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COULD "SITE-CITY INTERACTION" MODIFY SITE EFFECTS IN URBAN AREAS ?

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SUMMARY

At the scale of a city, surface structures like buildings could behave as secondary seismic sources and influence the seismic "free-field". Local interactions between structures through the soil could also be significant. Some experimental evidences of the "structure-soil" interaction were previously given [12]. The problem is herein investigated at the scale of an entire alluvial deposit and a whole city to analyze the potential influence of *"site-city interaction"* on free-field site effects.
Starting from these previous results, several site-city models are considered describing both superficial soil layers and surface structures. An horizontal layering and a real basin geometry [18] are separately considered to investigate 1D as well as 2D effects with various building types and densities. In the 1D case, the seismic wavefield radiated by the city is estimated. In the 2D case, one compares free-field amplification and amplification in various urban configurations taking into account basin effects. For the specific site considered, the various site-city models show that site-city interaction can lead to significant modifications of the free-field amplification. These results are in good agreement with previous numerical and reduced scale experimental results [12]. They show that the governing parameters of site-city interaction are the following: respective eigenfrequencies of both soil layers and surface structures, building density, heterogeneity of the city and, for a real alluvial basin, basin effects.

SITE-EFFECTS AND SOIL-STRUCTURE INTERACTION

The local amplification of seismic motion in alluvial basins could sometimes be strong [1,2,10,17,18]. Seismic wave propagation in surface geological structures can indeed lead to a large motion amplification due to the impedance contrast between the alluvial deposit and the bedrock. However, the amplification of seismic motion can also be considered as a result of the resonance of surface layers at peculiar frequencies. Site effects can then be analyzed in terms of wave propagation processes [2,5,17,18] or considering the vibratory resonance of surface geological structures [9,16,20,21].
The main governing parameters of seismic wave amplification are the following: soil layers depth, layers geometry, wave velocity and type, location and directivity of the source... The geometrical and mechanical features of the propagation medium then have a major influence on the amplification process. However,

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for alluvial basins located in densely urbanized areas, the surface structures such as buildings could influence seismic wave propagation at the free surface. Furthermore, as it has been shown in other papers [6,7,11,12,13,19,23], the vibration of a surface structure can generate a seismic wave field in the soil. In this article, the influence of surface structures on seismic site effects is analyzed in the case of an alluvial basin. Two cases are considered: a simplified model with a nearly 1D soil configuration and an actual basin profile located in the center of Nice (France).

SIMPLIFIED ANALYSIS FOR UNIFORM AND HETEROGENEOUS URBAN CONFIGURATIONS

Single layer model

For preliminary analyses, we firstly consider a simplified 1D model. As depicted in figure 1, this model consists in a uniform and periodical distribution of buildings on a one-dimensional alluvial layer over an elastic bedrock. The respective properties of the buildings, the superficial layer and the bedrock are given in Table I. The velocity ratio is chosen as 5. The eigen frequency of the building (taking SSI into account) is 2 Hz and that of the alluvial soil layer depends on its depth d through the classical relation $f_0=\beta/4d$, where β is the shear wave velocity in the layer. Material damping in each medium is taken into account (linear visco-elasticity). The excitation is chosen as a 2nd order Ricker signal (SH wave) centered at frequency $f_R=f_b=2Hz$ of magnitude $A_0=2$ with vertical incidence.
The solution is computed by the Boundary Element Method in frequency domain [3,8] and inverted afterwards in time domain to get the time responses to a Ricker signal. The buildings are elastic bodies and their eigen frequencies are chosen at 2 Hz (SSI taken into account).

This simplified model is considered for purpose of parametrical study and its parameters are modified as follows :

- The depth of the alluvial layer d takes the following values *12.5m*, *25m*, *33m* and *50m* to have various ratios between the fundamental frequency of the soil f_S and that of the building f_b, that is respectively $f_b/f_S=0.5, 1, 1.5, 2$ *et* 3.
- For each depth value d, the building density D_S of the city takes the following values : *0.2*, *0.34*, *0.5* and *0.66*. This density is defined as the ratio between the total surface $L_C = N*l$ at the building basement and the length of the whole city L, that is : $D_S=L_C/L$. The length of the city being kept constant equal to *500m*, the respective numbers of buildings are as follows : $N = 10, 16, 25$ and 33.
- The frequency of the incident wave f_R takes the different values of the building eigen frequency $f_B=2Hz$ and soil fundamental frequencies $f_S = 4, 2, 1.333, 1$ and $0.666Hz$.

We investigate the dynamic responses at the top of the buildings, at the free-surface between buildings and outside of the city. The uniform urban configuration is analyzed first and the heterogeneous urban configuration afterwards.

Table I : Mechanical properties of the soil and the structures for the simplified site-city models.

SOIL			
Bedrock		Alluvial layer	
β	1000 m/s	β	200 m/s
α	2000 m/s	α	1500 m/s
ρ	2200 kg/m^3	ρ	1800kg/m^3
Q_P	200	Q_P	50
Q_S	100	Q_S	25

STRUCTURE	
H_B	30 m
2B	10 m
f_B	2 Hz
ζ	0.05
D	0
ρ	250 kg/m^3

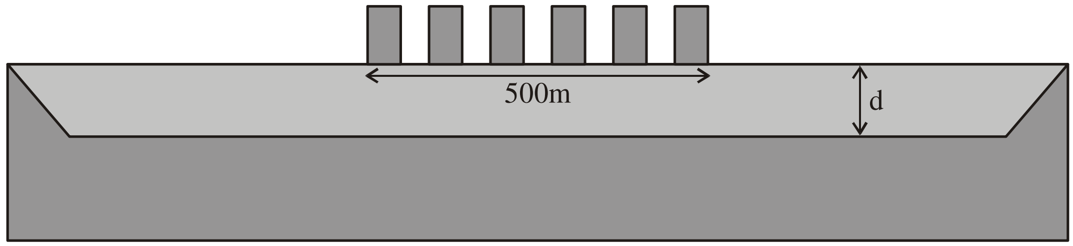

Figure 1: Simplified 1D soil model with uniform urban configuration.

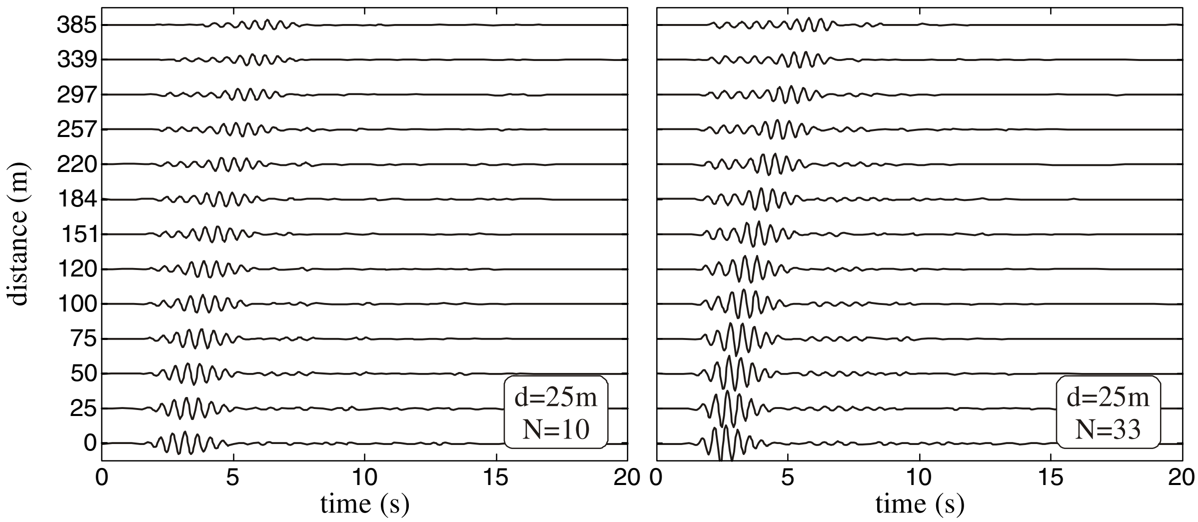

Figure 2: Perturbation wave field at 2Hz for a uniform urban configuration and various building densities: N=10 (left) and N=33 (right).

Uniform urban configuration

For the simplified model depicted in figure 1 considering a uniform urban configuration (one type of building only of fundamental frequency f_b=2Hz), we will firstly analyze the influence of the building density on the seismic wave field radiated by the city. In figure 2, the radiated seismic wave field is plotted for various locations along the surface and two different building densities N=10 (left) and N=33 (right). This wave field corresponds to the perturbations u_P between the total urban field in the city u_C and the purely free-field case u_{FF} that is $u_P=u_C-u_{FF}$.

From these curves, it can be noticed that the radiated wave field is significant for large distances away from the city. Furthermore, the amplitude appears to be higher for a larger building density: in figure 2, there is a stronger radiated wave field for N=33 (right) than for N=10. The duration of the perturbations can also influence significantly the original free-field motion since it depends on the building vibration and should be influenced by such parameters as building density, layer depth or building type (eigen frequency). These various parameters will be considered in the following sections.

Heterogeneous urban configuration

In this section, two different types of buildings are considered: 6 buildings of fundamental frequency f_b=1Hz and 7 buildings of fundamental frequency f_b=2Hz. They are both included in the simplified model depicted in figure 1 to investigate the city effect for heterogeneous urban configurations.

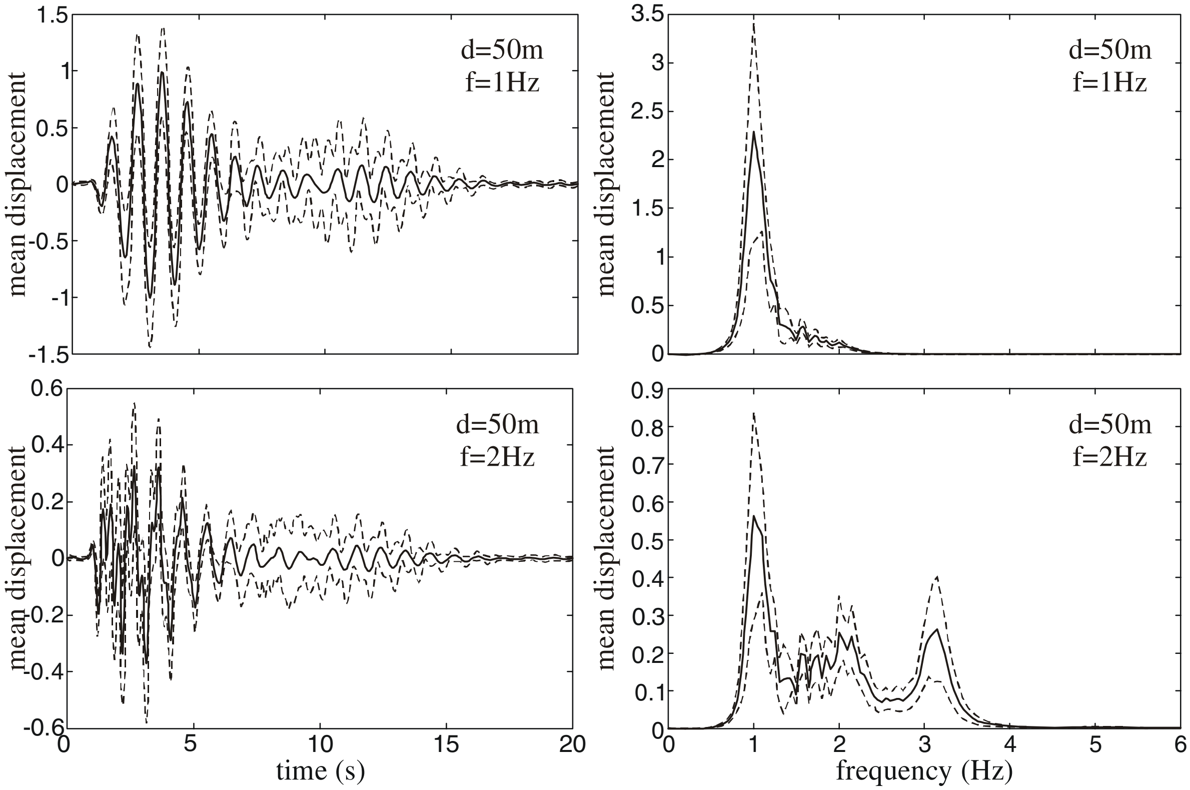

Figure 3: Perturbations in between the buildings (time response and spectrum) for a heterogeneous urban configuration ; f_R=1Hz (top) and 2Hz (bottom), layer depth d=50m.

Modifications of the seismic motion within the city

For the heterogeneous urban configuration, the seismic motion within the city will then be analyzed. The displacement wave field at the free surface (between buildings) and the corresponding spectrum are displayed in figure 3 for a given superficial layer depth (d=50m) and different excitation frequencies f=1Hz (top) and f=2Hz (bottom). Solid lines give the mean values of the perturbations for various locations and dotted lines correspond to the standard variation.

As shown by the time curves as well as the spectra, the perturbations are much stronger at 1Hz than at 2Hz. For the chosen superficial layer depth (d=50m), the eigen frequency of some buildings coincides with the fundamental frequency of the layer (nearly 1Hz) and the city effect is then maximum at 1Hz. It appears clearly on the first spectrum (top right) which shows a large peak at 1Hz corresponding to a strong city effect.

From figure 3, it can also be noticed that the ground motion variability is rather large when considering the standard deviations (especially after t=5s). Another point concerns the time duration of the perturbation wave field: it can contribute to a significant lengthening of the free-field signals mainly when the city effect is large (top left).

Influence of both depth and frequency on the radiated wave-field

In figure 4, the perturbation wave field (u_P=u_C–u_{FF}) radiated by the city is displayed for two Ricker signals of frequencies f_R=*1Hz* (left) and f_R=*2Hz* (right) for superficial layer depths *d=25m* (top) and *d=50m* (bottom).

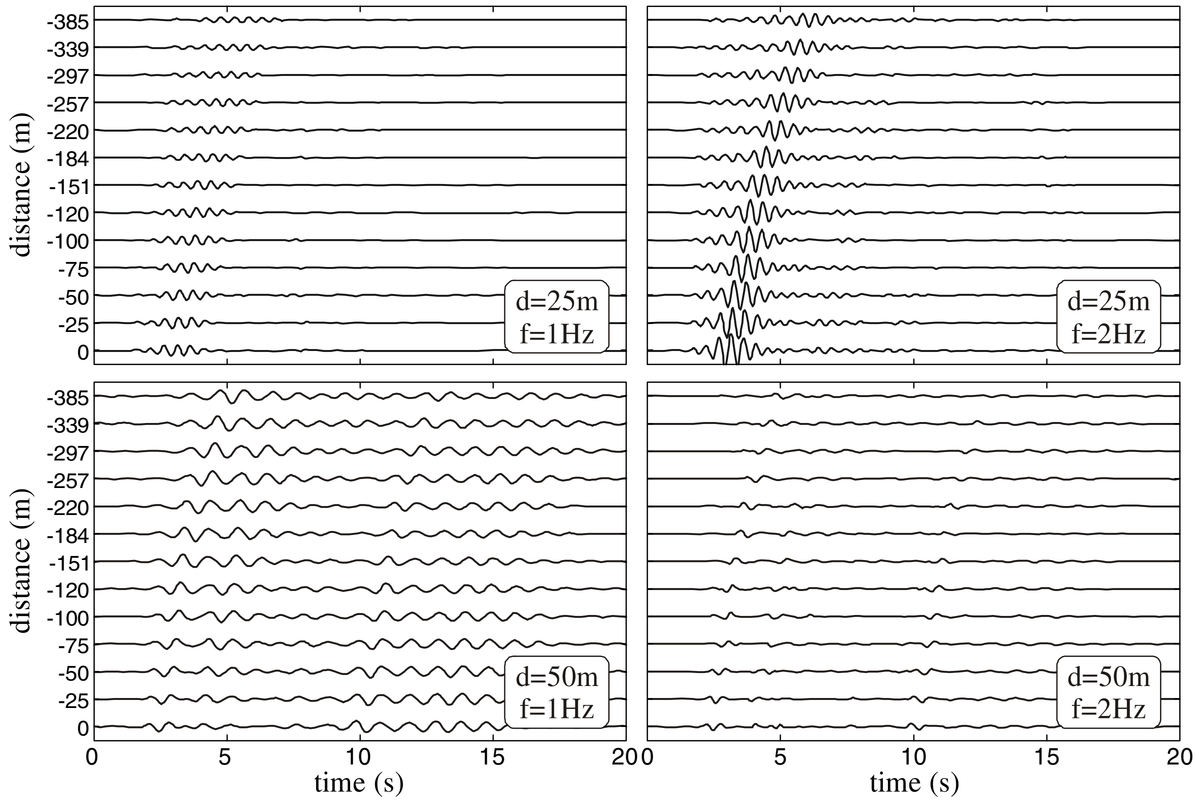

Figure 4: Perturbations radiated away from the city for a heterogeneous urban configuration ; f_R=1Hz (left) and 2Hz (right), layer depths d=25m (top) and d=50m (bottom).

This radiated wave field has very different features for various superficial layer depths:

- For *d=25m*: the amplitude of the radiated wave field is not very large at 1Hz (top left) since this frequency does not correspond to the fundamental frequency of the layer. Whereas at 2Hz (top right), the radiated wave field is much stronger even for large distances away from the city. It is mainly due to the buildings of frequency $f_b=2Hz$.
- For *d=50m*: since the fundamental frequency of the superficial layer is 1Hz, the interaction with the buildings is larger at this frequency as shown by the amplitude of the signals in figure 4 (bottom left). The influence of site-city interaction on the signal duration is much larger than for the previous case (d=25m and f=2Hz). For f=2Hz and d=50m (bottom right), the radiated wave field is very small and the city effect appears negligible. There is a slight interaction between the 50m deep layer and the buildings with a 2Hz eigen frequency.

From figure 4, it can be concluded that the coincidence between the eigen frequencies of the buildings and the fundamental frequency of the superficial layer leads to a significant site-city interaction around this frequency. In the next section, we will investigate the case of an actual alluvial deposit taking into account its geometry.

SITE-CITY INTERACTION FOR AN ACTUAL ALLUVIAL BASIN

Basin-city model

We will now investigate site-city interaction in the case of an actual geological profile, that is the seismic interaction between an alluvial basin and a building array. We will then consider a geological profile located in the center of Nice (France). A detailed analysis of "free-field" amplification (that is without the city) has been performed previously [18,20,21]. From these results, several basin-city models are considered including both the actual geological profile and the surface structures.

In this paper, one type of structure (fundamental frequency f_b=2Hz,) is considered for the basin-city model and various building densities are chosen. In figure 5, the basin-city model is depicted for a given building density. The seismic wave propagation is modeled in the frequency domain by the Boundary Element Method [3,8]. Vertically incident SH-wave is considered for the seismic excitation. The numerical results are computed afterwards in time domain to analyze the perturbation wave field radiated by the city in the alluvial basin. Both amplitude and duration are investigated in the next section.

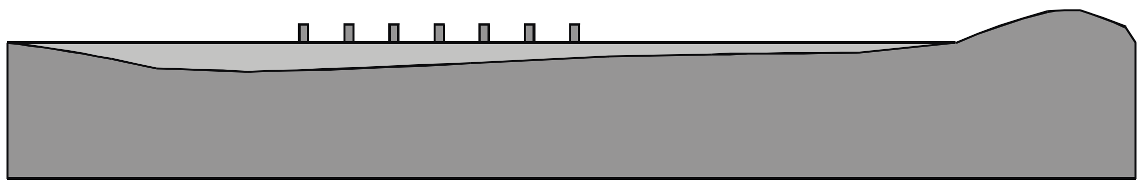

Figure 5: Basin-city model for the analysis of the site-city interaction (Nice, France).

Seismic wave field radiated in the basin

We consider the basin-city model depicted in figure 5 with 33 buildings along the surface. Site-city interaction is analyzed in time domain in terms of perturbation wave field radiated by the city in the alluvial basin ($u_P=u_C-u_{FF}$). This wave field computed along the basin surface is displayed in figure 6 for two frequencies f=1Hz and f=2Hz. From these results, the main conclusions can be derived as follows:

- The main radiated wave field is located in the deepest part of the basin (left)
- The wave field amplitude is larger at 1Hz (top) than 2Hz (bottom). As shown by the analysis of "free-field" site effects [18], the first frequency value (1Hz) corresponds to the largest amplification in the basin located in the deepest part (left). This result means that site-city interaction could be stronger when the excitation frequency coincide with the fundamental frequency of the basin even if the buildings eigen frequency is different. There is then a dynamic interaction between the basin and the building array.
- The duration of the seismic wave field is larger since the vibration of the buildings generates progressively radiated wave fields between 2 and 10s.
- The direction of the radiated wave field is mainly oriented from the center of the basin (location of the city) towards the deepest part of the basin (left). It is especially the case at 1Hz since the maximum amplification values are reached at this frequency in the deepest part of the basin [18]. For an actual alluvial basin, site-city interaction is then controlled by a strong directivity effect due to the propagation of surface waves in the basin.
- Finally, the basin effects due to lateral heterogeneities tends to strengthen site-city interaction since the seismic wave field radiated by the city is trapped into the basin. In figure 6, the reflections of the radiated wave field on the basin edges appear clearly at 5s and 10s.

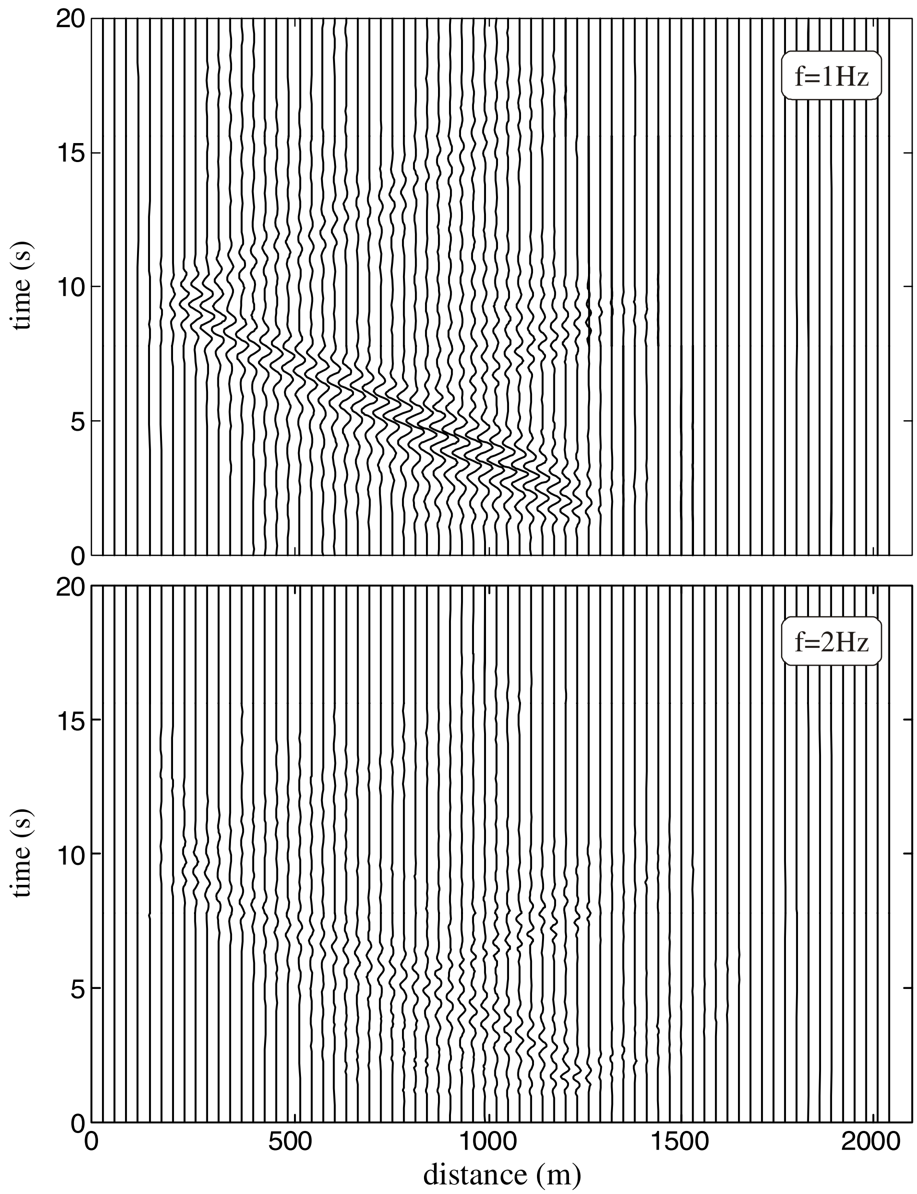

Figure 6: Perturbation wave field radiated by the city in the basin at 1Hz (top) and 2Hz (bottom).

CONCLUSION

At a local scale, the vibration of a surface structure (building) can induce a seismic wave field in the superficial soil layers [11,12,19]. At the scale of an alluvial basin, the site-city models considered herein show that site-city interaction can lead to a significant seismic wave field modification when compared to the free-field case (i.e. without buildings). Near the eigen frequency of a given building type (homogeneous urban configuration), resonance effects are observed and site-city interaction is found to be strong. As already shown by previous experimental results [11,12], the coincidence between the fundamental frequencies of the soil layers and eigen frequencies of the surface structures is the main governing parameter of the city effect in urban areas.

When comparing the simplified city model to the basin-city model, the influence of the lateral heterogeneities on site-city interaction is found to be significant since the seismic wave field radiated by the city appears to be trapped within the alluvial basin. Finally, the full characterization of the seismic wave field in densely urbanized areas could often raise the need for investigations on site-city interaction effect depending on such parameters as: basin and city fundamental frequencies, buildings arrangement and density as well as basin effects. Other types of investigations are currently in progress to quantify the influence of such parameters [4,6,13,14,15,22].

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