

How to advantageously manage the effective ellipticity of seismic waves in metamaterials?

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Abstract. In addition to the research advances made on the interaction of seismic waves with rigid elements in the ground or with holes, this paper explores the possibilities of acting on the free surface displacement. In particular it is about looking at the beneficial effects of a decrease of horizontal surface displacements in case of Rayleigh waves which directly affect the design of buildings. 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.

1. Introduction

The high density of deep foundation or ground reinforcement techniques for buildings in urban area [1], leads civil engineers and physicists to investigate interactions of these buried structures with the seismic signal (Figures 1 and 2).

In the past, a few authors 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. To illustrate the interaction of seismic wave with structured soils, researchers had to develop specific theoretical and original experimental approaches in particular because of the complexity of the wave propagation in the Earth's surface layers [2, 3]. In this article we develop arguments for the kinematic effect influence of structured soils and their development to seismic metamaterials.

2. Overview of field experiments on structured soils under seismic disturbance

No-one can dispute the validity of the physics of mechanic wave propagation in all type of materials, at all range of frequency. Figure 4 shows the transposition of structured nanomaterials to meter-scale earth objects: natural rock or soil strata (1D model) or 2D model made of concrete columns.





Figure 1. Hight density of different types of deep foundations

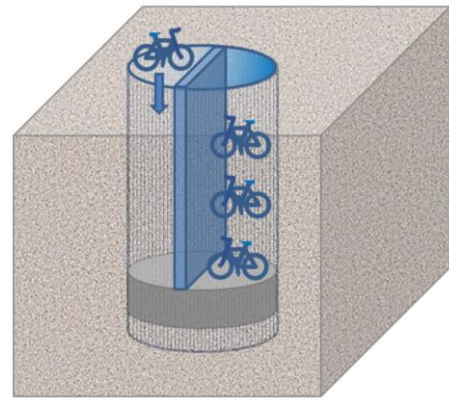
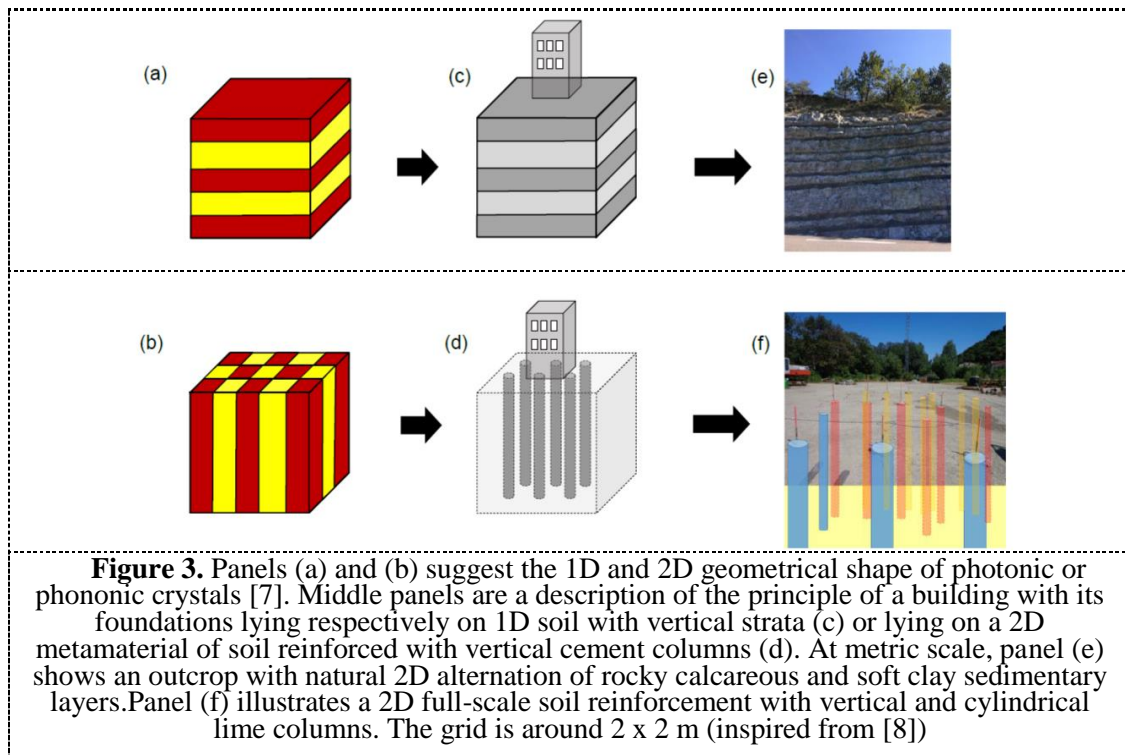
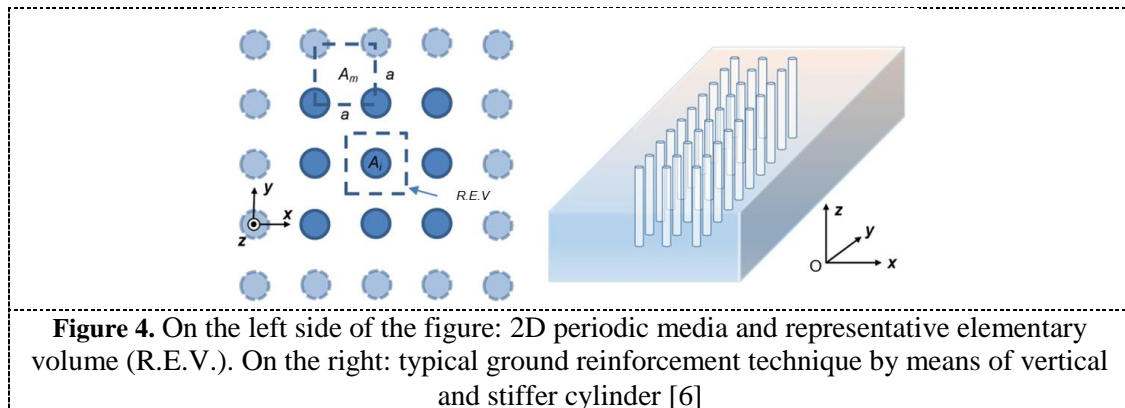


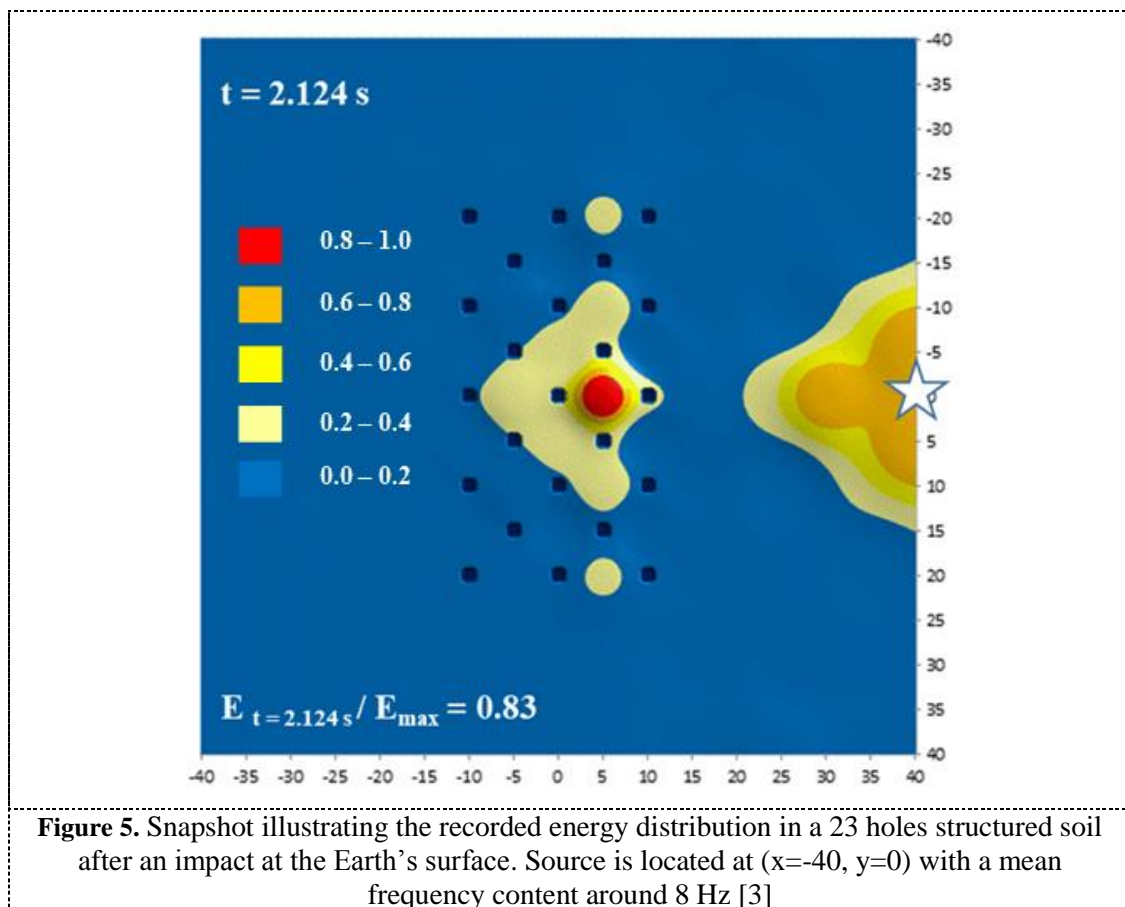
Figure 2. Principle of underground bicycle parking system in Japan (diameter of the hole: 8 to 12 m)



The main type of structured soils made of cylindrical voids [2, 3] and rigid inclusions [4, 5], includes seismic metamaterials (Figure 4). We called this historical category, “Seismic Soil-Metamaterials”.



Full-scale experiments were conducted in 2012 with cylindrical holes and allowed the identification of a clear focusing of the waves. The distribution of energy inside a grid can be interpreted as the consequence of an effective negative refraction index (Figure 5). Such a flat lens is reminiscent of what Veselago and Pendry envisioned for light in Electromagnetism [3]. The structure (i.e. the “lens”) total size was 20 m in width and 40 m in length and was made of 23 holes (2 m in diameter, 5 m in depth, triangular grid spacing 7.07 x 7.07 m).



The frequency dependence of the horizontal to vertical Fourier spectra ratio when the signal passes through the lens has been also observed. Finally, the change of the “effective” ellipticity of waves recorded at the free surface is also opportunity because it is beneficial to reduce the horizontal component of the signal for building design.

3. Effective ellipticity study

The device is basically studied here 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 6).

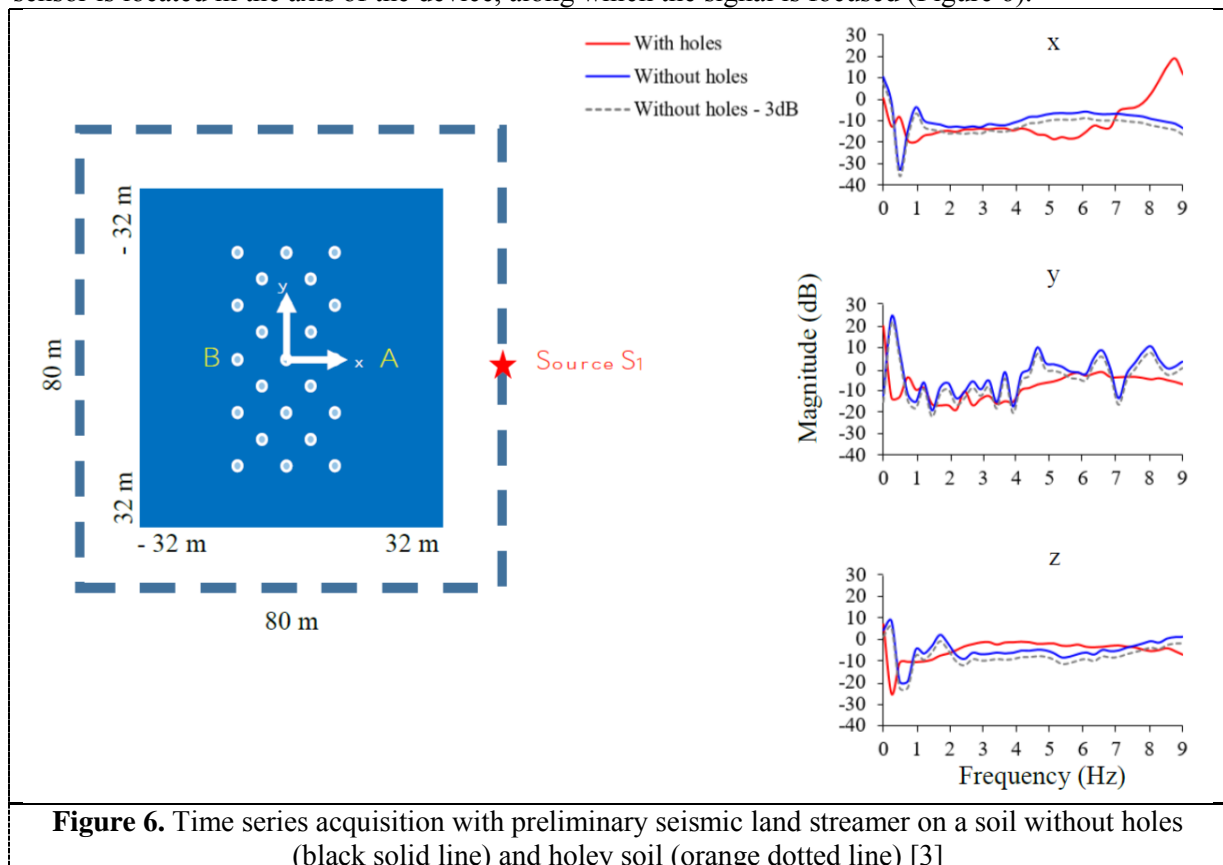
We have also drawn the magnitude of the original soil transfer function minus 3 dB (gray dotted line) to illustrate the efficiency of the holey-ground.

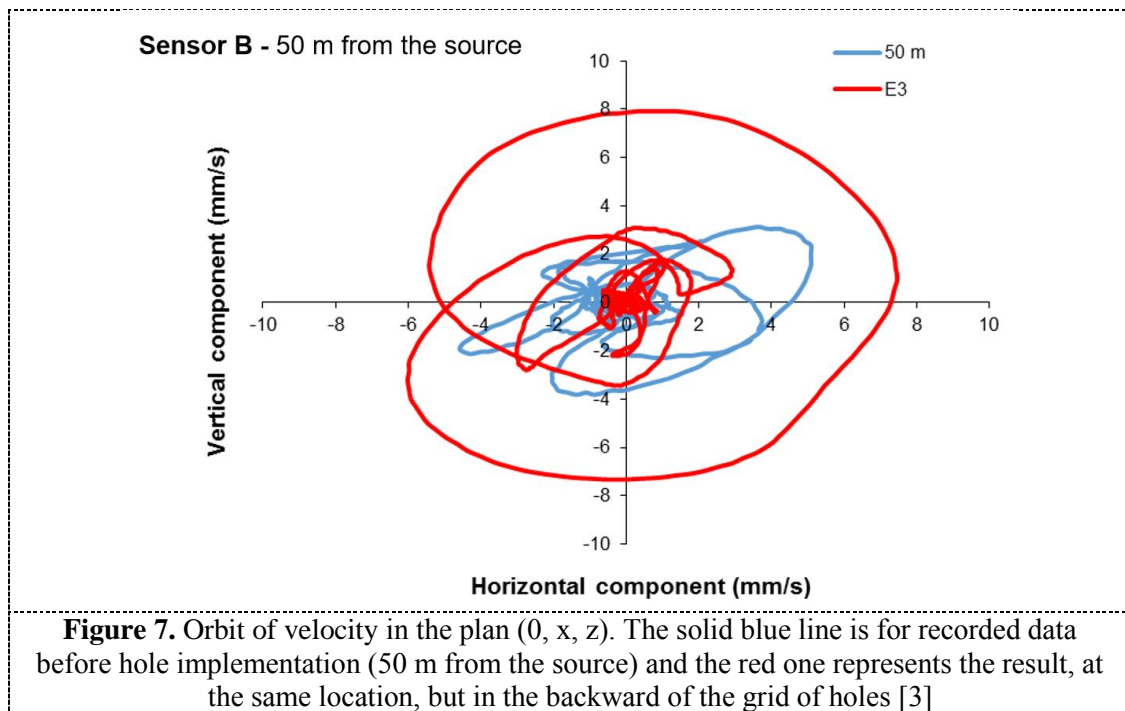
The other aspects of the energy distribution in the structure (effective negative index and flat lensing, seismic metamaterials, dynamic anisotropy) are developed in [3].

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.

Let have a look in time domain. Figure 7 shows the orbital diagram for particle velocity and we can observe a complete change in the shape of this diagram, before and after implementation of holes in the soil. The sensor is located 50 m away from the source. This confirms the modification of the main amplification direction described just above. The amplitude in x and y is also greater because the sensor is located in the axis of the device, along which the signal is focused (Figure 6).





4. Link with Earthquake Engineering

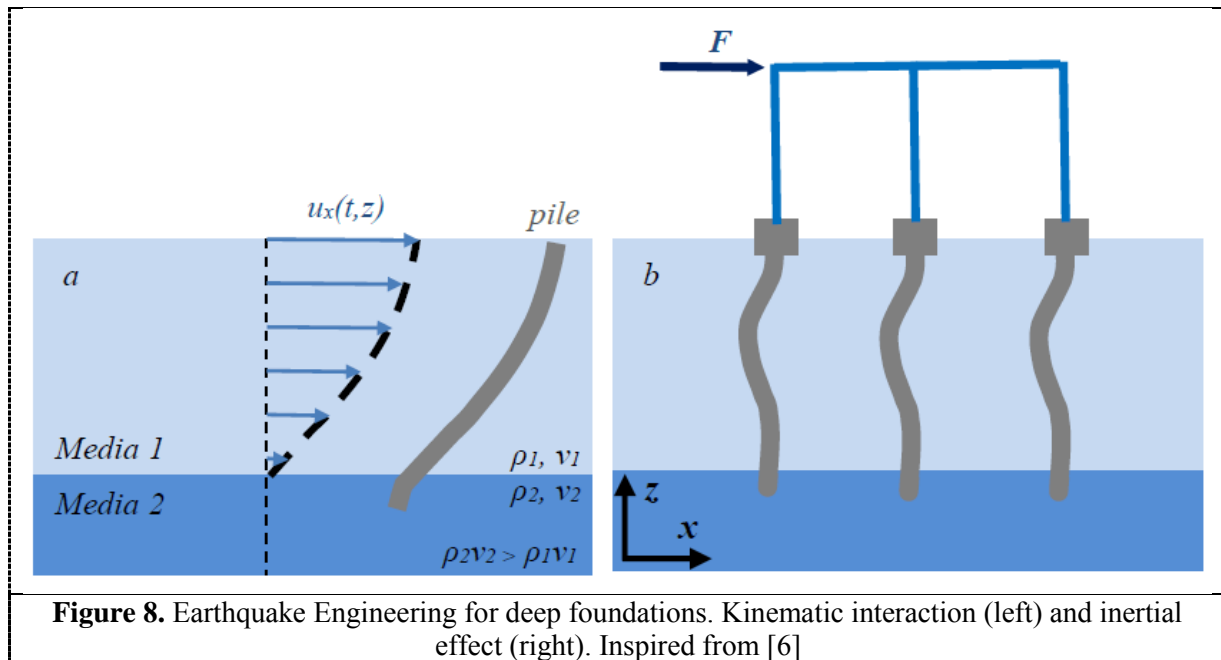
The response of a structure to earthquake shaking is affected by interactions between three linked systems: the structure, the foundation, and the soil underlying and surrounding the foundation.

Soil-structure interaction analysis evaluates the collective response of these systems to a specified ground motion. The terms Soil-Structure Interaction (SSI) and Soil-Foundation-Structure Interaction (SFSI) are both used to describe this effect [6].

The term free-field refers to motions that are not affected by structural vibrations or the scattering of waves at, and around, the foundation. SSI effects are absent for the theoretical condition of a rigid foundation supported on rigid soil. However, in the case of structured soils and, among them, seismic metamaterials, we are specifically looking to interact with high concentration of foundations in the soil (piles, retaining walls, inclusions, etc.).

Earthquake Engineers can act in different ways for the design of structures. In most of the cases, they can directly use the input data from the local regulation which is the result of a deterministic or probabilistic analysis of the seismic hazard.

Kinematic interaction results from the presence of stiff foundation elements on or in soil, which causes motions at the foundation to deviate 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 (Figure 8).



The main novelty brought this last decade by structured soil is the opportunity to modify the kinematic effect described above.

5. Future prospects

Most of the vibration energy affecting nearby structures is carried by Rayleigh surface waves. Earthquake Engineering is mainly concerned with the horizontal component of bulk and surface waves.

Studies carried out shows that the wave propagation in “soft” soils could be dramatically modified by structuring soils. Thus, changing the horizontal component is an asset for Civil Engineering [6].

The arrangement of all the buried elements in urban grounds (large diameter wells, deep and dense foundations, tunnels, etc.) can be a new avenue to interact actively on the content of the seismic signal.

References

- [1] Brûlé S, Enoch S, Guenneau S 2017 *Rev. Fr. Geotech.* **151** 4.
- [2] Brûlé S, Javelaud E.H, Enoch S, Guenneau S 2014, *Phys. Rev. Lett.* **112** 133901.
- [3] Brûlé S, Javelaud E.H, Enoch S, Guenneau S 2017, *Sci. Rep.* **7** 18066.
- [4] Achaoui Y, Antonakakis T, Brûlé S, Craster R.V, Enoch S, Guenneau S 2017 *New J. Phys.* **19** 063022.
- [5] Aznavourian R, Puvirajesinghe T, Brûlé S, Enoch S, Guenneau S 2017 *J. Phys.: Condens. Matter.* **29** 433004.
- [6] Brûlé S, Cui F 2017 *Practice of Soil-Structure Interaction. Application to foundations and retaining walls* (Paris: AFNOR) p 218.
- [7] Joannopoulos J.D, Johnson S.G, Winn J, Meade R.D 2008 *Photonic crystals: Molding the flow of light* (Princeton: Princeton University Press) ed. 2. p 304.
- [8] Brûlé S, Enoch S, Guenneau S, Craster R 2017 *Seismic metamaterials: controlling surface Rayleigh waves using analogies with electromagnetic metamaterials. World Scientific Handbook of Metamaterials and Plasmonics* (Singapore: World Scientific) p 301-337.