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Investigation of the Effect of Metamaterials on the Mitigation of Seismic Waves

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ABSTRACT
Assemblies of various elements that are often arranged in repeating patterns are used to create metamaterials. Their distinctive characteristics result from their substantial geometry and organization. Rather than the chemistry of the material, the geometry of the microstructure creates the novel properties of metamaterials. Metamaterials can be used in elastic wave filtering and vibration protection. Metamaterials have a wide range of uses since elastic waves are frequently encountered in a multitude of fields, including surface acoustic wave devices, seismology, and civil engineering. As a result, seismic metamaterials have become more prevalent over the past ten years. Typically, the frequency range in concern for structures subjected to seismic loads is 0 to 30 Hz. It has been demonstrated that the incorporation of resonators into an elastic structure can lead to many interesting effects, such as the generation of low frequency standing waves, negative refraction, cloaking, and filtering of seismic waves. The theoretical and practical challenge is to create, within the required frequency interval, "energy sinks" or "band gaps" where waves are channeled and thus diverted away from the main protected structure. Thus, the impact of waves on the structure can be diminished by using a certain configuration and geometry for the various structural elements or by including a particular element in the structure.

Keywords: *Frequency band gap, seismic metamaterials, vibration, waves.*

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I. Introduction

Metamaterials can be considered as an engineered materials; they are made of a group of any kind of elements that are organized in repeating patterns. The geometry of the metamaterial structure can make it cloak elastic waves for a specific range of frequencies that is called a frequency bandgap, and it can be used for protection from vibration or filtering of acoustic, optical and seismic waves.

II. Laboratory scale metamaterials

In 2018, El-Sherbiny et al. [1] have analyzed the response of three different 1D continuum models under the effect of harmonic load excitation. A rod attached to a density of axial resonators (Fig.1), a Timoshenko beam of infinite bending stiffness and an Euler beam attached to a density of transverse resonators (Fig.2). The models exhibited a highly attenuated response in a range of frequencies that is called the band gap frequency.

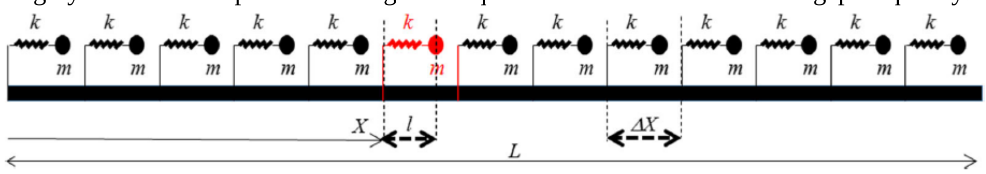


Fig. 1 A one-dimensional continuum connected with a discrete number of resonators.

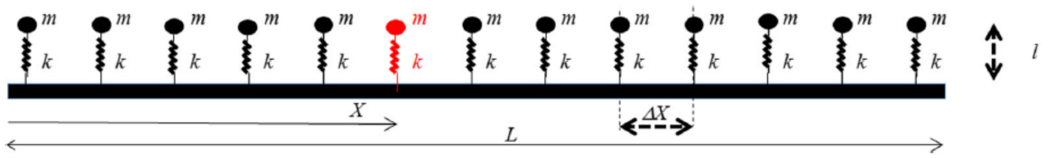


Fig. 2 A Timoshenko or an Euler beam that is transversely deformable.

Also, they presented the functions that can deduce the upper and lower limits of the band gap. Moreover, they numerically analyzed a 2D geometry with uniformly distributed oscillators to investigate its response under longitudinal or transverse excitation. Under harmonic load excitation using FE program ANSYS, the model was analyzed, and the resulted band gap was in the frequency range from 319 to 423 Hz as shown in Fig.3.

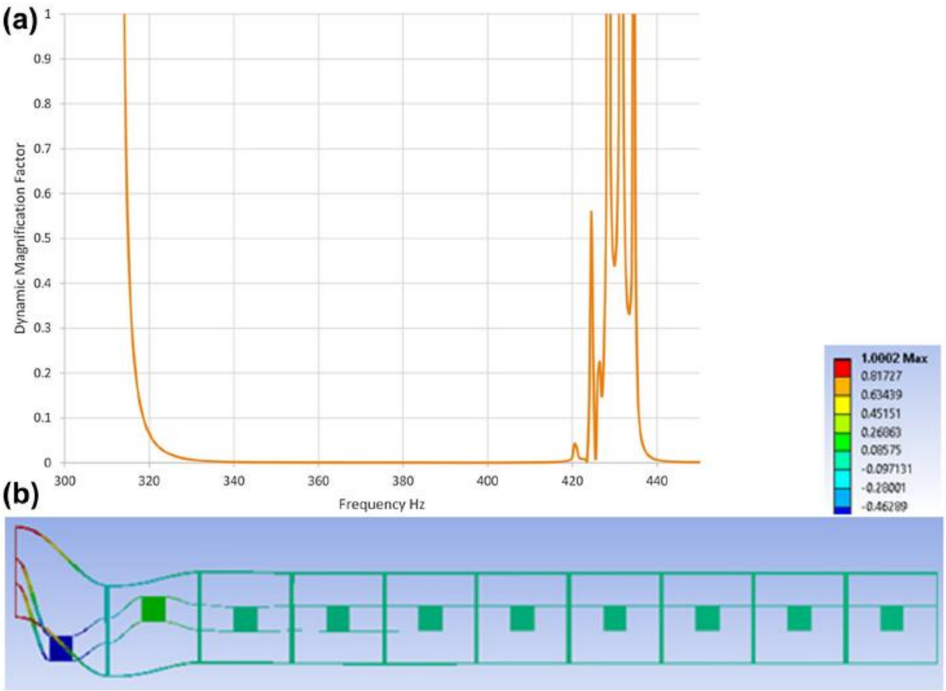


Fig. 3 a) Dynamic magnification factor D versus excitation frequency f for the 2D model. b) Maximum deformation at frequency f = 400 Hz.

Furthermore, the same model was printed as a 3D microstructure model containing a density of resonators using a shaking table device and a frequency bandgap was obtained as shown in Fig.4 [2].

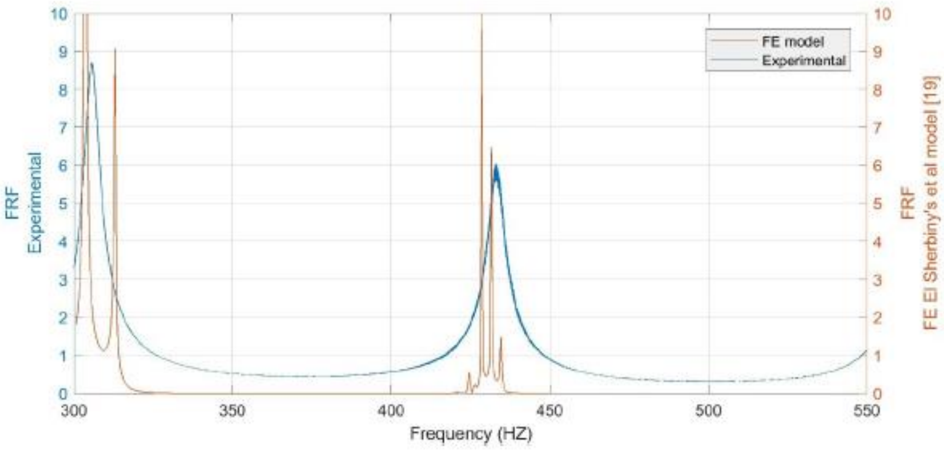


Fig. 4 The ratio between the acceleration at the top of the structure to the acceleration at the base (Acc_t/Acc_b) (called here the frequency response function, FRF) vs the excitation frequency.

III. Large scale metamaterials

Seismic metasurfaces

On a wider scale, in 2016, Colombi et al. [3] studied a meta-surface made of spatially graded subwavelength resonators on an elastic substrate as shown in Fig.5. They concluded that this seismic metamaterial structure can convert the destructive seismic waves into harmless bulk shear waves when the waves have been approaching the short side of the wedge. Moreover, when approaching the long side of the wedge, the waves have been diverted into the bulk.

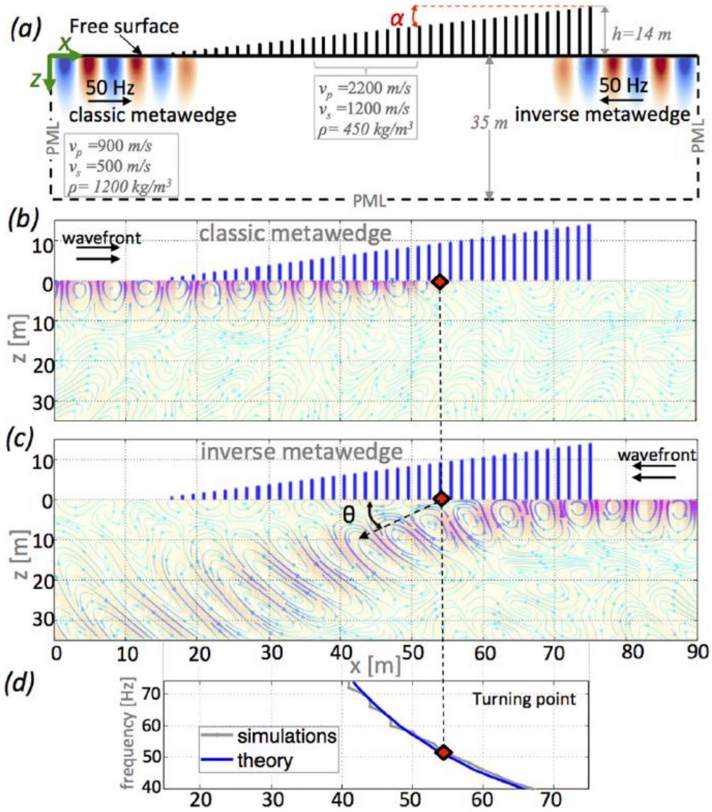


Fig. 5 (a), the geometry and material parameters. In (b,c) are for increasing, and decreasing, respectively resonator height relative to the direction of Rayleigh wave incidence. Panel (d) gives the theoretical prediction versus measured, from numerical simulation, of the turning point position for various frequencies for the wedge in (a).

Xingbo Pu et al.[4] proved the importance of fluid-solid interaction in the dynamics of the seismic metasurfaces. They analytically studied the seismic metasurfaces while propagating Rayleigh waves through a porous layer of soil (Fig.6) equipped with local resonators and showed that the band gap is influenced by the variation of the water table level. Also, Wenlong Liu et al.[5] proposed an ultra-wide band gap metasurface and applied it in bridge engineering.

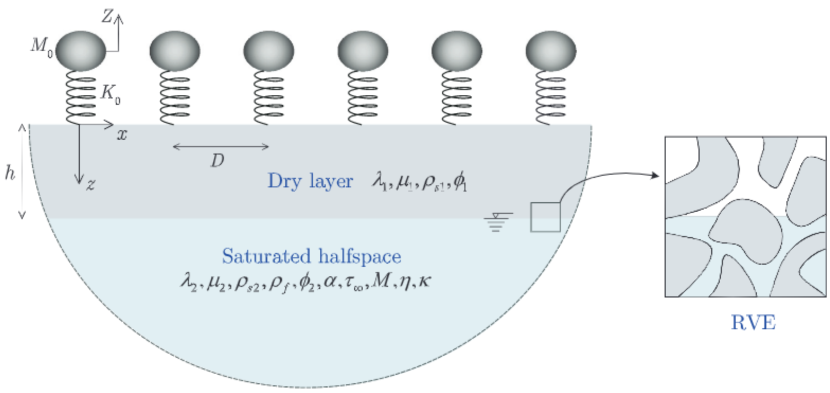


Fig. 6 Schematic of a seismic metasurface on a porous layered medium.

Then, Jean-Jacques Marigo et al. [6] simulated an array of plates over a semi-infinite elastic ground and analyzed its effect on the propagation of the seismic waves. Also, in 2021, Palermo et al. [7] investigated the propagation of waves in a non-linear metasurface consisting of an array of non-linear oscillators attached to the free surface of a homogenous substrate. Then, they studied the influence of non-linearity on the spectral gap width and frequencies. Moreover, they investigated the combined effects of non-linearity and energy loss on the dispersive properties of the metasurface.

Seismic metafoundations

A new design paradigm of composite foundations was proposed by Casablanca et al. [8]. It retains the resistance of a standard foundation to a vertical load (i.e., a building on top), while offering the advantage of filtering the energy of S-waves propagating through it with frequencies within its band gap.
It was concluded that S-waves with frequencies greater than 4.5 Hz (the starting frequency of the theoretical band gap) are attenuated and that the device studied can filter more than 50% of the wave energy within that band gap (see Fig.7).

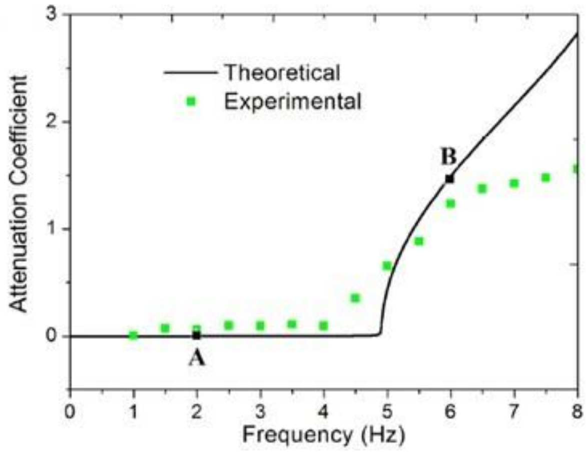
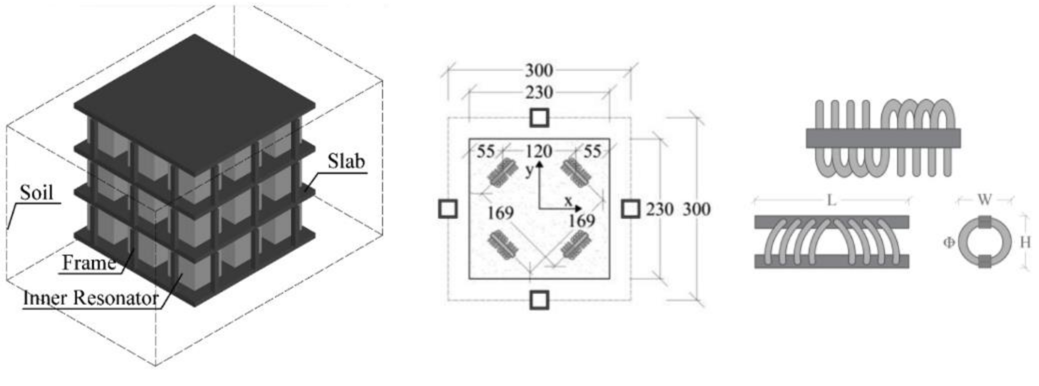


Fig. 7 Comparison between the theoretical attenuation coefficient (solid line) and the experimental one (green squares).

Moreover, Lei Xiao et al. [9] explored that the soil-structure interaction can improve the seismic mitigation performance of a periodic foundation. Likewise, Xinnan Liu et al. [10] introduced a combined layered periodic foundations with different unit cells in tandem as seismic metamaterial structure (see Fig.8). They also studied varying configurations of the metamaterial and showed its low starting frequency attenuation zones.



(a) (b) (c)

Fig. 8 Schematic mechanical model of the periodic foundation: (a) isometric view of the periodic foundation; (b) configuration of a single unit cell equipped with steel wire ropes (measures in cm); (c) details of a single wire rope.

Furthermore, Colombi A et al. [11] discussed in detail the role of the metabarrier and the metafoundation in the mitigation of seismic waves impact on buildings. The metabarrier surrounds the structure and cloaks the seismic waves and the metafoundation supports the structure and reduce the effect of waves. They performed a full 3D numerical simulation considering various parameters such as soil type, size, number of resonators and source directivity (Fig.9).

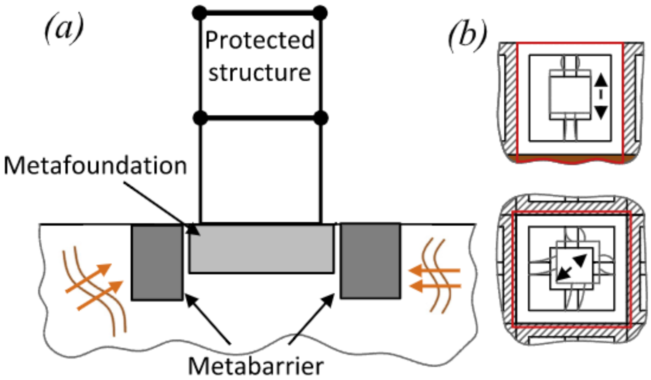


Fig. 9 Differences between the metabarrier vs. The metafoundation. The metabarrier encloses the superstructure without bearing its weight while the metafoundation does. (b) Sketches for two types of unit cells for a resonant metamaterial characterized by a different motion polarization. Resonators with a vertical polarization (top) can be useful to attenuate Rayleigh waves, while full 3D resonators (below) interact with both vertical and horizontal polarizations.

Soil inclusions

Brûlé et al. [12] demonstrated an experiment about a seismic metamaterial constituting of a mesh of vertical empty inclusions bored in the initial soil (see Fig. 10). The metamaterial structure was exposed to seismic waves generated by a monochromatic vibro-compaction probe. The energy in the field was measured before and after installing the boreholes and a strong reflection of surface waves by the seismic metamaterial has been confirmed.

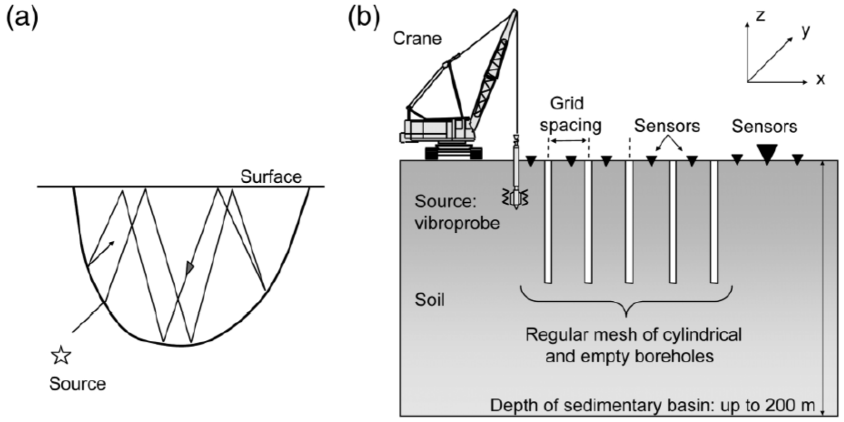
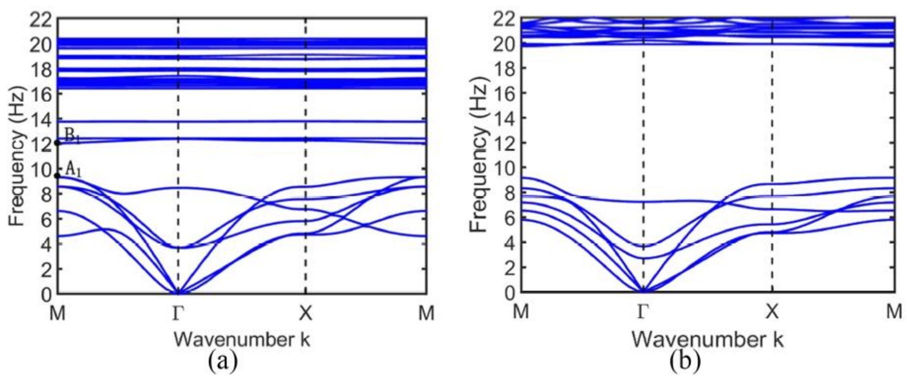


Fig. 10 (a) a seismic wave in an alluvium basin and (b) the seismic testing device cross section in the x-z plane.

Moreover, an elastic metamaterial with periodically square concrete filled steel piles embedded in soil was analyzed by Du at al. [13]. They achieved a seismic shield for guided Lamb waves and surface waves. Complete band gap with specific frequencies were developed. They found that the periodic composite constituting of periodic square shaped piles produces a wider band gap than that of rectangular or cylindrical shaped piles (Fig.11). Band gap highly depends on the shape, dimensions, and material properties of the structure.



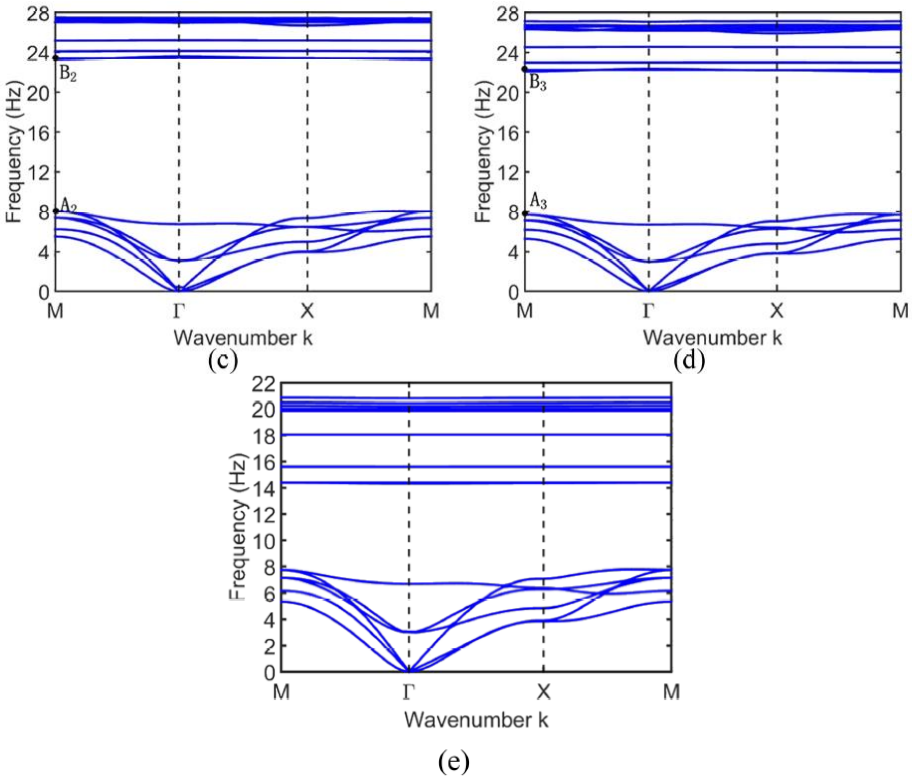


Fig. 11 Band structures with different structures for Lamb waves: (a) hollow cylinder, (b) hollow rectangle pile, (c) hollow square pile, (d) concrete-filled square pile, (e) soil-filled square pile.

Then, Xingbo Pu et al. [14] controlled the surface waves artificially using periodic wave barriers. In addition, Dian-Kai Guo et al. [15] explored the coupled interference of the seismic resonators with the anisotropy of the surrounded soil material so that the seismic waves, within a certain frequency range, can be cancelled for earthquake protection (Fig.12).

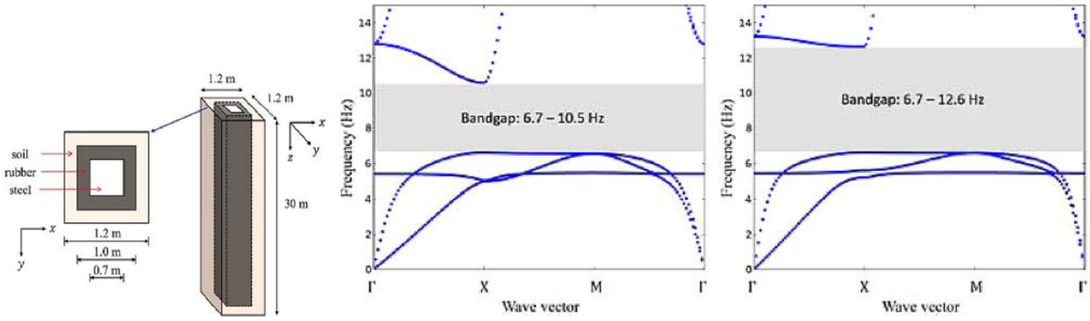
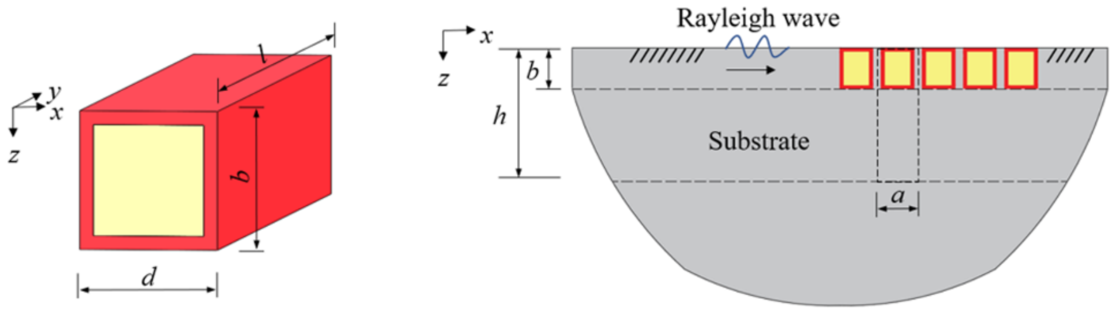


Fig. 12 The geometric configuration of the unit structure and the resulted band gap for different transverse shear modulus of the soil.

Furthermore, Xiao Wang et al. [16] proposed a 1D and 2D seismic metamaterials composed of common building materials to avoid expensive materials. The seismic metamaterial consisting of periodic infilled pipes (see Fig. 13) filtered the Rayleigh waves and the band gap width depended on the distance between two adjacent infilled pipes and the properties of the soft filling material.



(a) (b)

Fig. 13 a) In-filled pipe; b) seismic metamaterial composed of periodic infilled pipes and a substrate.

As shown in Fig.14, Xinyue Wu et al. [17] succeeded to broaden the band gap in a low frequency range by proposing a seismic metamaterial structure consisting of pillars above the ground and core-shell inclusions embedded in the soil. This metamaterial structure is aimed for protecting large infrastructures or civil engineering architectures.

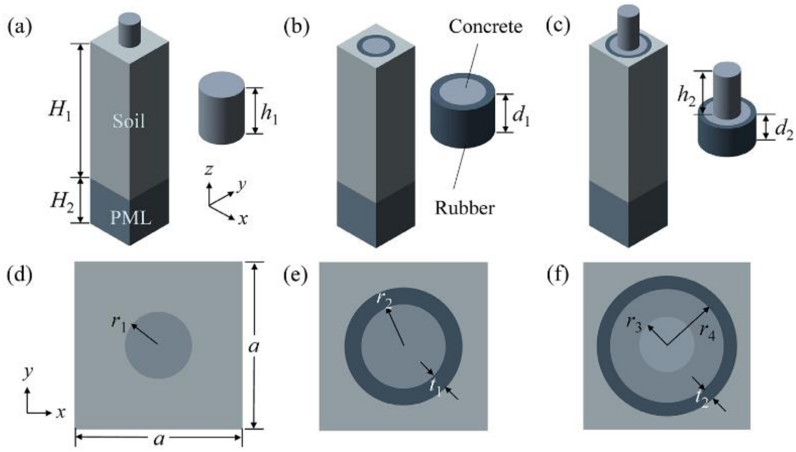


Fig. 14 Unit cells of (a, d) pillar, (b, e) core-shell inclusions, (c, f) combined metamaterials.

Moreover, A novel type of 2D seismic metamaterial was demonstrated by Ting Ting Huang et al. [18]. Fig.15 illustrates the metamaterial structure consisting of auxetic foam-coated hollow steel columns. This structure was analyzed, and a parametric study was performed. The width of the band gap depended on the shape and height of the unit cell in addition to the properties of the auxetic foam.

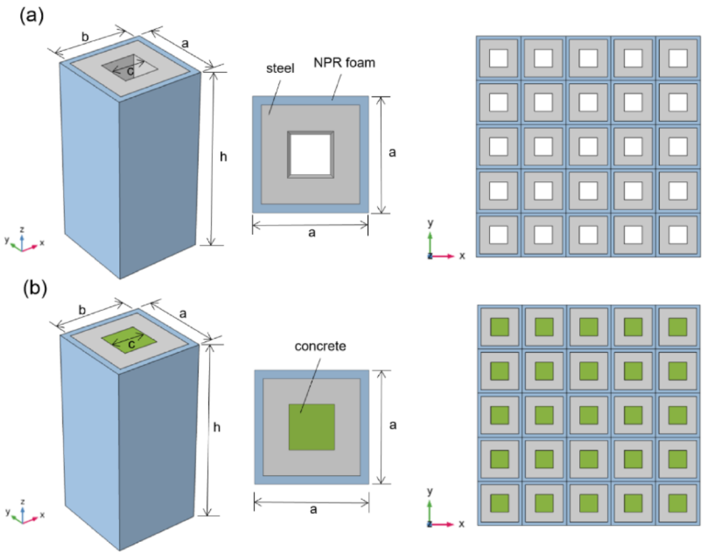


Fig. 15 Schematic representation of the SM structure: (a) unit cell and arrays composed of auxetic foam and hollow square steel column; (b) unit cell and arrays of concrete-filled column.

The geometry and material of the seismic metamaterial structure play a major role in cloaking seismic waves and controlling the width of the band gap as presented by T. Venkatesh Varma [19]. They studied several seismic metamaterials with different geometries and materials and consequently they found that the steel columns are more effective but expensive. Non-reinforced concrete could be a more effective alternative when casted as columns coated with soft soil (as shown in Fig.16).

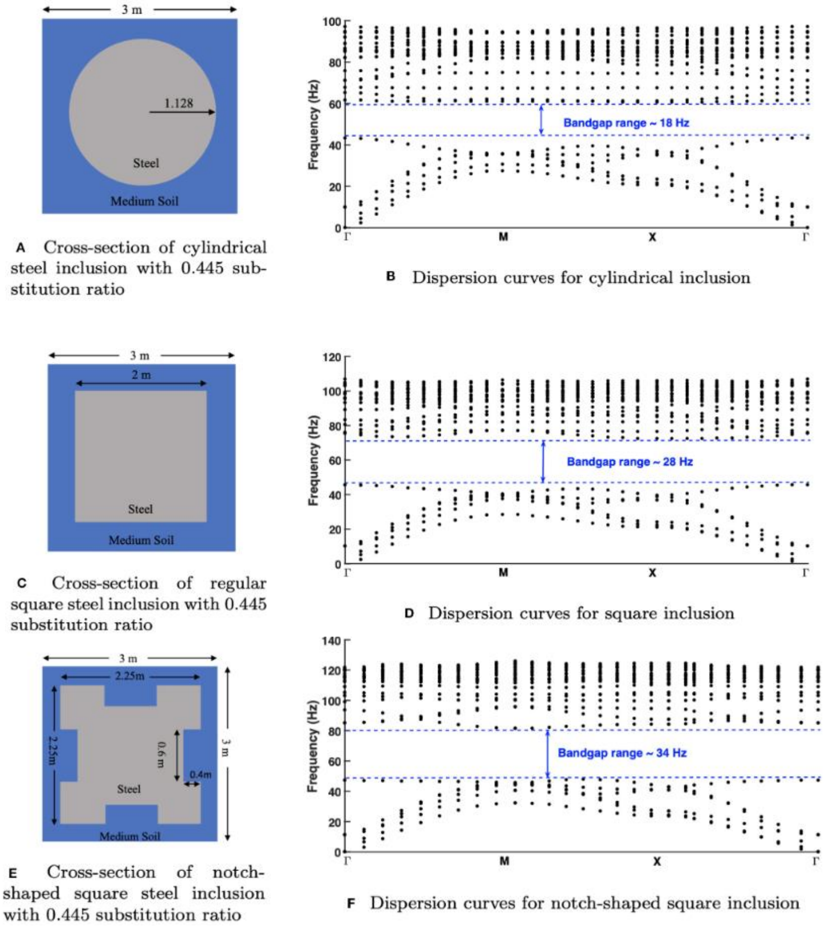


Fig. 16 Unclamped configuration of (A) cylindrical, (C) regular-shaped square and (E) notch-shaped square geometry inclusions. (B, D and F) Dispersion curves for cylindrical, regular-shaped square and notch-shaped square inclusions. There is an enhanced bandgap range with regular-shaped square (~28 Hz) and notch-shaped square (~34 Hz) inclusions in comparison to cylindrical inclusion (~18 Hz).

The application of metamaterials is also introduced in railways by Ting Li et al. [20] to shield the ground vibrations resulted from the high-speed rail system. They developed a 3D coupled train-track-soil interaction model (Fig.17) and investigated the variation of the number of inclusions, the distances, and the train speeds on the mitigation effects for the induced ground vibrations.

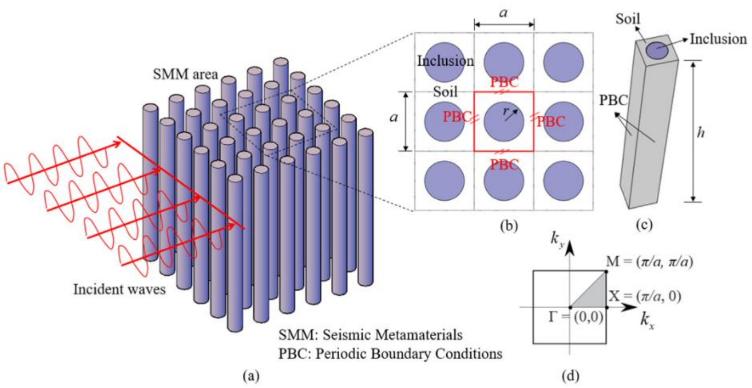


Fig. 17 Schematic representation of the SMM (a) Periodic array of barriers (b) Plan view (c) Unit cell in Comsol Multiphysics (d) The first Brillouin zone with the irreducible part (light grey triangle of vertices Γ-X-M).

Also, periodically arranging built up steel section in a soil medium showed a 50% reduction in surface wave amplitude as presented by Muhammad et al. [21]. Fig. 18 shows the two analyzed models and Fig.19 shows the resulted bandgaps in different mediums.

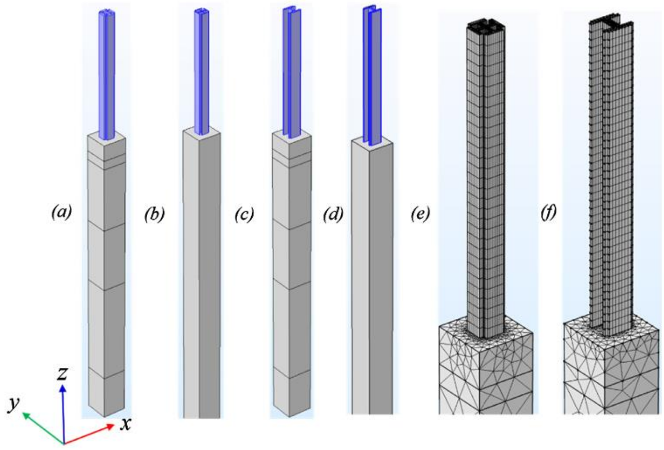


Fig. 18 The unit cell model developed for solving dispersion relation. A unit cell of Sample 1 in blue with (a) layered soil substrate and (b) single layer homogenous medium. A unit cell structure of Sample 2 in blue with (c) layered soil substrate and(d) single layer soil profile (e–f). The adopted hexahedral mesh in barriers and the tetrahedral mesh for substrate.

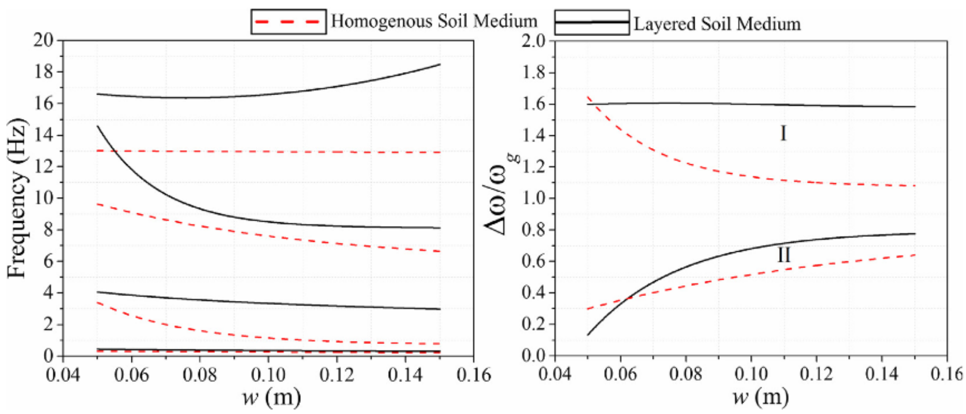


Fig. 19 (a) Comparison of the first and second bandgaps of single and six layered soil media for Sample 1. (b) Relative bandwidth corresponding to the first and second bandgaps for both types of soil media. Solid black lines correspond to layered soil substrate while red dashed lines correspond to single layer soil medium.

IV. Conclusion

The last decades, the concept of metamaterials has been investigated in many researches in different fields. Its contribution in seismic protection of buildings has been proved either by installing metamaterial structures in the surrounding soil or above its surface or in the foundations of the building.

This idea can be useful in many civil engineering applications in order to prevent harmful or undesirable elastic waves of vibrations. It can be used to design structural systems with tailored and tuned frequency band gap in the required range of frequencies to avoid or attenuate the harmful effects of undesirable elastic waves of seismic, wind or machine vibrations.

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