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STRUCTURED SOILS IN EARTHQUAKE ENGINEERING

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ABSTRACT

In Soil Dynamics, the high ratio of soil substitution by deep foundations or ground reinforcement techniques in urban area, led researchers to believe in a significant impact of these elements on the kinematic effect during a seismic disturbance. Exploring this idea, a promising way is to achieve a complete dynamic artificial anisotropy by implementing geometrical elements, full or empty, in the soil. For body or surface waves, the physical process is the coupling of the scattered field displacement with local resonances of stiff elements implemented in the soils. This approach could theoretically lead to enhanced wave-path control, attenuation by energy-dissipation, etc. The Holy Grail would be the achievement of a complete shield for all seismic wave polarizations over a large frequency bandwidth with a seismic metamaterial reminiscent of a perfect flat lens and a seismic cloak detouring surface seismic waves around a designated area.

Keywords: Soil Structure Interaction; Kinematic effect; Seismic Metamaterials; Seismic Cloak

1. INTRODUCTION

In Civil Engineering, the high density of deep foundation or ground reinforcement techniques for buildings in urban area (Brûlé et al. 2017a), leads Physicists to believe in a significant interaction of these buried structures with the seismic signal. In the past, a few authors (Woods 1968, Banerjee et al. 1988) obtained significant results with vibration screening in the soil itself for a local source such as industrial vibratory machines located on concrete slab for example. Léon Brillouin (Brillouin 1946) reminded that « *All waves behave in a similar way, whether they are longitudinal or transverse, elastic or electric* ». However, to illustrate the interaction of seismic wave with structured soils, researchers had to bring specific theoretical and original experimental approaches in particular because of the complexity of the wave propagation in the Earth's surface layers (Brûlé et al. 2014, Brûlé et al. 2017b). In this article we bring arguments for the kinematic effect influence of structured soils and their development to seismic metamaterials.

2. KINEMATIC EFFECT: GOING FURTHER

Except for a few cases of study with full numerical modeling, a complete study of both the structure and deep foundations (piles, shear-walls) is rather complex and usually the problem is split into two canonical sub-problems: kinematic and inertial interactions (Figure 1).
Kinematic interaction results from the presence of stiff foundation elements on or in soil, which causes motions at the foundation to depart from free-field motions. Inertial interaction refers to displacements and rotations at the foundation level of a structure that result from inertia-driven forces such as base shear and moment.
Novelties of this last decade are the development of the interaction of structured soil with the seismic signal propagating in superficial Earth's layers (Brûlé et al. 2016) and then an active action on the kinematic effect described above. The second research advance is the experimental modal analysis of composite systems made of soil, piles and structures by means of numerical analysis and the confirmation of these predictions by full-scale experiments held in situ.

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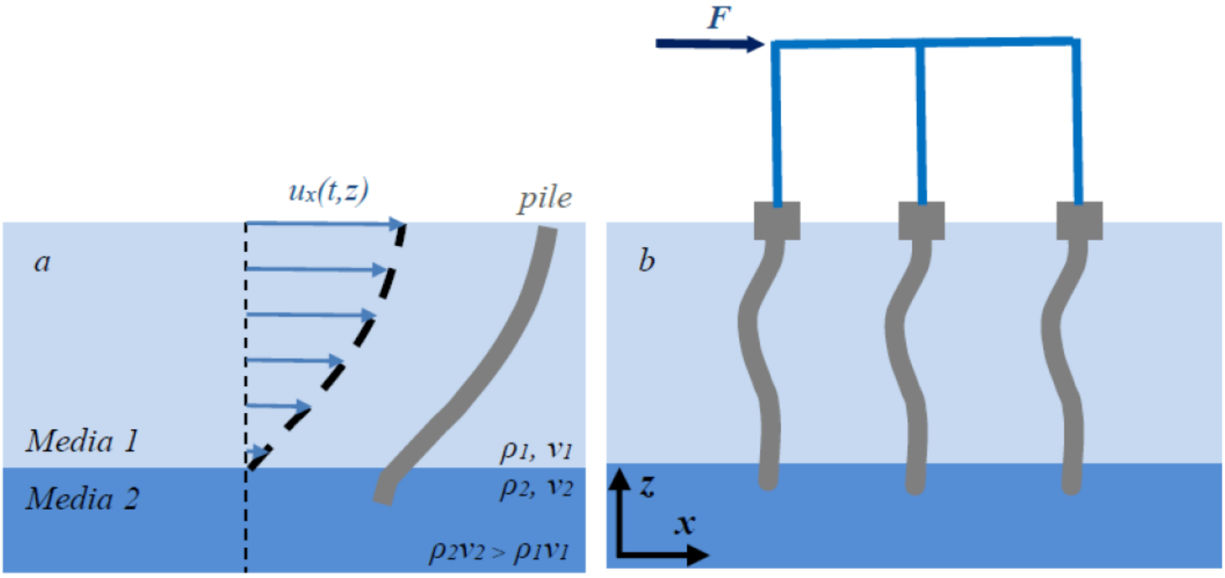

Figure 1. Kinematic interaction (left) and inertial effect (right) for pile foundation.

3. SOIL HOMOGENIZATION AND ITS LIMITATIONS

3.1 Static homogenization

From a practical aspect in a pseudo-static approach, the soil is characterized with equivalent properties deduced from homogenization method (Figure 2). In most cases, an equivalent shear modulus G_{eq} is proposed depending on the mesh size and diameter of the inclusions. In the case of a soil reinforcement, the substitution rate α is defined as the ratio of the surface of an inclusion A_i to that of the elementary cell A_m (Equation 1). The representative elementary volume is named R.E.V.

$$\alpha = \frac{A_{\text{inclusion}}}{A_m} \tag{1}$$

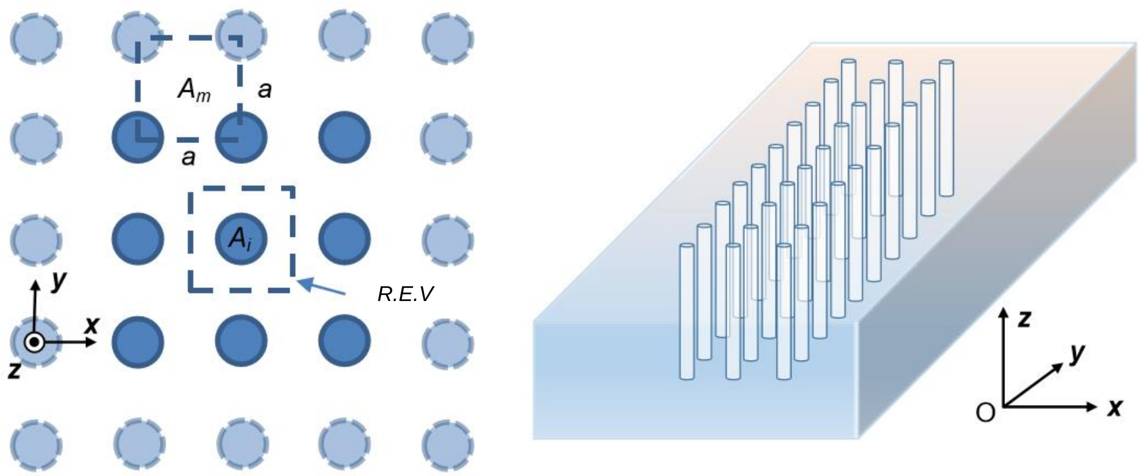

Figure 2. On the left side of the figure: 2D periodic media and representative elementary volume (R.E.V.). On the rigth: typical ground reinforcement technique by means of vertical and stiffer cylinder.

Starting from the initial shear modulus of a homogeneous and elastic soil (G_{soil}), an evaluation of the equivalent shear modulus G_{eq} of the soil reinforced by vertical cylindrical inclusions (G_{inc}) is proposed by Hashin (Hashin 1983) assuming a perfect adhesion between the soil and the inclusions. This averaging is valid for static conditions (Equation 2):

$$G_{eq} \cong G_{soil} + \frac{\alpha}{(1-\alpha)/2G_{soil} + 1/(G_{inc} - G_{soil})} \tag{2}$$

The values of the equivalent modulus by homogenization are framed by the Voigt and Reuss bounds (upper and lower bounds) corresponding to the harmonic and arithmetic averages:

$$\left(\frac{1-\alpha}{G_{soil}} + \frac{\alpha}{G_{inc}}\right)^{-1} \leq G_{eq} \leq (1-\alpha).G_{soil} + \alpha G_{inc} \tag{3}$$

Figure 3 shows the variation of G_{eq} as a function of the substitution rate α for G_{inc} / G_{soil} = 30. For α lower than 20%, the gain provided by inclusions remains limited and does not exceed 20%, regardless of the contrast of rigidities between the ground and the inclusions.

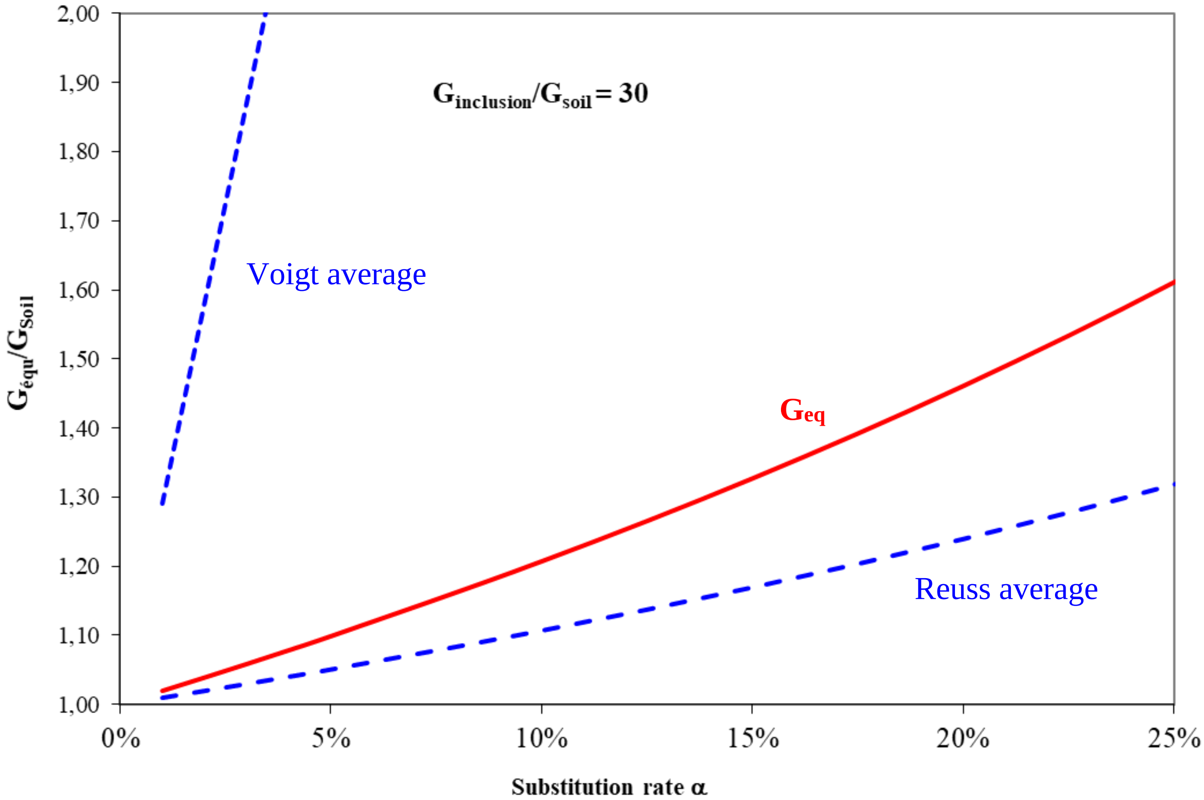

Figure 3. Equivalent soil shear modulus as a function of the substitution rate by vertical and stiff inclusions.

3.2 Dynamic homogenization

A ground reinforcement must be technically and economically feasible on worksite. Indeed, it remains realistic to explore the dynamic effects of anisotropy in addition to the pseudo-static approach.

Strictly speaking, dynamic homogenization involves wave scattering and frequency-dependence properties. For the material to be strictly homogenized, the length-scale of the propagating wave must be much larger than the microscale of the composite. The leading order effective property then

corresponds to the static effective property and higher order terms provide dispersive corrections to this, see (Boutin et al. 2015) for a comprehensive low frequency asymptotic analysis of acoustic metasurfaces.
If frequencies are high enough for periodic materials, stop bands in the structures can be observed and the method of asymptotic high-frequency homogenization provides excellent results (Antonakakis et al., 2014).
Due to shear wave velocity in "soft soil" (a few hundred meters a second) and frequency content of seismic signal (few hertz), wavelengths may be similar or greater than the grid-spacing *a* (Figure 2).
Thus, for the matrix-soil properties, we consider the static effective properties and for the composite material made of matrix-soil plus inclusions, we are looking for the inclusions local resonance effect.

4. OVERVIEW OF FIELD EXPERIMENTS ON STRUCTURED SOILS UNDER SEISMIC DISTURBANCE

4.1 Recent history

The main type of structured soils made of cylindrical voids (Brûlé et al. 2014) or other geometry (Du et al. 2017) and rigid inclusions (Achaoui et al. 2017, Aznavourian et al. 2017), include seismic metamaterials. We called this historical category: "Seismic Soil-Metamaterials" (Brûlé et al., 2017c).
Recent full-scale experiments in 2012 with cylindrical holes allowed the identification of the Bragg's effect and the distribution of energy inside a grid, which can be interpreted as the consequence of an effective negative refraction index. Such a flat lens is reminiscent of what Veselago and Pendry envisioned for light in Electromagnetism (Brûlé et al., 2017b). Another effect on ground displacement is the frequency dependence of the horizontal to vertical Fourier spectra ratio when the signal passes through the lens (20 m in width, 40 m in length) made of 23 holes (2 m in diameter, 5 m in depth, triangular grid spacing 7.07 x 7.07 m).

Another category of seismic metamaterial consists of a set of meter-scale resonators buried in a large volume of soil. We call this group "Buried Mass-Resonators" (BMR), not developed here (Finocchio et al., 2014; Palermo et al., 2016, Miniaci et al., 2016). An alternative of these "BMR" (Brûlé et al., 2017c) is to design a smaller and multilayer device with the k-damping concept, to isolate seismically the structure (Antoniadis et al., 2017) at the location of the foundation itself.

4.2 In situ experimental set-up

Here the device is basically considered as a filter without any consideration of initial soil properties. We have calculated the magnitude in dB of the transfer function $|T(\omega)| = |B(\omega)/A(\omega)|$ for the initial soil (solid blue line) and for the structured soil with holes (solid red line). A is the point located in the x-axis, before the grid of holes and B is behind the mesh (Figure 4). We have also drawn the magnitude of the original soil transfer function minus 3 dB (gray dotted line) to illustrate the efficiency of the holey-ground.
The other aspects of the energy distribution in the structure (effective negative index and flat lensing, seismic metamaterials, dynamic anisotropy) are developed in Brûlé et al. 2017b and summarized in Figure 5.

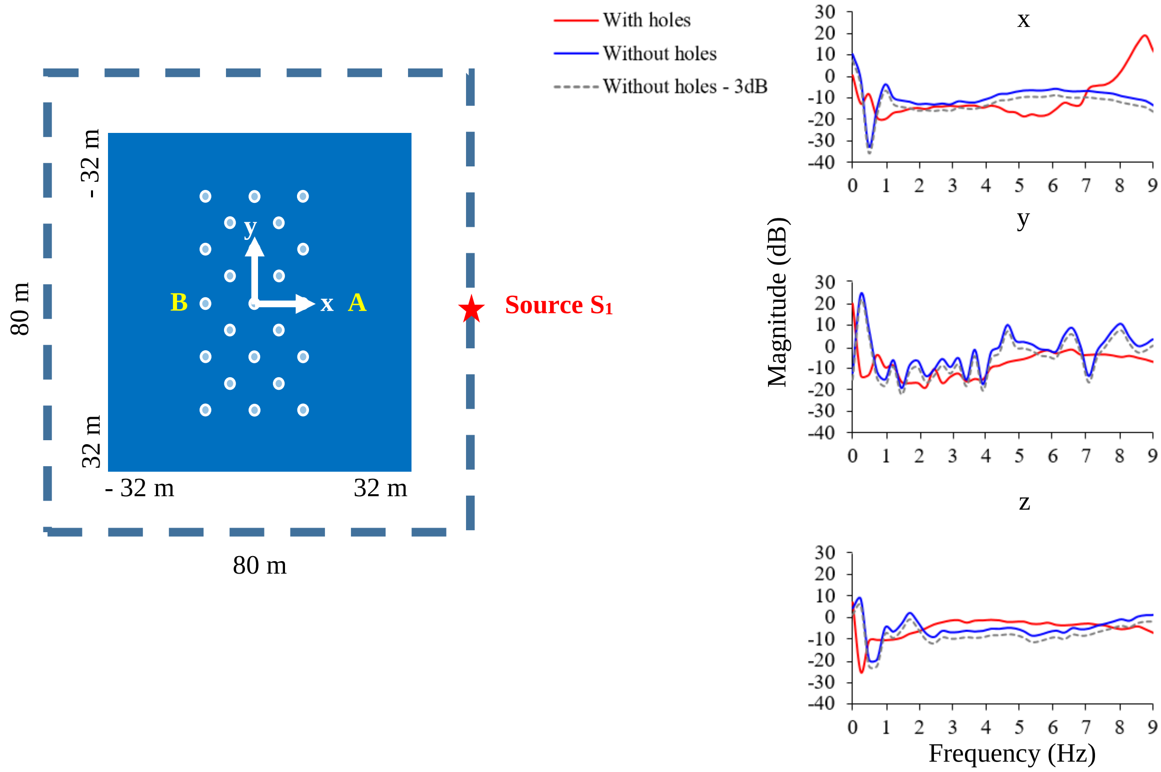

Figure 4. Structured soil made of 23 holes (left-hand side), source is located at (x=-40, y=0) with a 3 to 9 Hz source and mean frequency content around 8 Hz. Magnitude in dB of the transfer function for the original and structured soil in x,y and z directions (right-hand side).

4.3 Results and interpretation

These results show the change of the magnitude of the transfer function in range of frequency 1-7 Hz for the 3 components of the sensor and the effect is more effective in the x-axis *i.e.* a decrease of more than twice the initial value (-3dB). Except for the vertical component, the attenuation in frequency is better with the holey-ground in the range of 1 to 7 Hz.

Here we show the kinematic effect of a holey-ground which can be summarized as an inversion of the ratio of amplification between the vertical and horizontal component of the ground motion.

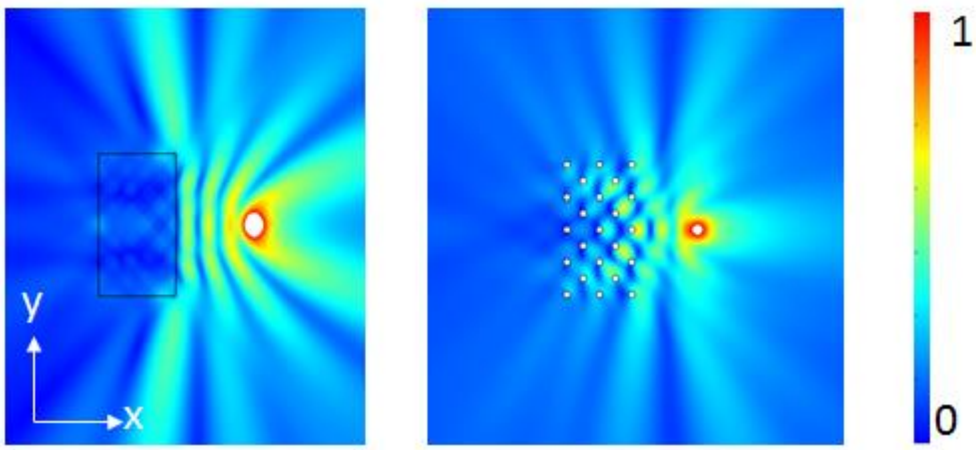

Figure 5. Finite element simulation (comsol Multiphysics) of the flat lens effect for a time-harmonic seismic

source at 8 Hz placed near an effective medium deduced from high-frequency homogenization, see Brûlé et al. 2017b (left), and same for the structured soil with parameters like in Figure 4 (right).

5. PERSPECTIVES AND CONCLUSIONS

The last decade is marked by the emergence of metamaterials, structured soils and, among the later, seismic metamaterials. Well beyond the important scientific and technological advances in the field of structured soils, the concepts of superstructures "dynamically active" under seismic stress and interacting with the supporting soils (soil kinematic effect) and its neighbors is clearly highlighted. Thanks to asymptotic theories, some useful analogies can be drawn between electromagnetic and seismic metamaterials, and thus much of the knowledge gained in the past twenty years in photonic devices can be translated in the framework of structured soils for an enhanced control of surface waves.

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