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State of the art on the recovery of mechanical energy in the city. The role of seismic metamaterials

État de l'Art sur la conversion de l'énergie mécanique en ville. Le rôle des métamatériaux sismiques

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ABSTRACT: Studies on structured soils, including seismic metamaterials, have shown the existence of complex wave phenomena within and around the structured zone. The aim is to assess areas where seismic or vibratory energy is concentrated, and to decide whether it would be worthwhile to exploit them by judiciously placing piezoelectric energy sensors. The article presents what is already being done with vibration sensors implanted in civil engineering structures and shows the potential interest of seismic metamaterials in this context. The modification of the surface signal by both structured soil and surface resonators meets the challenges of Civil Engineering through the effects of soil-structure interaction. Seismic metamaterials can therefore not only be considered for building protection, lensing and minimizing the effects of potentially deleterious Rayleigh waves, but also have potential applications in energy harvesting using ambient seismic noise.

RÉSUMÉ: Les études sur les sols structurés, dont les métamatériaux sismiques, ont montré l'existence de phénomènes d'onde complexe à l'intérieur et autour du sol transformé. Il s'agit d'évaluer les zones de concentration d'énergie sismique ou vibratile et de décider de l'intérêt de les valoriser en plaçant judicieusement des capteurs d'énergie piézoélectriques. L'article présente ce qui se fait déjà avec des capteurs de vibrations implantés dans des structures de génie civil et montre le potentiel intérêt des métamatériaux sismiques dans ce contexte. La modification du signal en surface à la fois par le sol structuré et les résonateurs de surface rejoignent les enjeux du génie civil par les effets de l'interaction sol-structure. Les métamatériaux sismiques peuvent donc non seulement être envisagés pour la protection des bâtiments, les effets de lentille et la minimisation des effets des ondes de Rayleigh potentiellement délétères, mais ils ont également des applications potentielles dans la collecte d'énergie en utilisant le bruit sismique ambiant.

Keywords: Energy harvesting device; seismic noise; seismic metamaterials; structured soils; smart city.

1 INTRODUCTION

In recent years, there has been growing interest in finding new ways to produce clean, sustainable energy. A new type of devices has emerged. They are called Energy Harvesting Devices - EHDs (Khaligh et al., 2010). One of the most innovative and promising methods is to harvest energy from pedestrian or road traffic, for example.

2 REVIEW OF SOME TYPES OF ENERGY HARVESTING DEVICES

When people walk, run or climb stairs, they generate kinetic energy that can be converted into electricity using various energy harvesting technologies.

Among all the energy related human activities we can consider in urban environment, traffic is one of the most energy-expensive ones, and, furthermore, it is characterized by great waste. Only 30% of the fuel potential is used to transfer kinetic energy to the vehicle and the largest part of this energy is dissipated in decelerating phases by brakes and gases (Ye et al., 2010).

The use of speed bumps is basically to slow the vehicle in certain areas such as school, residential streets, dangerous corner, and near car park area such as a bus station and hypermarket. “Powerbumps” are innovative energy harvesting devices that reduce the speed of vehicles by converting the kinetic energy otherwise wasted by brakes into electricity (Pirisi et al., 2012).

The amount of energy that can be gained from pedestrians depends on several factors, such as the number of people walking, their weight, and the frequency and intensity of their footsteps.

Piezoelectric tiles are one of the most common technologies used to harness energy from pedestrian traffic. These tiles are embedded in the ground and generate electricity when they are compressed by the weight of people walking on them. They can be installed in public spaces such as parks, plazas, and sidewalks to generate electricity that can be used to power lights, sensors, and other low-power devices.

Kinetic pavements are similar to piezoelectric tiles but designed to generate more energy. They use a more advanced technology that allows them to generate energy not only when compressed, but also when flexed. Kinetic pavements are typically made of a composite material that contains piezoelectric fibers.

The stairs generate electricity through the kinetic energy produced by people walking up and down them. The energy is then stored in batteries and used to power the station’s lighting system.

An energy harvester can be constructed by combining a mechanical structure with an energy transducer. The former commits itself to capture the mechanical energies and regularizing them into internal strain energy or kinetic energy of relevant components. Then, the transducer converts regularized energies into electricity to power low-consumption devices (Yin et al., 2023). The harvester system (figure 1), by means of the piezoelectric effect, converts the mechanical energy of the human being walking, running or jumping, in exploitable electric energy.

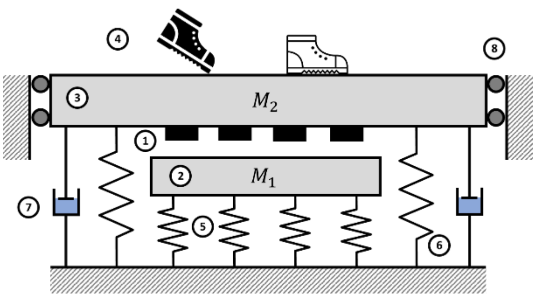

Figure 1. Schema of the harvester system (adapted from Malki et al., 2020). Legend: 1– piezoelectric patches, 2 – mass M_1, 3 – plate (mass M_2), 4 – pedestrian steps, 5 – substrate springs, 6 – centered springs, 7 – dashpot, 8 – sliding device.

3 HUGE OSCILLATORS IN THE CITY AND METACITY

Metacity was a concept first put forward in the late 1980s on the basis of experimental observations of soil response and its devastating effects. It has been known since the 1950s that the natural frequencies of any man-made structure are influenced by soil-structure interaction, particularly on soft soils, and that the presence of structures on the surface of a homogeneous half-space can significantly modify ground motion (Clouteau and Aubry, 2011; Guéguen et al., 2000; Trifunac, 1972; Wong et al., 1977). Most of the time, the problem of ground response is disconnected from that of the resonant response of buildings or group of buildings (figure 2a).

On the basis of studies carried out on the interaction of cities with the seismic signal (what could be viewed as a form of multiple scattering similar to that in Phononic Crystals PCs), some authors propose further extensions of this concept (Wirgin and Bard, 1996) based on analogies with electromagnetic and seismic metamaterials (Kadic et al., 2013; Merrit and Housner, 1954). This theoretical approach is consistent with studies of several authors on the influence of the trees of a forest on the surface waves (Maurel et al., 2018).

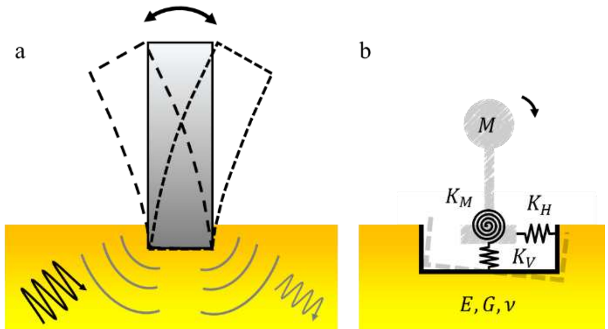

Figure 2. (a) The building vibrates as a result of seismic waves, then through inertial effects, becomes a secondary source of vibration itself. (b) Soil-foundation interface is modelled here in the case of three degree of freedom with analogic Maxwell models (K_H, K_V, respectively horizontal and vertical stiffnesses, K_M is the rotational stiffness of the model).

The concept here is to position sensors in areas where vibratory motion is amplified by surface resonators (Brûlé et al., 2019; Brûlé et al., 2020). Seismic metamaterials come into play by virtue of their ability to concentrate the mechanical energies of seismic waves and seismic ambient noise. It should be noted that seismic metamaterials were first studied in the case of earthquakes (Brûlé et al., 2014). City vibrations are also of interest to researchers, who are using the fiber optics (D.A.S. – Distributed Acoustic Sensing) already installed in cities as a gigantic network of seismic sensors (Rodet et al., 2022). Distributed Acoustic Sensing is a technology that enables continuous, real-time measurements along the entire length of a fiber optic cable. For example, each building can be modeled as an oscillator with soil-foundation interface conditions. These interfaces can be represented by rheological models with several degrees of freedom (figure 2b).

4 ROLE OF SEISMIC METAMATERIAL

The main paradigm shift lies in the search for the specific modal signatures of all these objects (structured soils, foundations, etc.), which requires the implementation of specific material means in the field (seismic sensors, sensor density, etc.) and also analysis tools to extract the data of interest (Brûlé et al., 2024).

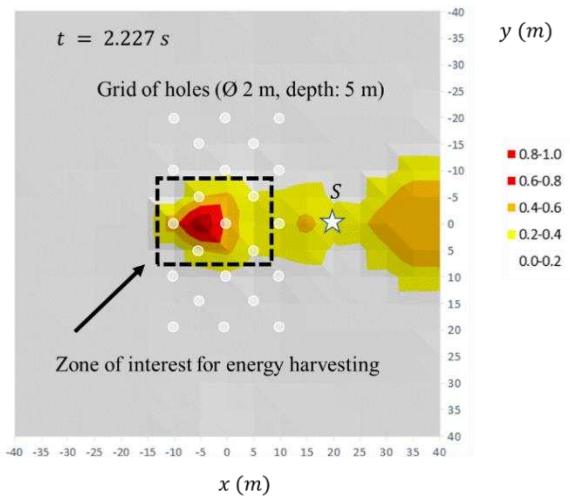

Figure 3. Example of a staggered hole pattern (20 – 40 m). The impact source (S) is located at 10 m from the long side. The energy scale is arbitrary and normalized. The figure shows energy concentrations at locations of interest for positioning vibration sensors (Brûlé et al., 2020).

The transposition of the principles of periodic media to materials as specific as terrestrial materials requires rigorous definition of the validity conditions. In particular, these conditions are the strain range of the soil making possible the justification of an elastic behavior and a thick and homogeneous sedimentary site to limit the reflection effects of the underlying geological layers of contrasted impedance.

The interpretation of the measurements is carried out from the perspective of the physical phenomena expected in periodic media. The seismic lenses tested (Brûlé et al., 2024) are explored as phononic crystals and metamaterials. By the effects observed, we point out the diffraction including Bragg reflection and double image of the source as a result of the negative refraction of a flat lens.

However, a metamaterial 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. These possibilities of local resonances are verified for Helmholtz resonators or very soft soils with rigid inclusions. On a macroscopic scale, a metamaterial is likely to exhibit properties that are not found in nature, such as negative refractive index. In addition to these early interpretations, there is an analysis of the modification of the polarization of surface waves. This new reading of the data opens the discussion on other descriptions of phenomena such as the existence of local resonances of rigid elements placed in a soil, and no longer of empty cylinders, as well as on static or dynamic homogenization approaches, dynamic anisotropy, transformational optics, surface resonators, etc.

The modification of the signal by the fact of a structured soil and surface resonators are the link with Civil Engineering and the soil-structure interaction practiced in Earthquake Engineering (figure 3). Research subjects converge in seismology and on the effects of secondary sources generated by surface buildings.

5 SEISMIC AMBIENT NOISE

In urban areas and for the frequency range of interest for civil engineering structures (0.1 Hz to 30 Hz), the orders of magnitude for particle velocities at ground level are 10^{-6} to 10^{-5} m/s. For accelerations, values are of the order of 10^{-5} to10^{-3} m/s^2.

The rapid development of sensor sensitivity, miniaturization, falling costs and energy storage capacities will make it possible to exploit seismic ambient noise excacerbated by structured materials (in the ground or in buildings).

6 DISCUSSION AND CONCLUSIONS

The development of building construction is steadily moving towards smart buildings and cities. All free energies will be exploited: solar, geothermal, wind energy, seismic ambient noise, etc. A decisive turning point in the evolution of seismic metamaterials is their ability to create energy channels - rather chaotic, but potentially profitable for installing sensing devices.

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