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Seismic Metamaterial in Geotechnics

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ABSTRACT: The concept of seismic metamaterials is spreading rapidly in the field of civil engineering. This article aims to illustrate the recent expansion of research fields associated with seismic metamaterials, a concept that first appeared in the 2010s. Three primary reasons have been identified. The first reason is that the physics of Phononic Crystals (PC) and civil engineering structures converge through soil–structure interaction in the context of seismic loading. Rheological analogues are used to describe behavior at the soil-foundation-engineering interfaces. As constructions are most often periodic, it is natural to transpose the tools of wave propagation in crystals to them. The second reason is the possibility of using metamaterials on different scales: mass-structured soils, foundations, structural elements of buildings, etc. The third and final reason is based on an extended definition of seismic metamaterials, which encompasses all structural components that interact with a propagating wave. A seismic metamaterial provides unconventional dispersion induced by local resonances that must be created, as in mass-in-mass oscillators.

KEYWORDS: Seismic metamaterial, Phononic crystals, Soil-structure interaction, Energy harvesting.

1 INTRODUCTION

In 2012, the concepts of Phononic Crystal physics and metamaterials were applied to the analysis of results obtained in full-scale seismic wave propagation experiments (Brûlé et al., 2012, 2013, 2014, 2017a and 2017b). There are opportunities to act on the dynamic response of soil models under 1D conditions. However, the challenge lies in exploring structured soils in 2D, as they require fewer on-site resources than 1D structures, to modify the wave propagation medium.

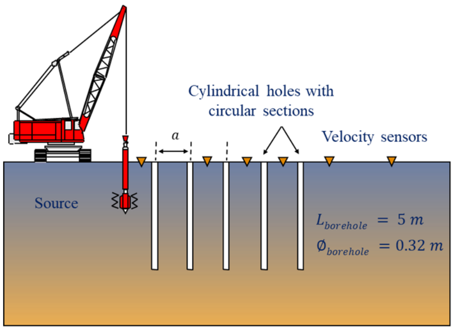

Figure 1. The testing principle of a 2D seismic lens for surface wave manipulation involves a periodic lattice of cylindrical boreholes. Excitation is provided by a 50 Hz mechanical vibrator operating in the horizontal plane (Brûlé et al., 2012).

Two experiments on 2D lenses were carried out on soft superficial soils, artificially structured by hollow vertical cylinders (0.3 or 2 m in diameter), arranged in a regular way. The whole constitutes a soil volume of finite dimensions, from a few meters to tens of meters apart, solicited by a single artificial source, close to the mesh of holes and mainly generating surface waves. These structured volumes of soil were called lens by analogy with optics. The sources consisted of vibro-probe devices placed inside boreholes, generating horizontal-plane displacements with a continuous harmonic signal at 50 Hz (Figure 1), or surface impact sources producing signals with frequencies between 3 and 10 Hz. Wave propagation phenomena were observed at the surface, within the lens, and near its perimeter, located at a distance of two to three times the width of the tested device. The maximum depth of the constructed and tested lenses was 5 meters. Figure 2 presents both numerical and experimental results of the experiment described in Figure 1. The energy emitted by the source is observed to be reflected by the rows of cylindrical boreholes, preventing transmission through the device.

The prospects include the development of anti-vibration barriers effective at frequencies of several tens of hertz, the potential to interpret local soil-structure interaction effects during earthquakes, and the ability to control the singular distribution of seismic energy around specific structures.

This article aims to demonstrate the rapid advancement of both theoretical and experimental approaches in the field of metamaterials within geotechnical engineering and construction.

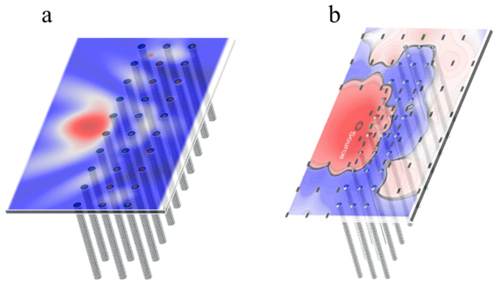

Figure 2. (a) Numerical simulation of the energy distribution for the seismic lens presented in Figure 1. (b) Experimental results showing the corresponding energy distribution (adapted from Brûlé et al., 2014). Black rectangles indicate the locations of the seismic sensors. The red cross represents the 50 Hz vibrating source. For both figures, the red color indicates high vibrational energy, while the blue color corresponds to low intensity.

2 SPECIFIC VOCABULARY

As a reminder, a Phononic Crystal (PC) is an anisotropic artificial structure composed of a periodic distribution of at least two materials with distinct elastic properties, or of a single perforated material. Frequency bands exist for which the propagation of acoustic or elastic waves is either evanescent or allowed/guided. PC interact with wave signals whose wavelengths λ are on the order of the lattice spacing a ($\lambda \sim a$). Since the discovery of photonic crystals in 1987 (John, 1987; Yablonovitch, 1987), physicists have been developing theoretical and numerical models to achieve enhanced control of light in materials structured at the nanometric scale, and of sound at the micrometric scale. A Metamaterial ($\lambda \gg a$) is defined as an artificial composite material made from the assembly of resonators of smaller dimensions, whose wavelength at resonance is much larger than their physical dimension. Local resonance effects have been confirmed in structures like Helmholtz resonators and in highly compliant soils with embedded rigid inclusions. At a macroscopic level, such metamaterials may display emergent properties not observed in conventional materials, including a negative refractive index.

In addition to these early interpretations, recent analyses have highlighted changes in the polarization of surface waves. This renewed reading of the data invites alternative explanations, including the presence of local resonances associated with rigid inclusions in the soil (as opposed to empty cylindrical voids), and paves the way for broader theoretical frameworks such as static and dynamic homogenization, dynamic anisotropy, transformational optics, and surface resonance phenomena. The alteration of seismic signals due to structured soils and surface resonators establishes a clear connection with civil engineering, particularly through the lens of soil–structure interaction as studied in earthquake engineering. This line of research also intersects with seismology, especially regarding the influence of secondary sources generated by surface structures such as buildings covering the urban landscape (Guéguen et al., 2000; Clouteau et al., 2011; Colombi et al., 2015, 2016; Brûlé et al., 2017c; Brûlé et al., 2019; Brûlé, 2023).

3 TRANSPOSITION OF CONCEPTS FROM THE PHYSICS OF COMPLEX MEDIA

One of the distinctive approaches of researchers in metamaterials is the pursuit of analogies in wave phenomena across various disciplines, including acoustic waves, electromagnetic waves, water waves, elastic waves, and seismic waves. By all accounts, the field of seismic metamaterials has reached a stage of maturity comparable to that once seen in other branches of physical sciences - equipped with a robust theoretical foundation yet still awaiting experimental validations capable of confirming the predicted phenomena.

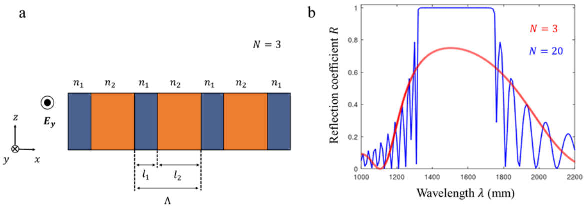

Figure 3. (a) Reflection coefficient R for an electric field $\boldsymbol{E}$ polarized along the y-axis (E_y) propagating through a periodic-structured material. The incident wave is normal to the surface of the material (zero incidence angle). The elementary unit cell consists of two materials with refractive indices n_1 and n_2, and respective thicknesses l_1 and l_2 along the x-direction. As an example, for $n_1 = 2.25$ (close to lithium niobate, LiNbO₃), $n_1 = 1.45$ (similar to glass), $l_1 = 167\,nm$ and $l_2 = 259\,nm$, the reflection coefficient R is plotted in (b) for different numbers of bilayers ($N = 3$ and $N = 20$).

While such an approach may appear unconventional in civil engineering, it is essential to acknowledge that discipline is still evolving in this area. Physicists often operate under the assumption that phenomena observable at a given scale can manifest similarly at other scales. Nonetheless, translating these concepts into experimental practice remains a significant challenge. The transposition of the principles of periodic media to terrestrial materials requires a rigorous definition of the validity conditions, particularly regarding the strain range of soils under seismic or dynamic loading that allows for the assumption of elastic behavior. The theoretical frameworks of condensed matter physics are particularly concerned with wave propagation phenomena in crystalline materials. Crystalline media are often approximated as infinite environments owing to the extremely small size of their lattice units. This assumption, however, is not valid for human-made structures, which are of finite dimensions. However, in a one-dimensional periodic medium consisting of N bilayers designed at one-quarter of the wavelength, it can be demonstrated that notable phenomena such as the Bragg mirror effect are already observable with just a few bilayers (Figure 3). It can be noted that an electromagnetic wave passing through a medium composed of N bilayers is almost totally reflected (reflection coefficient close to 1) for $N = 20$. For $N = 3$, a reflection coefficient R close to 0.75 is already obtained. A similar approach can be developed with terrestrial materials traversed by mechanical waves (Brûlé, 2023). In numerical studies of metamaterials, the frequency of a monochromatic wave is typically varied incrementally, while seismic signals are characterized by a spectral range and inherent randomness.

One of the challenges in seismic metamaterials is the ability to extract vibrational modes of interest within the structured soil. This involves two key considerations. First, the identification of modes is only possible if the signals propagating through the metamaterial are sustained, allowing induced modes to emerge within the structure. As previously mentioned, earthquake-type seismic signals have limited duration, typically lasting only a few seconds to a few minutes. Second, signal processing tools are required to extract the relevant modes. However, for this step to be effective, the wavefield within the structure must be sampled with sufficient resolution.

To ensure adequate temporal and spatial sampling, one approach is to deploy a large number of synchronized ground-based sensors arranged in a dense mesh. Alternatively, other tools may be employed, such as laser-based vibration measurement systems or laser Doppler vibrometers, which rely on the principle of laser interferometry. Another promising avenue involves exploring the potential of optical fibers for identifying vibrational modes (Rodet et al., 2024). To date, interferometric techniques have proven effective in laboratory settings, particularly in experiments simulating seismic wave propagation in thin plates (Colombi et al., 2015; Colombi et al., 2016). However, the extension of these methods to large-scale outdoor environments, aimed at capturing vibrational modes induced by seismic waves in structured soils, remains an open experimental challenge.

4 THE CONCEPT OF A SEISMIC METAMATERIAL IS HIGHLY CONDUCIVE TO SSI PRINCIPLES

A metamaterial provides unconventional dispersion induced by local resonances that must be created, as in mass-in-mass oscillators (Figure 8). This phenomenon can be sought at all scales, and in civil engineering one can identify similar situations, particularly in the way interfaces are described in soil–structure interaction. As a reminder, in 2020, a detailed proposal for a nomenclature was put forward to classify the main types of seismic metamaterials (Figure 4). This proposed framework aimed to establish a unified terminology and categorization method, facilitating clearer communication among researchers and engineers working in the field (Brûlé et al., 2020a). Structured soil is also referred to as a mechanical metamaterial (Felbacq, 2025). This gallery of resonators can be further enriched by introducing interfaces between the soil and the foundations.

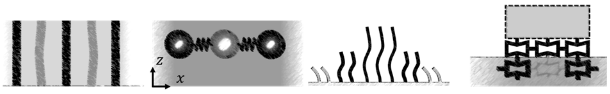

Figure 4. From left to right: seismic-soil metamaterial, buried-mas resonator, above-surface resonator and auxetic metamaterial (Inspired from Brûlé et al., 2020a).

A building's foundations ensure its contact with the supporting soil. In the case of a shallow foundation, which is a reinforced concrete element, one can consider the existence of a relative "stiffness" between this element and the soil (Merrit et al., 1954). Assuming that soil behavior under small-amplitude elastic deformations can be described by Hooke's law, and that physical elements can be represented as lumped masses while interfaces are modeled using established rheological models, the interaction between these elements can be analyzed using coupled oscillator systems (Figure 5).

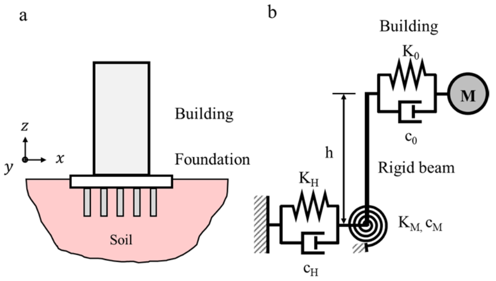

Figure 5. (a). Building and soil model. (b) Building and soil-building interface are modelled with analogic Kelvin-Voigt visco-elastic models (K_0 and c_0 are respectively the bending stiffness and the viscosity of the building, K_H, horizontal stiffness at soil interface, c_H, viscosity of the damper). M is the mass of the building, K_M is the equivalent stiffness for the bending mode and θ is the rotation (Brûlé et Cuira, 2018).

Once this representation is made (Figure 5), and assuming a purely elastic or equivalent elastic case (Figure 6), it becomes theoretically "easy" to envision a semi-infinite 1D or 2D network of oscillators as shown in the Figure 7. These examples of buried-mass resonators can be solved analytically for some cases or numerically using the finite element method (Krödel et al, 2015; Achaoui et al., 2016, Palermo et al., 2016, Zeng et al., 2018; Palermo et al., 2018; Xu et al., 2019). Since 2012, there has been significant activity focused on buried resonators of the mass-in-mass type (Figure 8).

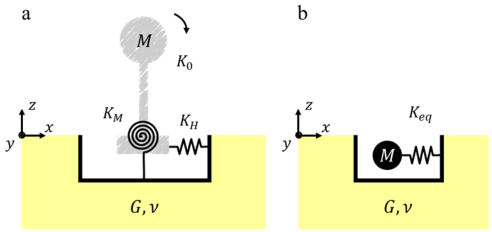

Figure 6. (a). Elastic building model with elastic connections between the soil and the foundation. (b) Equivalent model of (a).

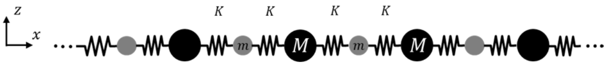

Figure 7. Example of a 1D lattice with two different masses (M and m) connected by identical springs.

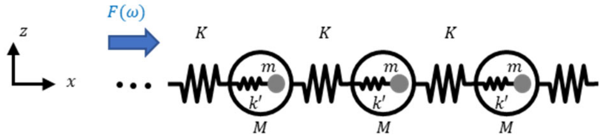

Figure 8. Example of a 1D lattice with mass-in-mass device.

The advantage of "mass-in-mass" oscillators is to lower the minimum frequency of the band gap and to widen its range (Figure 9). These 2D oscillator concepts can be found at the theoretical foundation bases of structures as well as in the constitutive materials of the structures, such as concrete (Figure 10). Some authors then refer to it as metafoundation (Chen et al., 2012; Xiang et al., 2012; Bao et al., 2012). It can be observed that, by 2012, these concepts were already well established in the literature.

5 RAPID EVOLUTION OF THE ORIGINAL CONCEPTS

Studies on real structured soils (Brûlé et al., 2017), have revealed the presence of complex wave phenomena both within and around the structured zones.

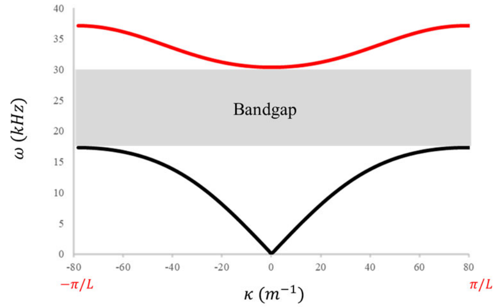

Figure 9. Band diagram for a 1D lattice of "mass-in-mass" type oscillators. L is the length of a unit cell, κ the wavenumber, and ω is the angular frequency. Here, $K/k' = 2$ and $M/m' = 1.44$.

For example, one objective may be to identify areas where seismic or vibratory energy (ambient seismic noise) is concentrated, and to assess the potential for harnessing it by strategically placing piezoelectric sensors to convert these vibrations, exacerbated by the device, into electricity (Brûlé et al., 2020b; Chaplain et al., 2025). It is also valuable to explore the use of vibration sensors embedded in civil engineering structures and to highlight the potential role of seismic metamaterials in this context. Seismic metamaterials could thus be used not only to protect buildings, focus, and mitigate the damaging effects of Rayleigh waves, but also offer promising prospects for energy harvesting from ambient seismic vibrations (Brûlé et al., 2024a, 2024b).

As another derivative of metamaterials, one can also mention metaconcrete. The concept of metaconcrete was first introduced by Mitchell and co-authors (Mitchell et al., 2014) as a modified form of concrete designed to mitigate damage and reduce the propagation of energy caused by dynamic loading (Mitchell et al., 2016). This innovative material incorporates metamaterials as a partial substitute for the standard aggregates typically used in conventional concrete. Each engineered aggregate consists of a heavy core enveloped by a thin, soft outer coating. This coating acts as an elastic spring, enabling oscillatory motion of the heavy core. Aggregate design can be optimized and improved within the targeted frequency range (Xu et al., 2020; Kettenbeil et al., 2018). These authors investigated how aggregate geometry and material properties influence the frequency band gap.

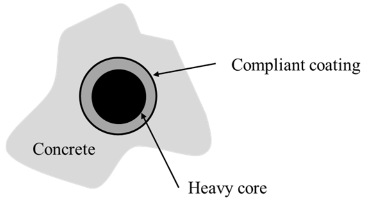

Figure 10. Metaconcrete with locally resonant material (Inspired from Mitchell et al, 2014).

There is very active research on metamaterials in general. For example, some authors explore auxetic properties of metamaterials (Tan et al., 2025). Others explore the ability of forest surfaces to modify the polarization of seismic waves or to influence the distribution of energy with trees (Maurel et al., 2018), metasurfaces for controlling seismic surface waves (Liu et al., 2020) while others develop the properties of meta-foundations (Ni et al., 2025), explore the zero-frequency bandgap of seismic metamaterials (Luo et al., 2025).

6 CONCLUSIONS

Seismic metamaterials are of great interest for both fundamental and applied research because the theoretical description of seismic waves can offer potential applications for modifying the signal (polarization changes, band gaps, energy distribution, etc.). However, terrestrial media are more complex than materials whose properties are perfectly known from laboratory experiments. Thus, the conditions of experimentation on real geological sites are crucial. What is remarkable across the numerous research works of the metamaterials community is the ability to identify singular phenomena at all physical scales. Nevertheless, several challenges exist in the approach to metamaterials. First, it is important to distinguish phononic crystals from true metamaterials. Next, natural soils offer little mechanical contrast between each other. Thus, to create "mass-in-mass" type oscillator networks, it is sometimes necessary to consider using metal to exceed densities of 5, compared to densities of 2.3 for concrete and 1.6 to 2.0 for most soils. Consequently, such applications are more likely to be limited to small-scale areas for cost reasons. Research on networks of concrete piles anchored into a deep substratum (Achaoui et al., 2017) offers promising perspectives, as these configurations are close to real-world construction practices. Potential applications are emerging, such as the mechanical energy harvesting.

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