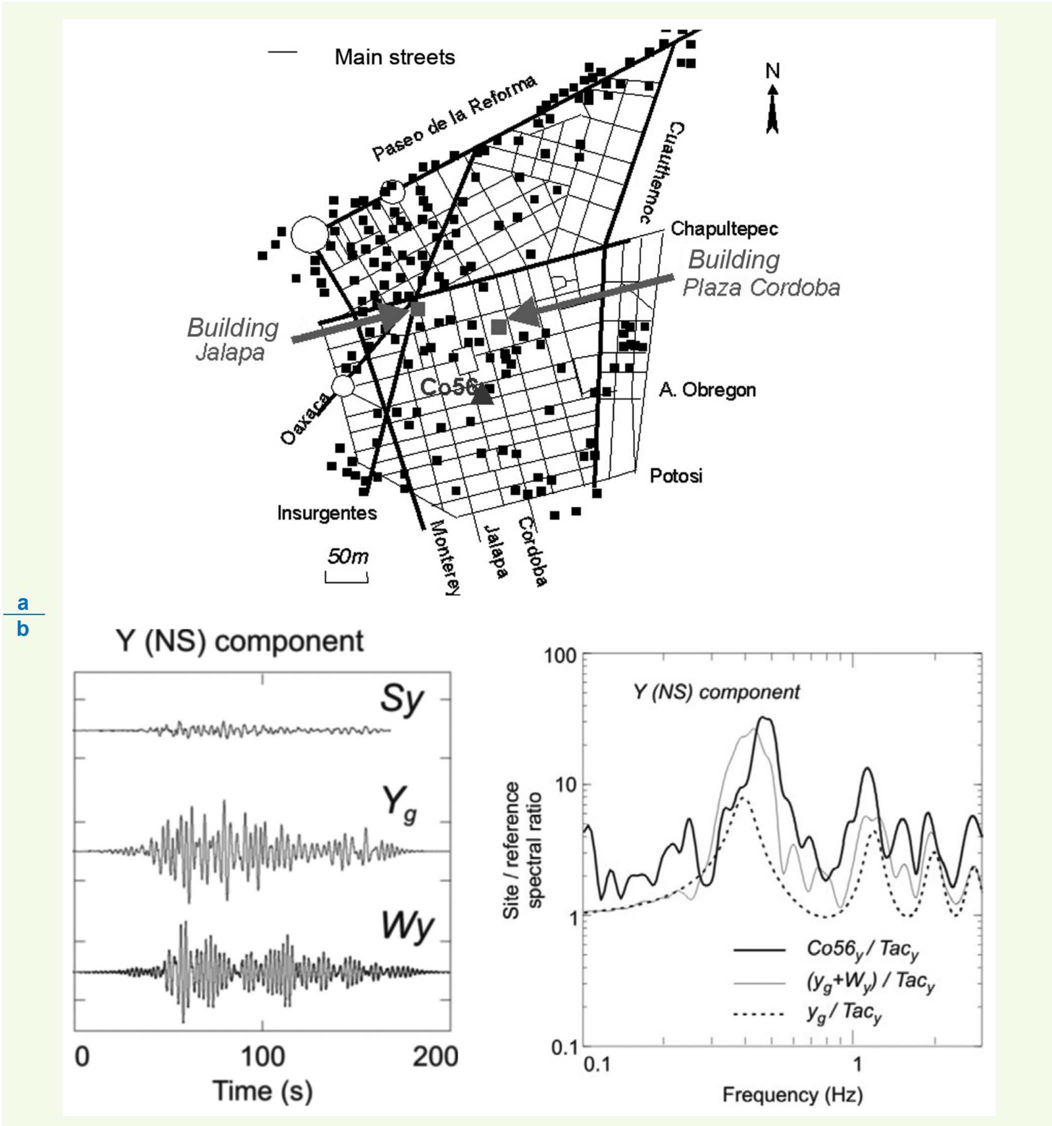


Figure 4
Site-city interaction modeling of Mexico City's Roma district
a. City model considered for Mexico City's Roma district (the squares represent the building positions); Co56 is the location where the site-city interaction effect has been calculated.
b. Soil motion calculated at the point Co56 (S_y is the signal at the boulder, Y_g the signal in the free field and W_y the signal including both the free field and buildings), and estimation of the site response in including (thin line) or excluding (dashed line) buildings compared with the experimental response using earthquakes (bold line)

amplitude and duration, whereas the soil frequency content displays an amplification around the site's fundamental frequency (0.5 Hz). In frequency terms, this model proves that soil-city interaction effects compensate for the frequency difference existing between the site's theoretical one-dimensional transfer function and the actual observed amplifications. Moreover, a parametric study using the same city model but changing the building characteristics (Guéguen, 2000; Guéguen *et al.*, 2002) definitively concludes that the maximum effects occur when building frequencies coincide with the soil frequency. This study has also demonstrated that the radiated wave field energy can reach 20 times the free-field energy.

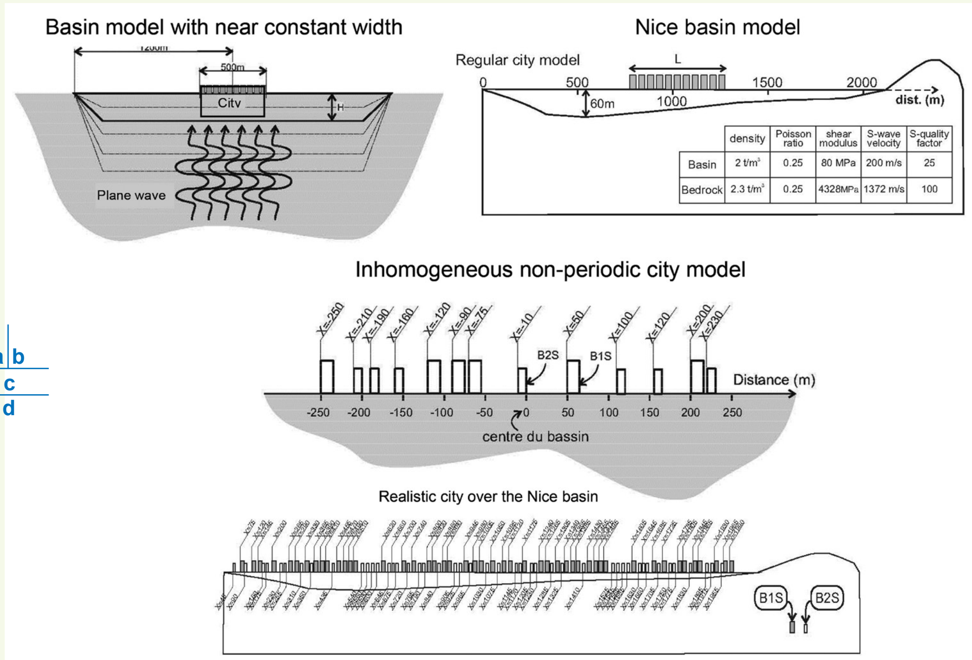
Multiple interaction

Incorporation of a multiple interaction requires more sophisticated numerical models, such as finite element models or boundary element methods, as well as more robust computing resources, especially if it is sought to include three-dimensional urban models. Initial results are thus more recent, whether regarding two-dimensional models (Wirgin and Bard, 1996; Kham *et al.*, 2003, 2006; Tsogka and Wirgin, 2003; Kham, 2004; Semblat *et al.*, 2008) or the three-dimensional type (Clouteau and Aubry, 2001; Mezher, 2004). This section will focus exclusively on presenting a few typical results for the two-dimensional case.

› The traditional two-dimensional model

Several city models are considered herein, all of which comprise a large number of buildings distributed over a two-dimensional valley. In all cases, the model response is calculated using the boundary element method for an SH wave with vertical incidence (Bonnet, 1999). We will first focus on the "traditional" simple model proposed in Kham *et al.* (2006) composed of a very streamlined geological structure. We have studied the sensitivity of this response to a few parameters (e.g. soil frequency / building frequency ratio, density of land coverage).

The geological structure **(Fig. 5a)** is a trapezoidal alluvial valley 2.4 kilometers wide underlain by an infinite elastic half-space. The mechanical properties of both the sediments and substratum correspond to a case of high impedance contrast (8.6) and standard damping (2% in the sediments, 0.5% in the substratum). Since sediment thickness is small compared to basin width (ratio less than 0.04), the valley response in the free field is basically one-dimensional, with however a few two-dimensional disturbances due to the late arrival of waves reflected on the basin edges.



a | b
c
d

Figure 5
City and basin models for a two-dimensional analysis of the site-city interaction, according to the boundary element method (Kham et al., 2006; Semblat et al., 2008):
a) upper left: traditional basin model
b) upper right: Nice Basin model
c) middle: non-periodic city used with the traditional model
d) bottom: Nice city model

Two urban configurations could then be examined. The first one **(Fig. 5a)** is a periodic city composed of N identical buildings regularly distributed over the 500-m central part of the valley. The second less regular model **(Fig. 5c)** comprises unevenly-spaced buildings that differ from one to the next. The precise geometric configuration of this non-periodic city is shown in **Figure 5c**. For the sake of simplicity, only two types of buildings have been considered (B1S and B2S), as characterized by their respective fundamental frequency (1 and 2 Hz) and their dimension. The buildings have been simplified by means of homogeneous and continuous elastic elements characterized by equivalent homogeneous mechanical properties. Calculations were performed for various configurations in order to estimate the sensitivity of site-city interaction phenomena for several key parameters:

• urban density $\theta = NB/L$, where N is the number of buildings, L the width of the urbanized sector, and B the width of the buildings. For the case of a periodic city, four distinct values of N (10, 16, 25, 33) were introduced, corresponding respectively to urban density values of 0.2, 0.32, 0.5 and 0.66. For the "non-periodic" city composed of buildings B1S and B2S, $\theta = 0.32$;
• sediment thickness H, which governs the one-dimensional resonance frequency of the valley at constant wave velocity S. Five thicknesses (H = 12.5, 25, 33, 50 and 75 m) were tested, corresponding respectively to the fundamental frequencies of 4, 2, 1.5, 1.0 and 0.67 Hz. Consequently, for the case of the periodic city solely implying buildings B2S, the frequency ratio between site and structures equals 2, 1, 0.67, 0.5 and 0.33, respectively.

The results **(Fig. 6a)** display soil motion disturbances for the case of the periodic city with maximum urban density (33 buildings). Comparison with the building-free case (free-field) clearly proves that the strongest disturbances occur for H = 25 m, i.e. when the valley frequency coincides with the building frequency (2 Hz). Let's also point out that regardless of valley thickness, the strongest disturbances systematically appear around this frequency, especially for H = 75 m, where the basin frequency corresponds to the upper structural vibration mode. These same observations are valid in the temporal domain **(Fig. 6b)**, where the model is subjected to a Ricker signal (Semblat and Pecker, 2009) with vertical incidence and a 2-Hz central frequency. Once again, the maximum effects easily appear for H = 25, 33 and 75 m, i.e. when the free-field response displays a resonance (whether fundamental or harmonic) around 2 Hz. One interesting finding is the overall effect of buildings, which slightly lower the amplification level at this frequency. Moreover, the variation in results is small regardless of position within the city, which seems to indicate a building group effect. These results, presented for just a single type of incident wave, were generalized by Kham (2004). In addition, Kham *et al.* (2006) observed a disturbance outside the city, which happened to be exacerbated with high urban density and the presence of a resonance between the city and the basin. It has also been shown that:

• in a periodic city, site-city interaction effects are beneficial, i.e. soil motion is reduced;
• this reduction increases with urban density and is maximized when the structural and soil frequencies overlap. Under optimal conditions (greatest density and perfect resonance), the level of reduction reaches 50%;
• the density effect may be significant, even when frequencies do not coincide. As an example, the energy from the radiated field compared to the incident field is of the same order of magnitude (67%) in both the "low density-resonance" and "high density-no resonance" cases;
• these reduction effects decrease substantially when the regularity of built space is interrupted: the reduction for non-periodic cities remains less than 15%, which may be explained by the small number of buildings at 2 Hz and/or a weak group effect due to the irregular layout.

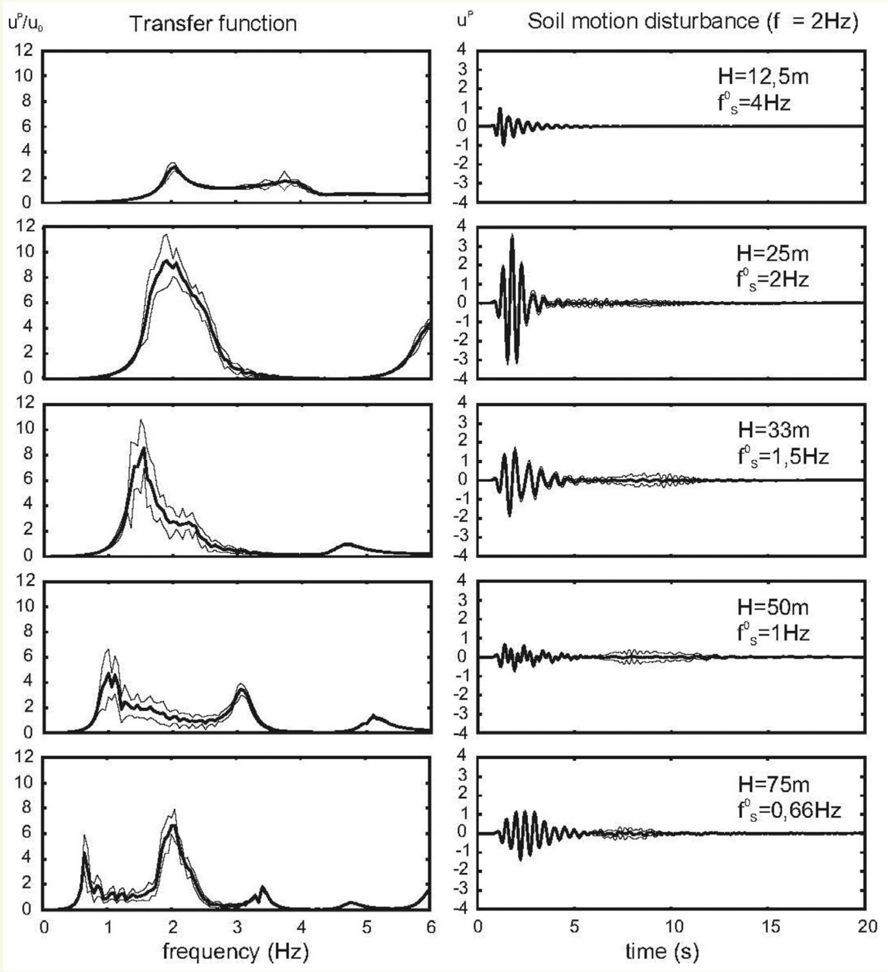


Figure 6

Calculation results for the traditional periodic city model
a) Left: Transfer functions (average +/- one standard deviation) for the traditional periodic city model (B2S building) with N = 33 and various values of H (solutions are compared to the model without buildings in dashed lines);
b) Right: Soil motion disturbance in the case of a Ricker signal with a central frequency of 2 Hz.

› Case of the city of Nice

Let's now consider a more realistic geological structure that corresponds to an east-west cross-section of the Nice Basin **(Fig. 6b)**. The free-field response (i.e. without buildings) indicates a fundamental resonance around 1 Hz in the deepest part of the basin (H = 60 m) with strong amplifications, due in part to the two-dimensional effects (Semblat *et al.*, 2000; Kham, 2004). The main results reveal that:

• nearly all cases lead to less soil motion energy inside the city, due to either the group effect (coinciding frequencies) or the inertia effect (urban density);
• the only exceptions correspond to the B2S periodic city and the easternmost part of the "realistic" city, both of which are exposed to a 1-Hz frequency Ricker signal. This may be interpreted as caused by the offset towards the lowest site-city model response frequency, owing to the presence of buildings where the incident wave energy is highest;
• a certain energy increase often appears at city borders (i.e. the city's edge effect). Such energy gains can reach 50%: the smallest structures set up at the immediate periphery of dense city centers may thus be exposed to greater soil motion.

Other calculations have also demonstrated that areas of the city may display local soil motion increases, due in large part to: the city's layout, the dynamic properties of buildings / the site, and input signal frequency (Semblat *et al.*, 2008). These findings confirm the effectiveness of the simple analytical approach presented by Guéguen (2000) and Guéguen *et al.* (2002), which proves that the site-city effect depends on: urban density, resonance between buildings and soil, the impedance contrast between sediments and substratum (to enhance wave trapping), and the ratio between average building height and sediment thickness.

CONCLUSION

From this compilation of observations, dedicated experiments and numerical calculations, we are in a position to draw a number of conclusions regarding the effects of buildings on seismic motion in urban areas (Bard *et al.*, 2005). Firstly, these results indicate that the effect is indeed real: the Volvi experiments proved that soil motion is greatly disturbed in the immediate vicinity of a building, and moreover centrifuge tests show that buildings actually "communicate" between one another via the soil. Numerical simulations have confirmed the existence of a strong interaction under favorable conditions (i.e. presence of resonance between soil and buildings, high urban density). The physical origin is multifold: waves are generated in the soil at the base of vibrating buildings and get trapped in surface layers provided a sufficient contrast. Group effects also appear whenever buildings are located close to one another. In the case of high urban densities and/or tall buildings, the inertia effect produces a few (slight) frequency offsets. This phenomenon becomes especially exacerbated whenever the soil and building frequencies overlap: the optimal conditions for a significant site-city interaction thus call for the simultaneous presence of a thin layer of soft sediments and a dense urbanization pattern with homogeneous buildings possessing similar frequencies.

Despite the current need for additional three-dimensional calculations, a number of general results still seem to emerge from a study of the site-city interaction phenomenon. In the case of a strong multiple interaction, effects on the whole appear to be beneficial: soil motion in the urban environment is reduced, in particular for homogeneous groups of buildings. Nonetheless, local amplifications might not be entirely eliminated. This overall beneficial effect should however be counterbalanced by the fact that the site-city interaction considerably increases seismic motion variability in urban areas. Some large amplifications might occur locally, though these are currently unpredictable as a result of their strong dependence on the incident wave field (both frequency and phase). On the other hand, sectors located at the periphery of dense and homogeneous urban centers are exposed to more extensive soil motion from site-city interaction effects beyond the urbanized boundary. This phenomenon is very similar to the observed basin edge effects, e.g. in Kobe.

From a seismological perspective, it seems important to analyze seismic recordings, in accounting for the urban environment along with source, propagation and site effects. This issue is especially important should dense networks be laid out in cities for the purpose of analyzing the seismic wave field. The observation and analysis of damage distributions should also take into consideration the site-city interaction since damage may not be solely due to the variability in vulnerability or to site effects. From the standpoint of seismic risks, the primary lesson is that urban sectors can undergo manmade modifications as well, which in turn may lead to many unpredictable developments, e.g. in the urban layout (by attempting to design "an optimal land use" in order to reduce soil motion) and in the temporal risk evolution (risks could change as new structures are built and others demolished).

Before these consequences can be confirmed however, the next required step consists of obtaining irrefutable experimental evidence of the occurrence of these effects in cities actually prone to earthquakes. It would thus be necessary to instrument such cities in a specific manner according to instrumentation diagrams and then implement new advanced signal processing techniques to separate incident waves from waves induced by the structures.

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