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Metabarriers with multi-mass locally resonating units for broad band Rayleigh waves attenuation

Antonio Palermo, Matteo Vitali, Alessandro Marzani*[,1]

Department of Civil, Chemical, Environmental and Materials Engineering – DICAM, University of Bologna, Viale del Risorgimento 2, 40136 Bologna, Italy

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ABSTRACT

Artificial soils engineered with periodic or resonant structures, also referred as “seismic metamaterials” have been investigated for earthquake mitigation applications. In particular, an array of sub-wavelength single-mass resonators buried close the soil surface, namely the metabarrier, has been recently proposed to attenuate the ground motion induced by Rayleigh seismic waves. Here we demonstrate that the use of multi-mass resonators allows for enhanced performances of the metabarrier, in terms of amount and bandwidth of ground motion attenuation, with a smaller array of resonators. To this aim, after reviewing the single-mass metabarrier, we describe the dynamic of a multi-mass metabarrier using analytical and numerical approaches. In particular, we provide a detailed study of a metabarrier with double-mass resonators and compare its performances with those of a single-mass metabarrier with equivalent overall mass. Finally, we exploit Genetic Algorithms to design a metabarrier with multi-mass resonators with minimal mass and able to target selected frequencies. As a case study, the fundamental frequencies of two concrete-frame buildings of known dynamic properties are considered. The example shows the possibility to protect multiple buildings from Rayleigh waves with more compact metabarriers.

1. Introduction

Artificial composite media engineered with periodic patterns or local resonant inclusions, respectively referred to as phononic crystals and metamaterials, can manipulate the propagation of elastic waves creating band gaps, frequency regions where waves do not propagate [1]. Band gaps in phononic crystals arise from destructive interference of waves due to the Bragg scattering mechanism, which occurs at wavelengths comparable to material periodicity length [2,3]. Conversely, metamaterials exploit resonant inclusions to absorb or redirect elastic energy around their resonance frequencies and can operate at sub-wavelength scales [4]. Band gaps “engineering” using periodic and locally resonant media allows for wave filtering and waveguiding applications across different length scales, ranging from micro and nano structures for thermal insulation to large devices for seismic wave attenuation [5]. In this latter context, periodic and locally resonant structures can define a new paradigm toward the protection of existing urbanized areas or strategic structures and infrastructures from seismic waves. To this reason, a significant number of novel isolation devices/strategies based on periodicity and local resonances have been recently proposed. Meseguer et al. [6] experimentally and numerically analyzed the attenuation of Rayleigh waves by a periodic array of centimeter size cylindrical holes in a marble quarry. By upscaling their results, the authors predicted the possibility of attenuating surface waves in the low frequency range (1–10 Hz) using giant periodic structures (>100 m). Similarly, Miniaci et al. [7] numerically investigated the feasibility of different periodic structures to attenuate both surface and bulk waves in the 1–10 Hz frequency range. Results revealed that only in really soft sedimentary soils, characterized by a bulk shear speed $c_s < 100$ m/s, surface and bulk seismic waves can be attenuated utilizing phononic crystals with unit cells of decameter dimensions. Analogous conclusions are drawn from the real scale experimental tests by Brüle et al. [8], which investigated the propagation of surface waves through a rectangular mesh of cylindrical boreholes, showing that meter size periodic structures can only target frequency ranges around 50 Hz. Thus, when the aim is targeting low-frequency seismic waves (1–10 Hz) in sedimentary soils with $c_s > 100$ m/s, the use of locally resonant structures seems to be the only feasible option.

In the last decade, different resonance-based barriers and foundations have been proposed as a mean to shield structures from incoming seismic waves, targeting the attenuation of longitudinal and shear bulk waves incoming to flat [9–14] and irregular surface topographies [15].

* Corresponding author.
E-mail address: alessandro.marzani@unibo.it (A. Marzani).
[1] ⟨https://www.unibo.it/sitoweb/alessandro.marzani/en⟩.

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However, in far field locations most of the earthquake energy is conveyed in the form of surface waves, which may become the dominant source of ground shaking in basin sites with complex stratigraphy, as observed during the 2012 earthquake sequence in Emilia Romagna region (Northern Italy) [16]. Recently, a "metabarrier" composed by an array of resonant structures buried below the soil surface has been specifically designed for surface Rayleigh wave mitigation [17]. The metabarrier is able to open a band gap in the Rayleigh waves' spectrum by converting a surface wave into a bulk shear waves. Surface-to-shear conversion is a physical phenomenon induced by the surface resonances and it has already been observed at the micro scale due to the resonance of microspheres [18] and micropillars [19], as well as at the geophysical scale due to the resonance of forest trees [20,21]. The exploitation of this mode conversion has strong potential for seismic isolation since the energy traveling in the form of Rayleigh waves is redirected into the soil depth and not back reflected at the soil surface where it could remain harmful for other structures.

The metabarrier design criteria must aim at generating a wide band gap in the frequency range below 10 Hz by using resonators with limited mass and dimensions for their practical implementation. This requirement poses a significant challenge as the band gap generated by surface resonances is generally confined to a narrow frequency range and its width is strictly related to the amount of resonating mass. Several strategies have been proposed to broaden the attenuation range of resonant metamaterials. Among others, approaches based on rainbow trapping [22], inertial amplification [23,24], combination of phononic and locally resonant media [25], chiral metamaterials [26] and architected lattices [27] have been proposed. Within the context of seismic isolation, only the rainbow trapping concept, which is based on the use of multiple resonators with different fundamental frequencies, has been utilized [12,20] since all the other strategies require complex resonant structures of impractical design. In this work, alternatively to the above proposed approaches, we investigate the possibility of using multi-mass resonators as a mean to enlarge the band gaps of the metabarrier, reducing the number of resonant units and keeping constant the overall metabarrier mass. We also prove that multi-mass resonators can be used in conjunction with a rainbow trapping arrangement to benefit from both ideas.

The work is organized as follows: after reviewing the dynamic of a single-mass metabarrier, an analytical model to design a metabarrier with multi-mass resonators is presented. Finite element simulations are then employed to show the superior attenuation of a double-mass system with respect to a single-mass configuration. Finally, we use Genetic Algorithms to design a multi-mass resonator with minimal total mass specifically tuned to target specific frequencies. The strategy is applied to design a four-mass metabarrier to protect two concrete frame structures.

2. Single-mass (SM) metabarrier: performances and limitations

The aim of this section is to investigate the performances of single-mass metabarriers with resonators of mass m and overall length L_{res}. We first recall the dispersion relation for a soil coupled with a metabarrier and then develop FE models to assess the metabarrier attenuation capabilities for varying resonator mass m and barrier length L_{res}.

2.1. Analytical model

Here, we review the dynamics of the metabarrier originally presented in Ref. [17] (see Fig. 1a). The metabarrier is composed of a certain number of identical single-mass (SM) resonators of meter size dimensions, each realized with a steel mass encased in a concrete shell and suspended by rubber connectors (Fig. 1b, c). The barrier is capable to redirect into the bulk, in the form of shear waves, the incoming Rayleigh surface waves at selected frequencies (Fig. 1a). Such mode conversion can be predicted modeling the soil as a half-space with appropriate dynamic boundary conditions to account for the resonators positioned at its surface. In detail, following a standard derivation for Rayleigh dispersion law, as in Ref. [28], surface waves on a semi-infinite domain can be described by the equations:

$$\nabla^2\Phi = \frac{1}{c_L^2}\frac{\partial^2\Phi}{\partial t^2} \quad \nabla^2 H_y = \frac{1}{c_S^2}\frac{\partial^2 H_y}{\partial t^2} \tag{1}$$

where t is time, c_L and c_S are the longitudinal and shear velocity of the soil, while Φ and H_y are the inhomogeneous dilatation and transverse potentials having the form:

$$\begin{aligned} \Phi &= B_1 \exp\left[-kz\sqrt{1-\frac{\omega^2}{\xi^2 c_L^2}}\right]\exp\left[i(\omega t-\xi x)\right] \\ H_y &= B_2 \exp\left[-kz\sqrt{1-\frac{\omega^2}{\xi^2 c_S^2}}\right]\exp\left[i(\omega t-\xi x)\right] \end{aligned} \tag{2}$$

In Eq. (2) ω is the wave angular frequency, ξ is the wavenumber along the x-direction of propagation. We remark that the decaying behavior along the depth z of the dilatation and transverse potentials is ensured for all the wave solutions, provided that the phase velocity $c = \frac{\omega}{\xi} \le c_S \le c_L$. Such requirement on the wave phase velocity restricts the sought solutions to those with a surface-confined nature.

We model each resonator as a vertical translational mass m connected by a linear spring of stiffness k to a rigid foundation of area A. Here, we remind that only the vertical resonance is able to open significant frequency band gaps in the spectrum of Rayleigh waves [17,20]. Thus, the resonant units can be modeled and designed such that the relative displacement (between the oscillating mass and the resonator foundation) in the horizontal direction is prevented, using for example a rigid vertical guide to constrain the translation of the masses (see Fig. A.1 in Appendix A). The resonator and its foundation have sub-wavelength dimensions at the resonator frequency, i.e., their dimensions are much smaller than the Rayleigh wavelength $\lambda_{\omega_r} = 2\pi c_R/\omega_r$ at the angular resonance frequency of the resonator ω_r (c_R is the Rayleigh velocity). Thus, we can assume a local soil-resonator interaction in the form of a uniform vertical stress $\sigma_{zz,0} = -\frac{m\omega^2}{A}\left(\frac{\omega^2}{\omega_r^2}-1\right)^{-1}$ exerted by the resonator foundation on the soil surface. This vertical stress represents a non-zero boundary condition for the semi-infinite medium, which is used together with the waves potentials in Eq. (2) to derive the dispersion law of the single-mass metabarrier [18]:

$$\left[\left(2-\frac{\omega^2}{\xi^2 c_S^2}\right)^2 - 4\sqrt{1-\frac{\omega^2}{\xi^2 c_L^2}}\sqrt{1-\frac{\omega^2}{\xi^2 c_S^2}}\right] = -\frac{\sigma_{zz,0}\,\omega^2}{\rho c_S^4 \xi^3}\sqrt{1-\frac{\omega^2}{\xi^2 c_L^2}} \tag{3}$$

where ρ is the soil density.

Fig. 2a shows the dispersion law for a single-mass metabarrier in a sedimentary soil, whose properties are given in Tables 1, 2, respectively. Due to the presence of surface resonators, pure Rayleigh waves do not exist while two distinct branches of "hybrid" Rayleigh waves with a phase velocity $c_{Rh} \ne c_R$ are found. In the lower branch, waves travel at a phase velocity $c_{Rh} < c_R$ approaching asymptotically the resonators natural frequency. On the contrary, the upper branch, characterized by a phase velocity $c_{Rh} > c_R$, terminates at the frequency where $c_{Rh} = c_S$, which marks the condition of existence for surface solutions (in accordance with the assumed potentials in Eq. (2)). In fact, modes with an apparent velocity $c \ge c_S$ cannot exists as surface solutions but only as shear bulk waves, thus resulting in an effective band gap (BG) for surface waves. According to Eq. (3), such BG is identified by its lower f_{BG}^- and upper f_{BG}^+ frequencies:

$$f_{BG}^- = f_r = \omega_r/2\pi \quad f_{BG}^+ = f_{BG}^-(\beta + \sqrt{\beta^2+1}) \tag{4}$$

$$\beta = \frac{m f_{BG}^- \pi}{\rho c_S A}\sqrt{1-\left(\frac{c_S}{c_L}\right)^2} = \frac{R^2-1}{2R};\; R = \frac{f_{BG}^+}{f_{BG}^-} \tag{5}$$

For the specific soil-metabarrier configuration a BG between $f_{BG}^- = 2.43$