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METAMATERIALS IN EARTHQUAKE ENGINEERING

Abstract: The origin of metamaterials is in electromagnetics in the end of 19th century. By using the analogy between electromagnetic and elastic waves, the application of metamaterials starts to grow in the field of optics, acoustics and nowadays there is a lot of research for their use in the seismic design. Large-scale metamaterials can be used as shield against seismic waves in hazardous area. With specific design (shape, height, width, material) and specific periodicity (periodic scheme and periodic constant), these systems can attenuate the waves before they reach the targeting structures in that way minimizing the damaging effect of the earthquake. This approach is efficient for protecting multiple structures at ones. Current and emerging research activities regarding seismic metamaterials will be summarized in this paper.

Key words: seismic metamaterial, seismic waves, resonator, bandgap, dispersion curve

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1. INTRODUCTION

In recent years, seismic metamaterials have received great attention from the scientific community, which has rendered several concepts for their potential engineering use. The trigger for their origin was the analogy between the electromagnetic and elastic waves and the findings in the band theory of solids throughout the concept of photonic crystals followed by the concepts of phononic crystals, sonic crystals and locally resonant metamaterials. Photonic crystals are artificial periodic structures that alter the motion of photons, by analogy, phononic and sonic crystals (fluid medium), affect the motion of acoustic waves. These periodic arrangements obey Bragg's law, which connects the lattice parameter of the system (distance between the centers of the elements) with the wavelength. This means that in order the system to distribute the wave energy inside the grid, the periodicity of the system has to be comparable to the wavelength and this link is unfavorable for application in the low-frequency range domain, that would require unpractical, large structures. With the introduction of locally resonant structures in this kind of periodic systems, in 2000, by Liu and co-workers [1], this limitation was overcome. The resonators couple with the propagating waves and pluck their energy at frequencies near their resonances. In this way the periodic constant can be below the wavelengths of interest. With this findings locally resonant metamaterials were established as artificial periodic structures with unique wave-manipulation performance that arise from the influence of their locally resonant units. The concept of metamaterials (phononic crystals and locally resonant metamaterials) can be applied for filtering and manipulation of the seismic waves that opens new possibilities in earthquake engineering.

2. DISPERSION CURVES

Metamaterials are artificial structures that manifest unique properties that cannot be found in the nature. They have ability to suppress the propagation of free waves in a certain frequency region that is called bandgap. To identify the formation and the width of the bandgap, the dispersion diagrams (band structure) are used. These diagrams show the relation between frequency and wave number and give information about the wave propagation behavior of the metamaterial. There are different techniques for deriving the dispersion curves. Finite element method is the most used. The band structure is obtained by solving the eigenvalue problem that is formed by FEM modelling of the parametric unit cell and by setting Floquet-Bloch periodic boundary conditions. This Floquet-Bloch theorem reduces the study of the infinite periodic system to the analysis of a single unit cell. Although the wavenumber k is unrestricted, it is only necessary to consider the wavenumbers going around the edges of the first Brillouin zone, Figure 1.

In an ideal homogeneous material, a plane propagates non-dispersively with linear relation between frequency and wave number, but for a structured material, bandgaps can occur, Figure 2, where R is the resonance frequency, that form the band-gap.

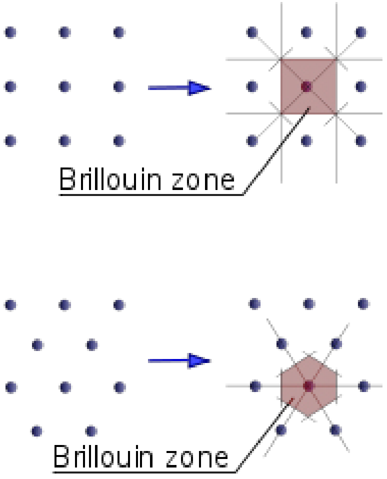

Figure 8 – Brilliounn zone

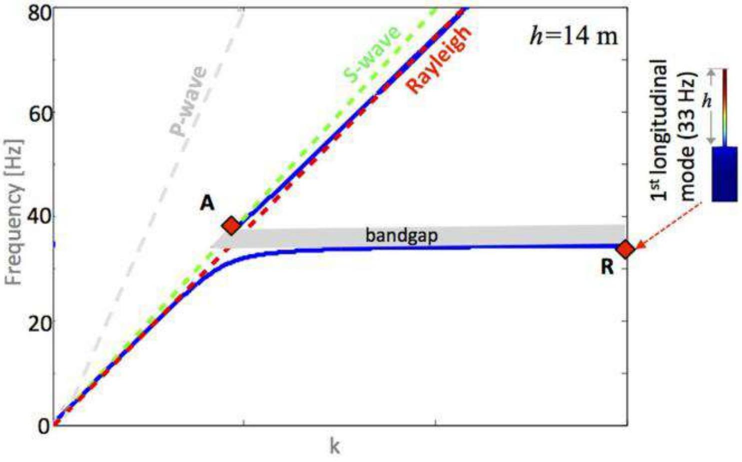

Figure 9 – Dispersion curves, [10]

3. CURRENT DESIGNS OF SEISMIC METAMATERIALS AND EXPERIMENTAL VALIDATION

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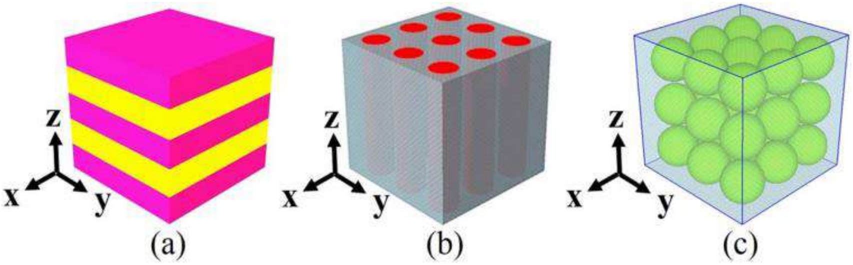

(a) (b) (c)

Figure 10 – Types of metamaterials, [4]

Brulé et al. [7] designed and tested large-scale seismic phononic crystal constructed of a mesh of vertical empty inclusions bored in the soil, Figure 4. The source wave (50 Hz) was comparable to the periodicity of the system, not too far off the Bragg's regime and partial stop-band was created. Unfortunately, 50Hz is still above the most damaging excitations in a common earthquake spectrum.

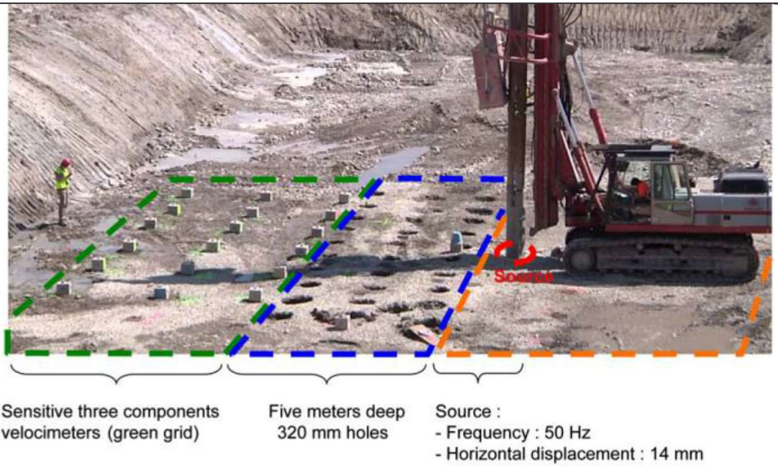

Figure 11 – Large-scale seismic phonic crystal

Kim and Das [17] suggested Helmholtz-like resonators in order to create a seismic shadow zone and possible solutions to transform elastic wave energy into sound and heat. The resonators were designed like empty boxes with a few side-holes, corresponding to the targeting resonance frequencies of seismic waves, envisioned to be buried in the soil around the building, Figure 5.

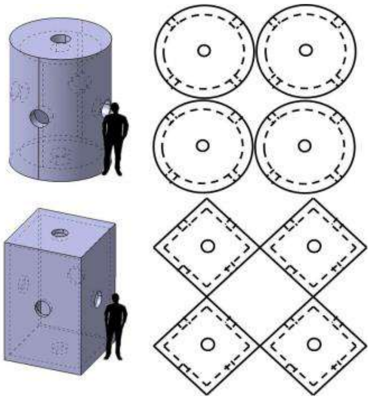

Figure 12 – Configuration of Helmholtz-like resonators buried in the soil

Qiujiao et al. [2] proposed design of periodic array of different shapes of steel piles embedded in the soil, Figure 6. The first three piles are hollow and the last one is filled with soil/concrete. From the numerical analysis it was obtained the formation of bandgaps for these systems is in the range 8-25 Hz. Geometrical parameters such as the filling fraction, thickness and height of the piles affect the results. In addition, material parameters such as the Young's modulus and mass density of the soil have significant impact on the location and width of the bandgaps.

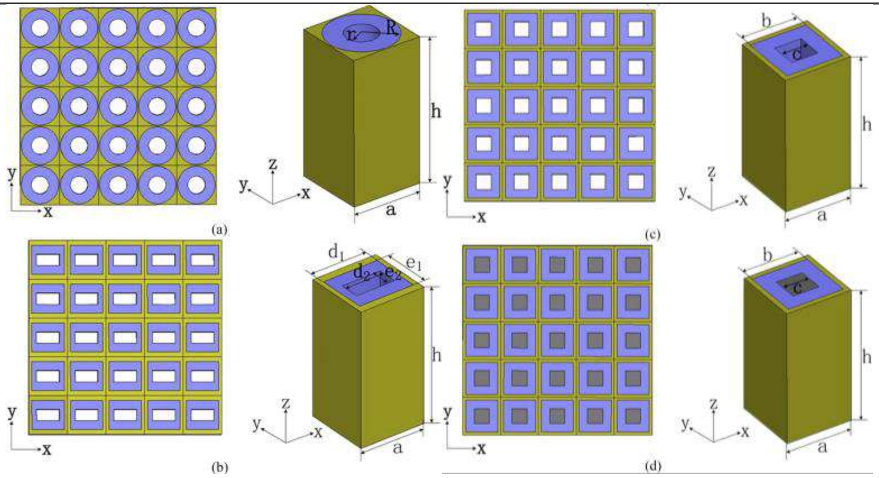

Figure 13 – Periodic array of steel piles embedded in soil

Miniaci et al. [15] considered different type of seismic metamaterials: a cross-like cavity, a hollow cylinder filled with soil and a locally resonant inclusion made of a soft rubber layer around a heavy core cylinder as inclusions in the soil, Figure 7. Furthermore, the authors investigate the influence of some geometric and mechanical parameters like ratio between the Young's modulus of the inclusion and matrix, cylinder thickness, filling fraction. Depending on the type of the element, different parameter has different influence. The bandgaps for the considered metamaterials are registered in the region bellow 10 Hz.

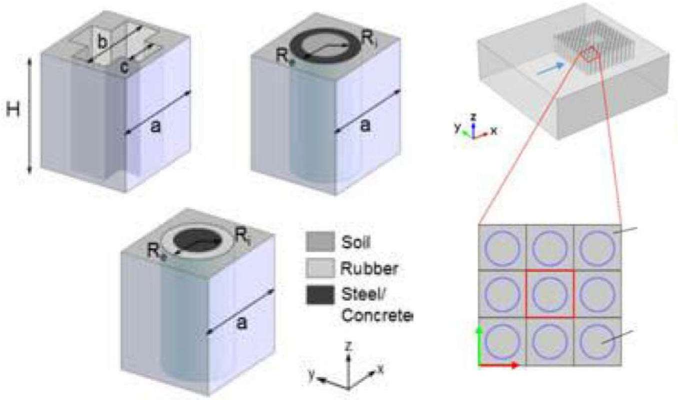

Figure 14 –Metamaterial with different types of inclusions

Achaoui et al. [8] used cubic array of steel spheres connected to a bulk concrete via steel or rubber ligaments, Figure 8. With modification of the parameter of the ligaments the bandgaps can be tailored and achieve multiple-resonance. This infrastructures, creates large stop band between 8 and 49 Hz, depending upon the ligaments used.

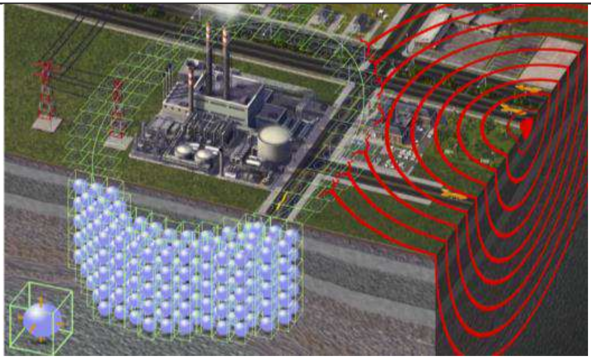

Figure 15 – Array of steel spheres connected to a concrete with ligaments

Krodel et al. [9] designed array of resonating structures buried around sensitive buildings. The periodical elements were constructed as cylindrical tubes containing a resonator suspended by soft bearings, Figure 9. To obtain broadband attenuation characteristics, each resonator in the array was designed to exhibit a different eigenfrequency by changing the stiffness in the connecting soft springs. To verify the design, a 1:30 scaled model was build with array of resonators constructed from aluminum tube, containing a resonant mass made of a cylindrical steel rod and connecting springs of polymeric material, build in a soil, Figure 10. The formed bandgaps are in the region bellow 10 Hz.

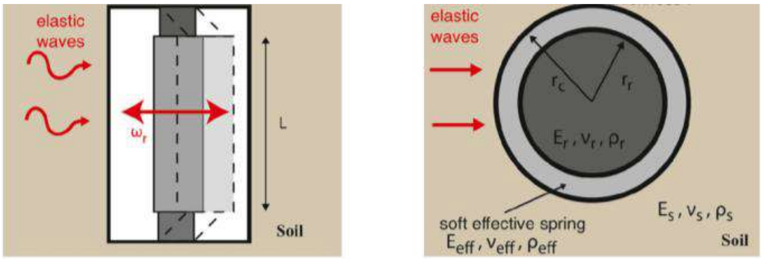

Figure 16 – Cylindrical tubes containing a resonator suspended by soft bearings

Figure 17 – Experimental setup for array of resonators

Achaoui et al. [13] proposed periodic array of steel columns, in a layer of soil, that are clamped to underlying bedrock, Figure 11. With this metamaterial, zero-frequency stop-band stretching all the way to 30 Hz is achieved. Some parameters like the filling fraction, periodicity, diferent boundary condition, different shape of the colums are investigated. The coupling of each column to its neighbours via steel plates is shown to be essential for obtaining broad ultra-low frequency stop-bands.

Figure 18 – Array of steel columns in a layer of soil clamped to underlying bedrock

Yan et al. [16] designed three dimensional periodic foundations with steel mass, rubber spring, embeded in the concrete matrix, Figure 12. Theoretical frequency band gaps can be as low as 32.9 Hz. When the input wave falls into the attenuation zones the response of the upper structure could be greatly reduced in comparison to the same structure without the periodic foundation.

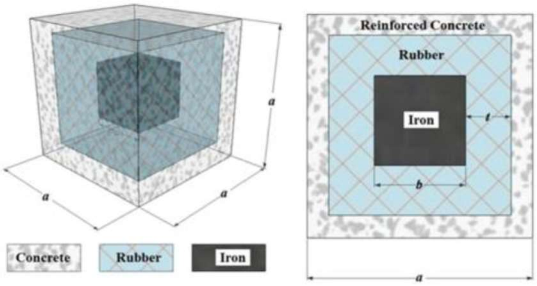

Figure 19 – Unit element of the metamaterial

Figure 20 – Experimental setup for 1D metamaterial foundation

Witarto et al. [4] designed and fabricated one-dimensional periodic foundation for small modular reactor using reinforced concrete and synthetic rubber (polyurethane) materials. The experimental test could not be performed at a full-scale size so a scaled model was designed for the study. Different excitations were used: white noise, frequency sweeping, seismic, and harmonic signals. Band gaps between 10-50 Hz were registered with 90% efficiancy of reduction of the acceleration response.

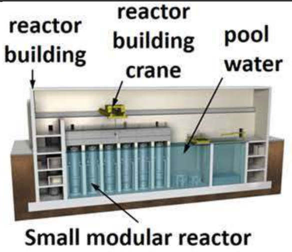

Figure 21 – The original structure

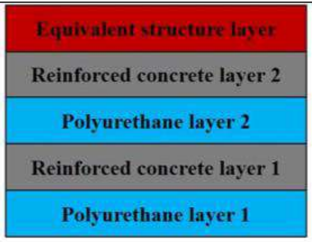

Figure 22 – One-dimensional periodic foundation

Figure 23 – The test for the scaled model of superstructure and periodic foundations

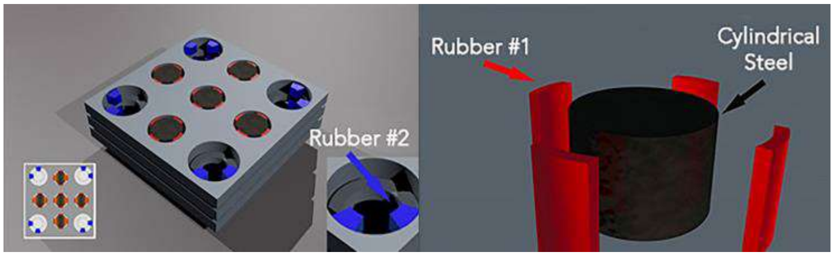

Figure 24 – Composite metamaterial foundation

Casablanca et al. [3] create composite foundations based on metamaterials - local resonance and a dual-stiffness structure, Figure 17. The foundations are made from reinforced concrete plates that are disconnected with an ultra-low damping surface of layers of steel and Teflon. Each plate has a matrix of nine cylindrical inclusions divided from the host with rubbers. The proposed design was experimentally validated, Figure 18. This system forms a bandgap above the frequency of 4.5 Hz and in the bandgap region it can filter more than 50% of the wave energy.

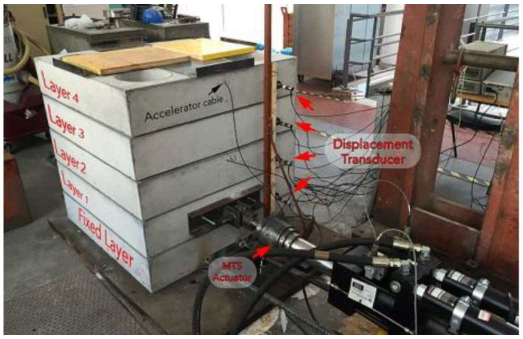

Figure 25 – The experimental set-up for the composite metamaterial foundation

Colombi et al. [10] designed array of rods placed on an elastic substrate that act like resonators - metawedge, Figure 19. These structures are capable of creating effective band-gaps for surface waves or filters that transform surface waves into bulk waves. The coupling between Rayleigh waves and the first longitudinal mode of the vertical resonators, creates large bandgaps bounded below by frequencies inversely proportional to the resonator height h. Nice results for frequencies around 50 Hz are obtained, but unfortunately higher than the relevant from earthquakes.

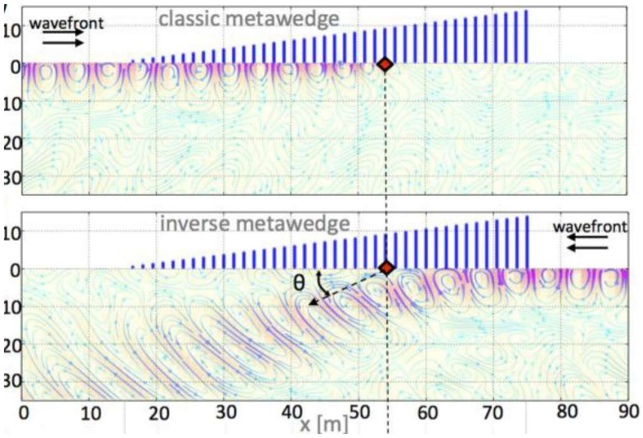

Figure 26 – Array of rods placed on an elastic substrate

Colombi et al. [12] explore the thesis that the trees from the forests can act like locally resonant metamaterials for Rayleigh surface waves. A geophysical experiment (seismometers-ambient noise) demonstrates that a Rayleigh wave, propagating in soft sedimentary soil at frequencies lower than 150 Hz, experiences strong attenuation, when interacting with a forest, over two separate large frequency bands, but still, at frequencies higher than those primarily present in earthquakes.

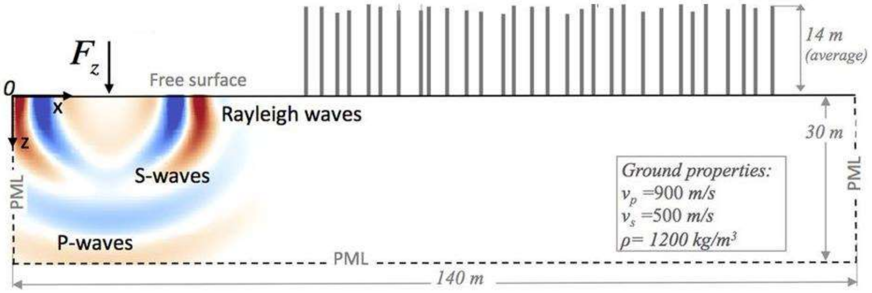

Figure 27 – Trees from forests as resonators

Brulé et al. [5] explore the idea that a district of buildings could be considered as a set of above-ground resonators. This comes from a fact that the urban patterns reminisce of the geometry of the metamaterials, Figure 21.

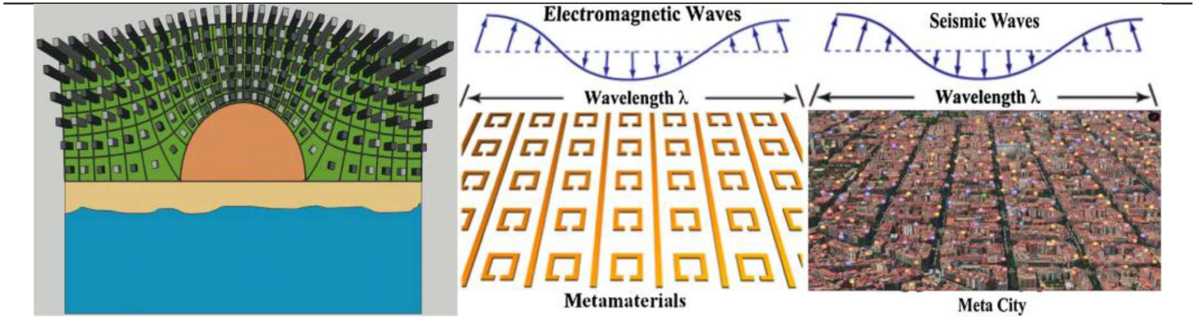

Figure 28 – Urban districts as metamaterials

4. CONCLUSIONS

Metamaterials has unique properties not found in nature. They can be used for controlling the propagation of seismic waves overcoming the disadvantages and limitations of classical system for seismic protection. Classical SI devices introduces a shift in the natural oscillation periods of the building, have significant fatigue, can produce large horizontal displacements, they ignore the soil-foundation interactions, they are incapable of isolating vertical earthquakes and can act only on one individual structure etc.

With specific design and specific periodicity, seismic metamaterials can attenuate waves before they reach the targeting structures. This approach is efficient for protecting multiple structures at ones. Resonant seismic metamaterials are better than the ones that relly on Bragg's law, but they have narrow bandgap. The width of the bandgap can be broaden [8], [9], but this kind of metamaterials are hard to build. The current designs are promising but still there is needs for further investigation.

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