Design for Extremes: Metamaterials for Vibration Control of Civil Infrastructure

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Abstract. The protection of civil infrastructure for extreme events is a critical challenge for civil engineers. Damaging vibrations caused by nearby rail systems, urban construction, adaptive reuse of buildings into recreational facilities, mechanical appliances, and related, during normal operations can affect the occupants. During extreme events, vibrations caused by strong winds or unexpected earthquakes have catastrophic consequences. Over two decades ago, metamaterials emerged in material science as an innovative solution in vibration control devices. Metamaterials are engineered composite materials that exhibit uncommon properties not typically found in natural materials. They are designed to filter incident waves in multiple engineering applications and are usually used in small scales for acoustic, thermal, electromagnetic, and energy applications. More recently, a new class of large-scale mechanical metamaterials known as seismic metamaterials has been designed to mitigate the impact of catastrophic earthquake events. This paper provides a state-of-the-art review of seismic metamaterials designed for civil engineering applications toward vibration mitigation, including structural control devices and seismic metamaterials surrounding areas covering community-level scale (phononic metabarriers and resonant metabarriers) or installed at the base of the building (metafoundations). Most of this review paper focuses on the published peer-reviewed work for the past 3 years. It identifies current limitations, opportunities, and future directions for this emerging technology.

Keywords: metamaterials, phononic metabarriers, resonant metabarriers, metafoundations, extreme events, seismic, earthquake

1 Introduction

The rise of natural hazard events has urgently recalled the life-threatening conditions of such disrupting natural phenomena, such as earthquakes, hurricanes, or flooding, in communities. Earthquakes are one of the most unpredictable and catastrophic events, even though it is one of the most investigated natural risks for structural engineering historically. On February 6th, 2023, an unprecedented earthquake sequence of Mw 7.8 and 7.5 earthquake events in Türkiye occasioned about 50,000 fatalities, at least 100,000 people injured and 19,000 building collapses, and more than 370,000 buildings severely damaged [1, 2] In terms of economic loss, direct physical damages exceeded $34 billion and were mostly estimated in residential and office buildings, schools, health facilities, bridges, roads, and transportation systems [3]. Evidently, the conventional structural design of civil infrastructure, performed by prescribed design guidelines fixed in time and space, needs to be complemented efficiently. By introducing adaptive real-time solutions and achieving modern earthquake-resistant performance criteria, validation of design assumptions and examination of uncertain behaviors in alternative structural systems (e.g., hybrid timber-based buildings) could provide relevant insights for advancing earthquake engineering [4–6].

This paper focuses on the emerging technology of seismic metamaterials (SMs). These SMs are inspired by acoustic and electromagnetic metamaterials, which are used to control sound and light, respectively, enabling the built environment to act as a shield against seismic waves. To provide context on this topic, this paper is organized as follows. Section 2 presents recent advances of smart structures for vibration control for earthquake engineering. Section 3 provides current vibration mitigation contribution of soil stabilization techniques via embedding of materials known as geosynthetics. With these concepts established, Section 4 consists of synthesis and analysis of the contributions on SMs in the last 5 years. Section 5 covers limitations identified, opportunities, and future research directions of SMs.

2 Smart Structures

Vibration effects of dynamic excitations on civil infrastructure have been mitigated traditionally through vibration control systems. To this extent, several advanced mitigation technologies have been developed to reduce structural vibrations and protect civil structures during extreme events [7–9]. Based on desired performance objectives, structural control strategies (passive, active, and semi-active control) for isolation and reduction of the structural response have reoriented the capacity and flexibility of structures. For example, Bin and Harvey [10] evaluated the performance of a floor isolation system to protect the structural system and motion-sensitive equipment by studying the non-linear dynamic coupling between the structural and non-structural elements subjected to ground motions using vibration absorbers and isolators.

In terms of passive control devices recently developed, Chondrogiannis et al. [11] experimentally tested a K-damper as a negative stiffness device (Figure 1a) installed on building structures subjected to earthquake loading, and Sun et al. [12] developed a passive control device based on inertial amplification mechanism combined with viscous dampers installed along the elevation of a shear frame. More recently, new devices have been advanced for vibration control. Ramirez et al. [13] performed a mechanical characterization of a passive device, namely Shear-link Bozzo shown in Figure 1b via numerical and experimental laboratory tests. Prior generations of this device are installed in the Paradox Tower, Mexico (Figure 1c).

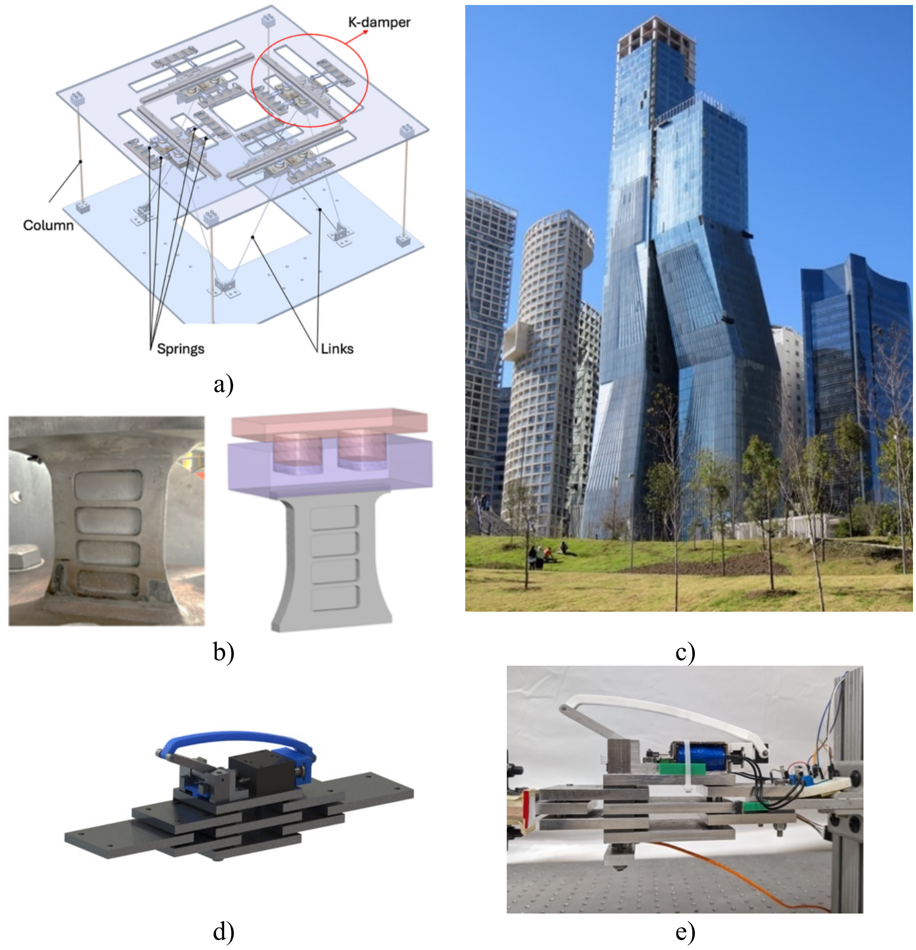


Figure 1: a) Negative stiffness K-damper (adapted from [11]), b) revised version of the Shear Link Bozzo [13], c) Tower Paradox located in Mexico equipped with Shear Link Bozzo heatsink (https://slbdevices.com/en/torre-paradox/), d) semi-active friction-based cam-lever device, and e) its physical experimental prototype.

Semi-active devices recently proposed include Downey et al. [14] characterizing the mechanical behavior of a brake-inspired variable friction damper tuned by sliding mode control for short and tall buildings subjected to multi-hazard events such as wind, blast, and seismic loads. Palacio-Betancur et al. [15] proposed a semi-active friction damping device that has passive control capabilities with the potential to create up to 80% mechanical advantage for 1 voltage input actuator force. Figure 1d and Figure 1e show updated versions of the proposed device.

While devices are critical for the adaptative action of smart structures. The decision-making process of real-time adaptation of semi-active/active devices presents an additional challenge, particularly for long-term performance and sustainable energy consumption. Gutierrez Soto and Adeli [16], for example, studied evolutionary game theory concepts, distributed control and agent-based technology for vibration mitigation. This novel infusion of ideas created a replicator control algorithm. One application of this novel approach was used for tuning semi-active control devices for vibration reduction in a highway bridge structure subjected to earthquake loading. Javadinasab Hormozabad and Gutierrez Soto [17] further modified this data-driven replicator dynamic control methodology for load balancing among semi-active magneto-rheological dampers and passive base isolation bearings installed on a highway structure. The authors implemented a high-performance design optimization studying the patented Neural Dynamic model of Adeli and Park [18, 19] and a load balancing strategy for the voltage source distribution to mitigate structural damage produced by near-fault earthquake accelerograms.

A few limitations persist in reducing the seismic wave impact on the performance and serviceability of non-structural and structural systems. The exposition level of the built environment to the propagation and amplification of seismic waves is also related to the soil properties and configuration. Thus, understanding how to control and adapt the dynamic response and configuration of soil materials to reduce seismic wave propagation can extend the protection of critical infrastructure.

3 Material-based vibration mitigation of soil stabilization

Conventional stabilization techniques such as geosynthetics improve elastic response, shear strength, and stiffness. Geosynthetics are natural or synthetic materials manufactured from polymers or hydrocarbon chains, which are commonly in contact with soil, rock, or additional materials. This stabilization technique is intended to mainly provide enhancements on mechanical, hydraulic, and durability properties in geotechnical engineering problems including foundation and subgrade reinforcement, retaining walls, and roads. For the mechanical response of geosynthetics, tensile strength describes the load-strain capacity to elongation for reinforcement purposes, while compressibility defines the relationship between material thickness and applied normal stress for water transmissivity. Shearing resistance or friction between soils and geosynthetics is also a significant property to prevent the geosynthetic pulling out of the soil or the soil from sliding over the geosynthetic [20, 21].

The response of geosynthetics to cyclic loading aims to sustain more cycles and reduce the cumulative permanent deformation [22]. Akbulut and Pamukcu [23] experimentally tested cylindrical clay specimens with planar geosynthetics to investigate the behavior of the damping ratio and shear modulus using different geosynthetic types (geomembrane or geotextile) varying the number and confinement pressure. Taha et al. [24] simulated the dynamic response of a geosynthetics-reinforced pile foundation system and validated it with shaking table tests of a scaled model geogrid-pile foundation system, where the stiffness and damping were parameters numerically modeled to study the pile-soil interaction. It is important to note that geosynthetic performance is sensitive to temperature and time, so the surrounding environmental conditions should be carefully considered. In addition, geosynthetics can filter liquid and gas transportation and reduce waste storage emissions potentially harmful to human health and geoenvironmental systems [25].

Multiple types of geosynthetics have been designed and tested for geotechnical problems at experimental and large-scale levels. Planar geosynthetics certainly limit the dynamic response of the soil to 2D analyses and cannot provide soil confinement in perpendicular and lateral directions. Therefore, three-dimensional structures used for reinforcement and stabilization, named geocells, started to play an important role in earthquake vibration reduction for building foundations. Geocell-reinforced soils can confer lateral and vertical confinement, exhibit higher tensile and shear strengths, and have wider stress distribution [26]. The friction experienced between the infill material and the geocell and the restraints of geocell-reinforced soils to limit the vertical displacement of the infill material from the loading area induce significant confinement effects that can change the dynamics and vibration isolation.

Sheng et al. [27] investigated and designed a geosynthetics isolator to replace stacked soil bags for base isolation of buildings prone to metro transportation-induced vibration, thus removing vertical and horizontal vibrations considerably by improving the dynamic and mechanical properties of the soil. Although the contribution of the vibration mitigation effect of geosynthetics is not fully explored, few investigations have reported the promising attenuation capability to field vibration. According to the objectives and limitations of different engineering applications, such as geotechnical and transportation engineering, studies have evaluated and evidenced the significant vibration mitigation efficacy of geosynthetics for soil beds and railway ground-borne noise. Venkateswarlu and Hegde [28] evaluated the capacity of different geosynthetics-reinforced soil beds in terms of displacement amplitude reduction ratio and peak particle velocity by field experimental tests.

Kaewunruen and Martin [29] proposed a life-cycle performance assessment to evaluate the efficiency and sustainability and estimate costs associated with railway-induced vibration solutions combining ground improvement methods, geosynthetics, and metamaterials. Thus, geosynthetics have emerged as an attractive alternative to overcome multiple geotechnical and structural problems at the same time. Hegde et al. [30] conducted large-scale testing to evaluate the vibration isolation property for soil foundations subjected to an oscillator operated with a frequency from 5 to 45 Hz. The study implemented geogrids and geocells with different infill materials (sand, steel slag, and construction and demolition waste), as shown in Figure 2, to calculate and compare the amplitude attenuation factor and its efficiency varying the depth of the geosynthetics.

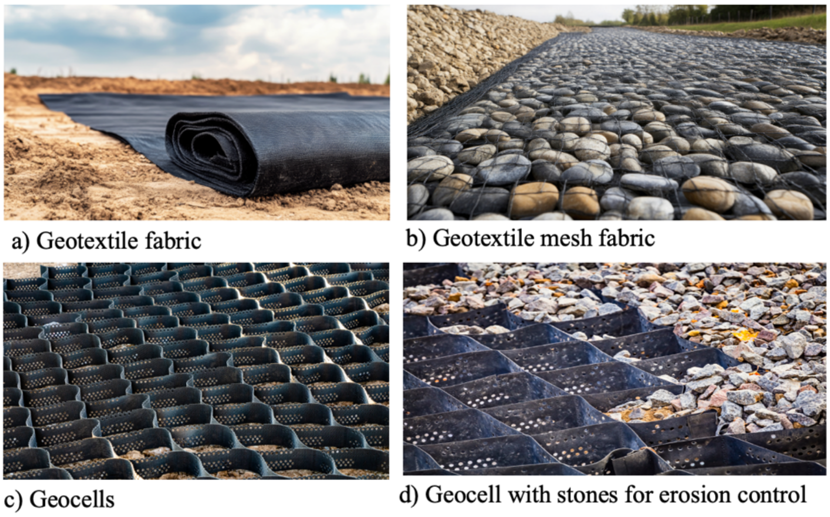


Figure 2: Examples of conventional soil stabilization using geosynthetic material

Most of the research conducted on geocells and vibration isolation systems is oriented to mitigate wave propagation generated from shallow vibration sources such as railway roads, rotary machinery, and traffic-moving loading for frequency contents up to 50 Hz. However, the unawareness of design methods, load transfer mechanism, multi-directional soil confinement, and the limited large-scale experimentation on geocells as a protective isolation system or a controlled barrier (passive or active control) to seismic waves have not been fully explored. Given the inherent geometrical shapes of geocells, dynamic properties can be designed at micro-scale to enhance their vibration absorption capacity when incident wave propagates, thus representing candidates for *metamaterial* studies described in the following section.

4 Metamaterial applications for earthquake engineering

The conception of metamaterials originally occurred with the aim of blocking or suppressing electromagnetic wave propagation through periodic atomic lattices in the field of materials science. By acknowledging such capability, potential engineering solutions gave rise in different fields to manipulate acoustic, elastic, and seismic waves by exploiting periodic structures from the nanoscale up to the macroscale [31, 32]. Metamaterial solutions can span from cloaking devices for electromagnetic wave manipulation and control [33] to tunable resonant solutions for civil engineering steel frames [34]. This section presents basic principles of metamaterials and the vibration mitigation property for earthquake engineering purposes under different research categories. Additionally, a brief collection of research works on the uncertainty quantification of metamaterials in earthquake engineering is provided.

4.1 Principles of Metamaterials

Metamaterials are artificially designed materials engineered to develop specific mechanical and dynamic properties considering periodic structures at different length scales and frequency levels. Such periodic structures are defined as substructures or unit cells connected in an identical pattern [35]. Exploring metamaterial properties such as periodic structural variation, high anisotropy, and frequency bandgap (BG) [36] has broadened the solution spectrum to overcome creatively and effectively existing limitations in engineering problems. Figure 3 shows how metamaterials have been adopted to address acoustic, thermal, mechanical, and electromagnetic challenges.

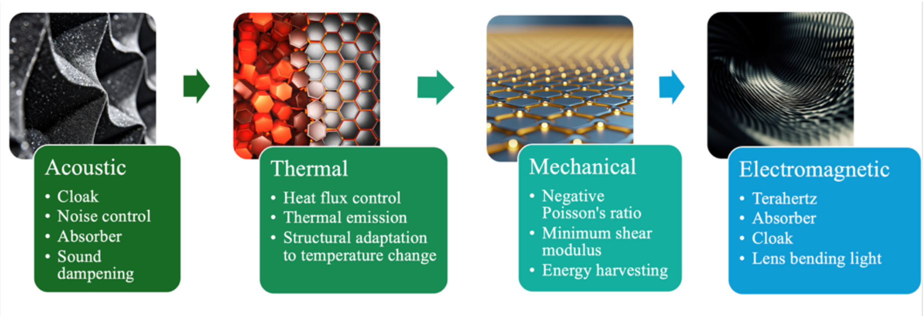
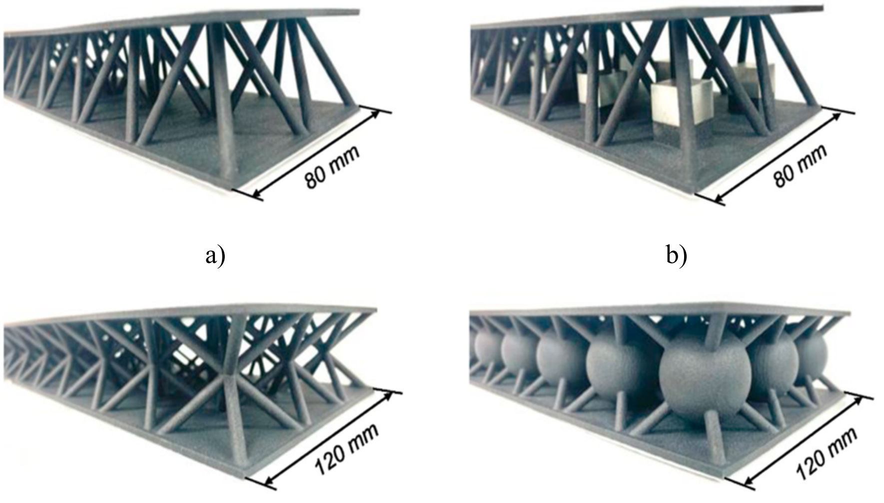


Figure 3: Engineering applications of metamaterials to address acoustic, thermal, mechanical and electromagnetic challenges

For vibration mitigation purposes, additively manufactured metamaterials have extended the conventional, limited resources into a vast, substantive design space to facilitate engineering solutions. It is well known that the design and manufacturing of metamaterials for multiple engineering applications have been empowered by the introduction of additive manufacturing [37]. D'Alessandro et al. [38] designed 3D-printed periodic structures for mechanical wave filtering implementing multiple frequency (BGs). Li et al. [39] presented a broadband vibration reduction strategy of locally resonant metamaterials and lightweight lattice-truss-core sandwich structures using selective laser sintering, a 3D printing technique. For the vibration mitigation performance validation, the periodic lattice-truss-cores sandwich plate specimens shown in Figure 4 were experimentally tested for different geometric and material parameters. Results indicated that metamaterial-designed sandwich structures can significantly extend further the frequency BG including damping effects, compared to the typical sandwich plate solutions. Herkal et al. [40] studied the vibration isolation capacity of 3D-printed Schwarzite solids for damping enhancement in dynamic systems.



a) b)

c) d)

Figure 4. Periodic lattice-truss-cores sandwich structures experimentally tested: a) single-later pyramidal lattice (SLPL), b) meta-SLPL, c) double-later pyramidal lattice (DLPL), and d) meta-DLPL. Source: [39].

Recent studies have adopted metamaterials as friction-based passive damping devices for vibration control in buildings. While Choi et al. [34] studied the plate-type local resonators (sandwiched composite) on a steel beam member to address vibration mitigation challenges. Given the potential of this technology, Choi et al. [41] proposed a performance-based design method that optimizes the design of metamaterials considering multiple objectives. Diana et al. [42] designed a layered metamaterial based on periodic plane lattices with chiral topology to distribute energy dissipation properly across the system by controlling relative rotations between layers.

4.2 Seismic Metamaterials

During the last decade, the introduction of SMs to control the propagation of seismic waves became a completely new application under metamaterials exploration. In earthquake engineering, most of the frequency content in seismic waves varies from 1 to 10 Hz [43]. Traditionally, earthquake engineering has focused on enhancing the bearing capacity of the soil beneath structures and strengthening superstructures and infrastructures. In contrast, SMs offer a novel approach by shielding vulnerable structures through the attenuation, reflection, and refraction of incoming seismic waves propagating at ultra-low frequency ranges, as mentioned previously.

For the vibration mitigation of SMs at this low-frequency range, regulation mechanisms such as Bragg scattering, local resonance, and inertial amplification have facilitated metamaterial-based solutions to address the wave propagation problem for earthquake protection. Although periodicity is a critical property in common, Bragg scattering dictates the attenuation effect when the wavelength is similar to dimensions and periodic conditions in such system, while local resonance fundamentally develops the attenuation based on negative effective dynamic properties (i.e., mass density, bulk modulus, Poisson‘s ratio) under wavelengths with several orders smaller than the structural characteristics of the system. Inertial amplification mechanism exploits engineered substructures that enhance the dynamic inertia of the SMs without increasing the overall inertia of the system. By amplifying internal displacements through mechanical links or levers, this approach allows for compact and efficient vibration control devices [44]. At all these regulation mechanisms, a dynamic property named frequency BG is forged to filter wave propagation and develop attenuation of wave energy for specific frequency ranges [45]. Thus, different sophisticated internal architectures modeled by periodic structures of one or more SMs arrangements can provide the wave attenuation effect to a wide range of seismic waves during propagation. Multiple studies have demonstrated the benefits and limitations of these typical regulation mechanisms in SMs.

For the Bragg scattering approach, the seismic wave propagation problem has been addressed efficiently using different SMs consisting of cylindrical-hole grid in soils, periodic foundations composed of different materials, and related. However, construction limitations are encountered when these large-sized SM solutions, at the meter- or decameter-scale, are designed to meet seismic wavelengths. On the other hand, the local resonance concept has reshaped the ideation of SMs to still achieve significant wave attenuation at selected frequency ranges while reducing some structural dimension limitations. Periodic arrays of surface-level vertical oscillators and resonators embedded in soil-concrete shells are served as relevant examples of locally resonant SMs in earthquake engineering applications. Manipulating and reducing seismic wave propagation using local resonance mechanisms also poses some limitations, such as narrow frequency BGs and constraints in ultra-low frequency targets. Unlike conventional local resonators, the inertial amplification mechanism allows for lower-frequency BGs with smaller and lighter structural components, making it practical for large-scale SMs. Most of the SMs investigation has been widely conducted to reduce the exposition of structures to ground-borne vibrations originated from seismic waves. For this, different categories have been established for SMs applications according to the material, geometry and arrangement, and frequency BG tuning, among others [32, 46]. Apart from vibration absorption, metamaterials have opened promising avenues for cloaking seismic surface waves, such as Rayleigh and Love waves, with the aim of rendering infrastructures "invisible" to these types of ground motions [47, 48]. By tailoring the effective properties of engineered composite materials, it is theoretically possible to redirect or attenuate wave propagation around a protected region, thereby minimizing its dynamic response. These studies highlight the potential feasibility of seismic cloaking in the future, which could pave the way for protective structures capable of withstanding surface wave impact by guiding energy around them rather than absorbing it.

This paper focuses on recent innovations in SMs subdivided into research categories studying phononic metabarriers, resonant metabarriers (metasurfaces or embedded locally resonant wave barriers), and metafoundations. Herein, phononic metabarriers are defined as protective barriers embedded in the soil’s depth and arranged in the surroundings of civil infrastructure. Resonant metabarriers consist of surface-level, partially, or fully embedded arrangements of thin resonant structures (e.g., resonant pillars), in a desired arrangement including periodic, quasi-periodic, or non-periodic, installed at the periphery of the protected structure. Finally, metafoundations are periodically arranged substrates placed at the bottom of the structure at the foundation level, comparable to a base-isolated system.

Phononic Metabarriers

Inspired by the concept of phononic crystals, phononic metabarriers have been developed to attenuate seismic wave propagation through Bragg scattering mechanism. These barriers are typically realized either by drilling an array of periodic boreholes within the soil to design open trench barriers or by embedding piles to form phononic pile barriers. In a pioneering study, Meseguer et al. [49] experimentally investigated the scattering of surface elastic waves by a periodic array of cylindrical holes in a marble quarry. Fifteen years later, the field of SMs emerged when Brûlé et al. [50] demonstrated the attenuation of soil vibrations at frequencies around 50 Hz using meter-scale boreholes arranged periodically along the surface of sedimentary soil. In Figure 4, Miniaci et al. [51] investigated an isolation strategy of remote shielding SMs using finite element analysis and dynamic simulations under the influence of geometric and mechanical properties of large-scale SMs for the layered soils. Achaoui et al. [52] evaluated SMs consisting of cylindrical columns arranged periodically and clamped to the bedrock for zero-frequency BG purposes. Even though the wave attenuation effect is numerically demonstrated for seismic wave excitations from 0 Hz, construction assumptions for rigid, fully fixed columns throughout length are not feasible. Subsequent studies explored alternative periodic pile configurations to attenuate surface waves in layered soils and poroelastic half-spaces [53]. Mandal and Somala [54] examined a periodic pile-soil system as a seismic barrier solution to understand the influence of geometrical and material parameters for Rayleigh wave attenuation in numerical simulations. Phononic metabarrier applications for seismic wave attenuation also unveiled alternative research directions of SMs as engineering solutions in railway-induced vibration problems. Li et al. [55] studied concrete-pile inclusions through a 3D coupled train-track-soil model simulated to determine frequency BGs according to the number of inclusions, initial distances, and train speeds for ground vibration effects.

Further experimental work by Chen et al. [56] on SMs composed of concrete phononic piles revealed broadband frequency BGs (below 7.2 Hz) and surface confinement of elastic waves. Kacin [46] numerically evaluated a triangular lattice of metamaterial-based cylindrical holes according to frequency BG characteristics corroborated in field experiments, where a vibration generator was used to compare seismic vibration reduction results with and without SMs in wider frequency ranges (from 1 to 50 Hz). Huang et al. [57] conducted an experimental study to assess the wave isolation performance of medium-scale open and filled periodic barriers. The results indicated that filled barriers can effectively attenuate seismic surface waves, providing insights into the design and implementation of large-scale phononic structures for seismic protection. Aravantinos-Zafiris et al. [58] numerically investigated the attenuation of surface seismic waves using large-scale phononic metamaterials with I-shaped and T-shaped cavities.

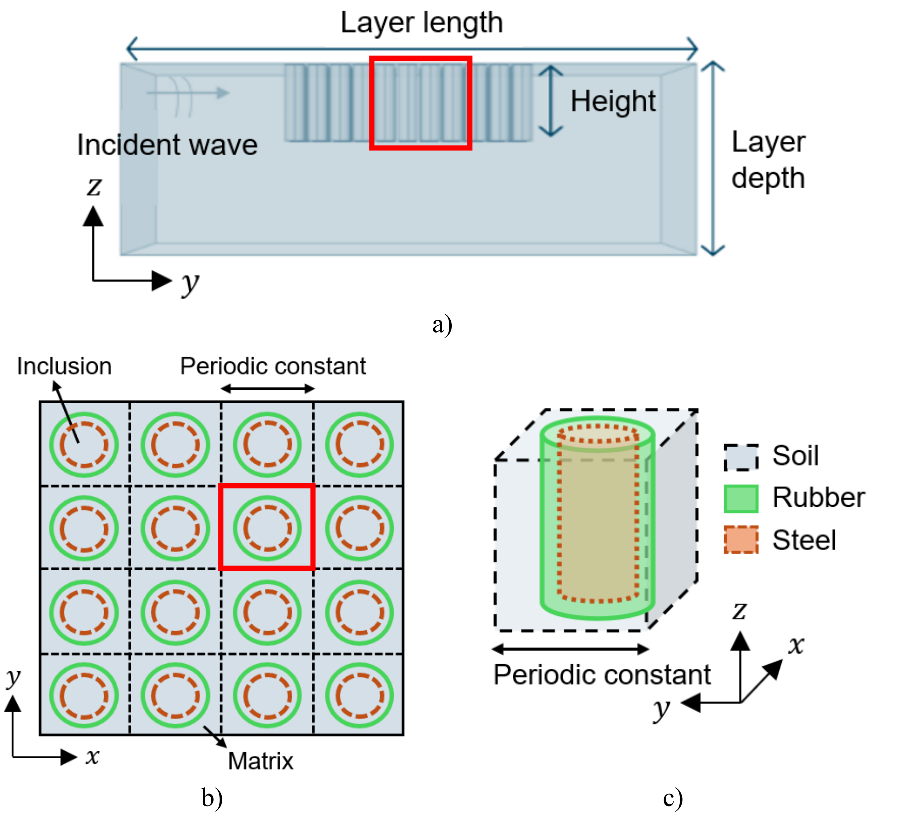
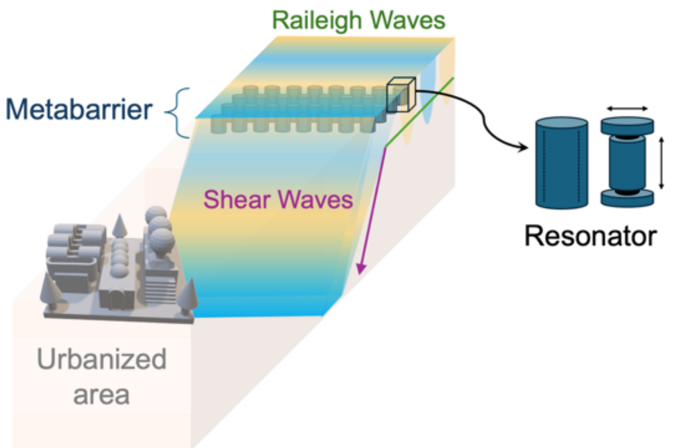


Figure 4. Representation of Shielding SM for seismic wave propagation (adapted from Miniaci et al. [51]): a) 3D large-scale metamaterial model, b) cross-sectional view for matrix of soil, rubber, and steel, and c) unit cell of the SM

Resonant Metabarriers

Due to the construction limitations associated with phononic metabarriers, including deep excavation and extensive structural modifications, alternative metamaterial solutions implying compact size and modular design with tailorable resonant frequencies started gaining relevance. As a result, compact metamaterial-based barriers, usually termed as resonant metabarriers, are of growing interest, aiming to achieve comparable vibration attenuation within a smaller footprint suitable for densely built environments. Resonant metabarriers are protective barrier systems based on periodic or non-periodic arrangement of structural units (such as discrete oscillators, pillars, beams, and plate-like structures) placed over or embedded beneath the soil surface and separately installed from the structure location. If these resonant structures are placed at the soil surface layer (ground level), they are called metasurfaces. The main advantage of metasurfaces lies in their ability to achieve wave control through simple, surface-level configurations, thereby eliminating the need for invasive construction methods or deep excavations. Likewise, resonant metabarriers can also offer promising vibration mitigation performance for railway-induced vibrations to protect civil infrastructure [60].

Krödel et al. [61] were the first to investigate locally resonant metastructures for seismic protection by embedding arrays of tuned resonators in the soil, where they validated their approach through scaled experiments and practical resonator designs suitable for full-scale civil engineering applications. Colombi et al. [62] investigated the ability of natural forests to act as large-scale seismic metabarriers for surface wave attenuation. By treating forest trees as periodically distributed vertical resonators attached to the soil surface, they demonstrated that forests could induce frequency BGs through a combination of longitudinal and flexural resonances. Experimental results confirmed significant attenuation of Rayleigh waves around 45 Hz, consistent with the predicted resonant behavior. Figure 5 illustrates three types of resonant metabarriers with composite cylindrical resonators. Palermo et al. [43] analytically designed a resonant metabaterrier (Figure 5a) for seismic Rayleigh waves relying on soil-embedded resonators composed of a steel cylindrical mass encased in a concrete hollow tube. Then, the seismic wave shielding effect was demonstrated in numerical simulations and a scaled experimental study. Lin et al. [63] proposed a seismic metabarrier based on negative-stiffness dynamic vibration absorbers arranged in lattices (Figure 5b) studying the frequency BG characteristics for seismic wave attenuation. Wang et al. [64] investigated horizontally placed columns built as a composite with a rigid, soft, and solid core and embedded in soils (Figure 5c) to devise a metasurface employing local resonance in surface wave propagation. Lee et al. [65] studied the soil-structure interaction component as part of a periodic building system designed in a surface-level resonant metamaterial for low-frequency ground vibration.



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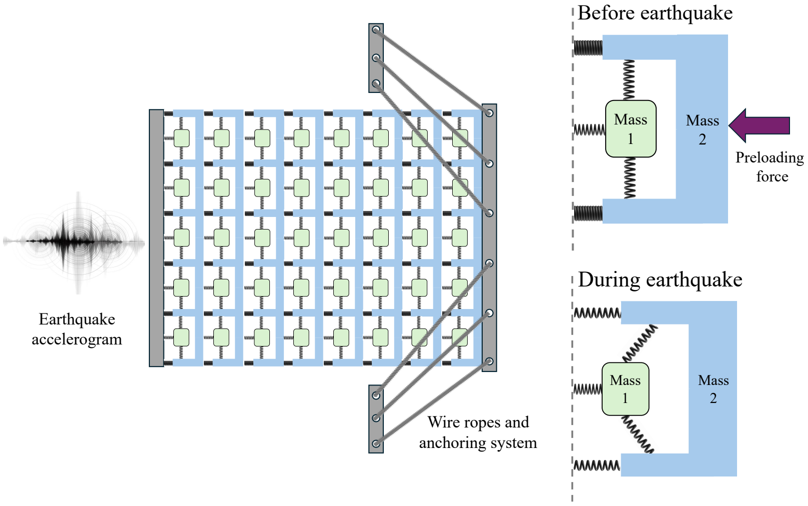

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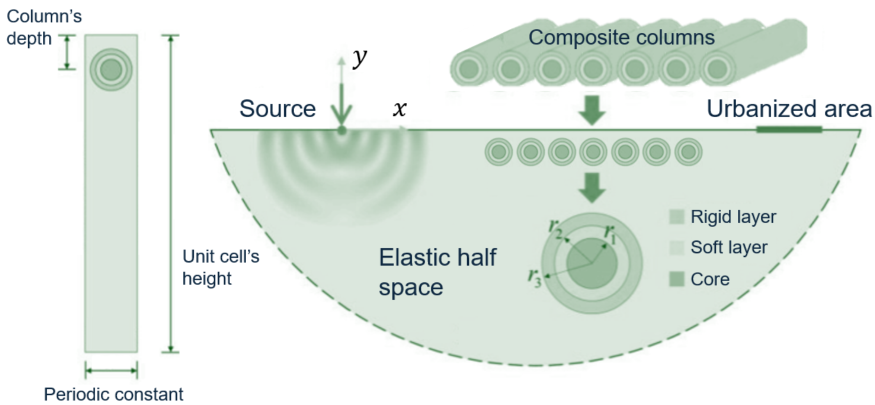


c)

Figure 5: (a) Deployment of the resonant metabarrier for urbanized area protection (adapted from Palermo et al. [43]), (b) Negative-stiffness-based metabarrier with closeup showing the preloading mechanism and stiffness dynamic changes (adapted from Lin et al. [63]), and c) Illustration of the horizontal composite columns for surface-wave attenuation (adapted from Lin et al. [64])

More recently, several efforts have been made to increase the BG frequency range of resonant metabarriers and enhance their seismic wave-filtering performance. Colombi et al. [66] proposed the concept of the “resonant metawedge”, a seismic metabarrier consisting of a graded array of vertical resonators designed to enhance the control seismic Rayleigh waves. This resonant wave barrier leverages the “rainbow trapping” mechanism, whereby the spatial variation in resonator properties leads to the progressive slowing and localization of different frequency components of seismic surface waves or surface-to-bulk mode conversion. Such a configuration enhances the filtering capabilities of the barrier by enabling the selective attenuation or redirection of targeted frequency bands, thereby offering a broadband solution for seismic wave mitigation.

Palermo et al. [67] proposed multi-mass resonators optimized by genetic algorithms so that minimal mass and wider frequency BGs are achieved to improve the vibration attenuation effect by finite element modeling, dispersion properties, and transmission curves. Cipolla et al. [68] evaluated and compared metabarriers including a damped-oscillator SM and modified refractive-index SMs to reduce peak ground accelerations for seismic hazard mitigation in industrial power facilities. Li et al. [69] proposed a radial SM consisting of steel rings embedded in soils at the foundation level to reduce Lamb and surface wave propagation according to different cross-section unit cells. Zhang et al. [70] investigated low-frequency BG characteristics of a SM consisting of pendulum-type resonators, with different material and geometrical properties, encapsulated in soil-concrete shells for seismic Rayleigh wave attenuation. Daradkeh and Jalali [71] studied the frequency BG modifications in a metabarriers arrangement (soil embedment configurations) including stacked, graded and ungraded, and wedge and double wedged configurations for seismic wave filtering. The resembling arrangements evaluated in this numerical investigation are displayed in Figure 6.

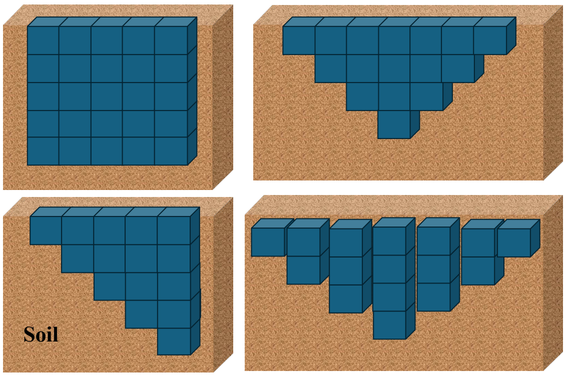
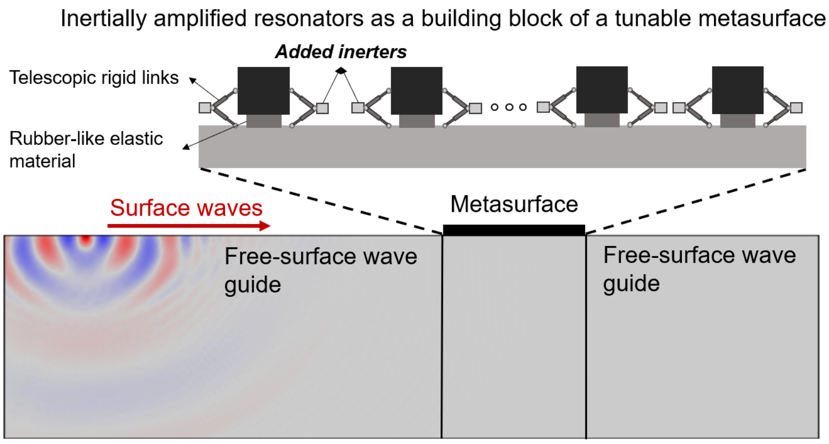


Figure 6: Arrangements of embedded unit cells including changes in number and spacing considerations (adapted from Daradkeh and Jalali [71])

Dong and Sheng [72] proposed an analytical model to devise inertial-amplified resonators for vibration absorption at ultra-low frequency excitation ranges (0.5 Hz – 5 Hz) coupling translational and rotational motions, demonstrating experimentally potential vibration mitigation performance for seismic applications. Zeighami et al. [73] developed a tunable locally resonant metasurface consisting of inertial amplified resonators (IARs) for Rayleigh-like waves attenuation. As introduced in Figure 7a, the IAR model is represented as a mass-spring system integrated with inerters capable of dictating the dispersive relation based on the geometrical configuration and mass property. Pillarisetti et al. [74] investigated the influence of resonance and anti-resonance mechanisms in surface-mounted prismatic resonators for frequency BG generation of Rayleigh waves while designing optimized resonators.

The seismic wave attenuation performance of resonant metabarriers is strongly influenced by their dynamic interaction with the surrounding soil. Specifically, the type of soil and its mechanical properties play a critical role in defining the efficiency of wave mitigation. For instance, silty-clay soils, due to their higher stiffness, exhibit larger seismic wave attenuation and wider attenuation frequency range. In contrast, soft sedimentary soils show less pronounced attenuation performance, both in terms of peak and bandwidth, because of weak dynamic coupling with the resonant masses of the barrier [75]. Despite these known effects, most of the previous studies model the soil as a homogeneous, isotropic, linear-elastic half-space, which oversimplifies the actual complexity of real soil behavior. To address this limitation, more advanced models have recently been proposed. Zeighami et al. [76] investigated the influence of soil heterogeneity by numerically modeling perfectly stratified media composed of horizontally layered soils. Their findings, supported by a complementary analytical framework [77], revealed that soil stratification suppresses the formation of BGs due to the emergence of higher-order modes, although significant attenuation still occurs at the resonance frequency of the metabarrier. Additionally, Pu et al. [78] incorporated poroelastic effects by considering fluid-solid interactions in a layered porous soil model with a water table, employing Biot's theory coupled with effective medium approximations. Furthermore, Kanellopoulos et al. [79] explored the influence of soil nonlinearity in metabarrier-soil-structure interaction (meta-SSI), demonstrating that resonant metabarriers become more effective as soil stiffness decreases. Conversely, for soils with shear wave velocities exceeding 350 m/s, the attenuation benefits of the resonant system significantly diminish.

While the majority of resonant metabarriers are specifically designed to control surface Rayleigh waves, a growing body of research has begun to investigate their potential for manipulating Love waves. These studies aim to extend the applicability of seismic metasurfaces to a broader range of surface wave types, addressing the unique characteristics and propagation mechanisms of Love waves in layered geological media. Palermo and Marzani [80] conducted a Love wave control study using resonant metasurfaces, horizontal resonators placed at the surface level, as shown in Figure 7b, derived by an effective medium approach. By coupling the resonant metasurface dynamics to the incident Love wave, a dimensionless analytical derivation was presented revealing critical dispersive properties for shear horizontal waves propagating to metasurfaces. Maurel et al. [81] investigated the potential for seismic Love wave trapping and mode conversion induced by a forest of trees, demonstrating that natural structures can exhibit metamaterial-like behavior under certain conditions. On the other hand, Xu et al. [82] derived an analytical formulation to describe the dynamic interaction between seismic Love waves and a tunable double-mass metasurface for shear wave manipulation.



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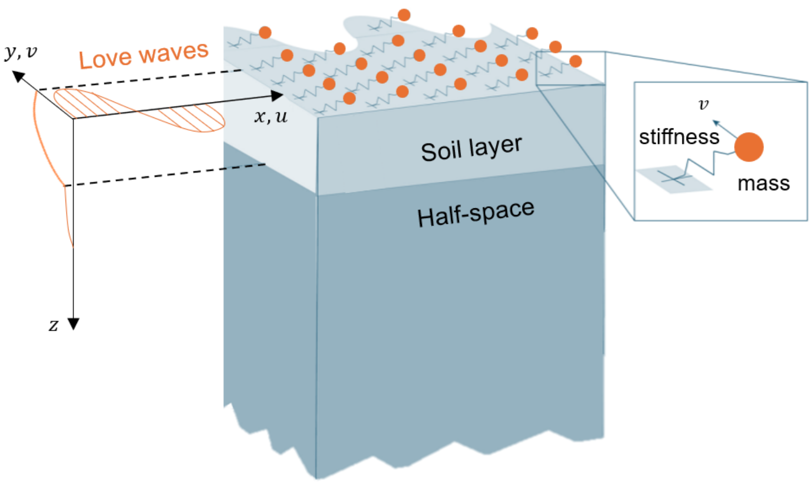


b)

Figure 7: a) Design representation of IAR model for Rayleigh-like *wave* attenuation *(adapted from Zeighami et al. [73]) and b) interaction between Love wave and metasurface of horizontal resonators (adapted from Palermo and Marzani [80])*

A more advanced approach for seismic Rayleigh wave control involves embedding a thick locally resonant metamaterial layer within the host medium. Unlike metasurfaces, resonant layers have a thickness comparable to the wavelength of incoming waves. Their interaction with Rayleigh waves generates leaky surface modes that radiate energy into the bulk, resulting in broader BGs and enhanced filtering performance [83]. The effectiveness of the resonant layer concept has been validated through a small-scale laboratory experiment, demonstrating considerable attenuation of surface Rayleigh wave amplitudes within targeted frequency bands [84]. As opposed to the most Rayleigh wave-oriented works, Zeighami et al. [85] designed a resonant layer of locally resonant metamaterials preventing seismic Love waves propagation using a homogenization technique in a parametric study, as presented in Figure 8. Chaki et al. [86] analytically proposed a periodic array of multilayered laminates vertically embedded in a substrate acting as a metabarrier structure for Love wave attenuation. By performing finite element modeling for the derived dispersive properties (i.e., dispersion relation and displacement fields), the comprehensive analytical framework addressed not just the Love wave hybridization problem but also facilitated design guidelines for tunable energy harvesting devices.

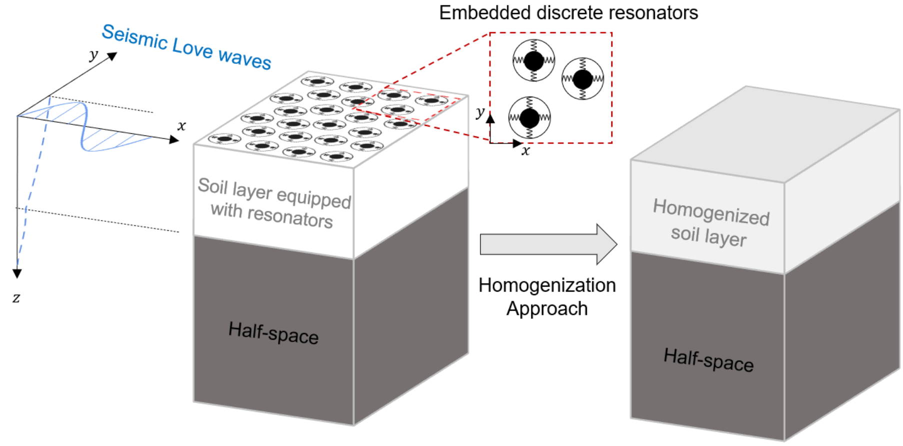


Figure 8: Locally resonant layer made of embedded mechanical resonators designed to filter out the propagation of seismic Love waves. (adapted from Zeighami et al. [85])

The possibility to combine different regulation mechanisms and reshape engineering solutions following design optimization strategies for efficient wave attenuation has sparked as a unique capability in metamaterials overall. For earthquake protection purposes, Li et al. [87] introduced a SM coupling inertial amplification and local resonance mechanisms (Figure 9) by finite element modeling to reduce seismic surface propagation, which approximately exhibited twice the attenuation capacity for low-frequency BG formation compared to locally resonant metamaterials. Nguyen et al. [59] numerically evaluated a periodic arrangement of meter-sized inerters embedded in a single-layer soil for Rayleigh wave manipulation, in which the unit cell design consists of a mass and an inerter device supported by rubber bearings in a concrete box. Giraldo Guzman et al. [88] proposed a systematic design methodology to find topology-optimized resonators with anti-resonance frequencies in locally resonant metasurfaces for surface wave control.

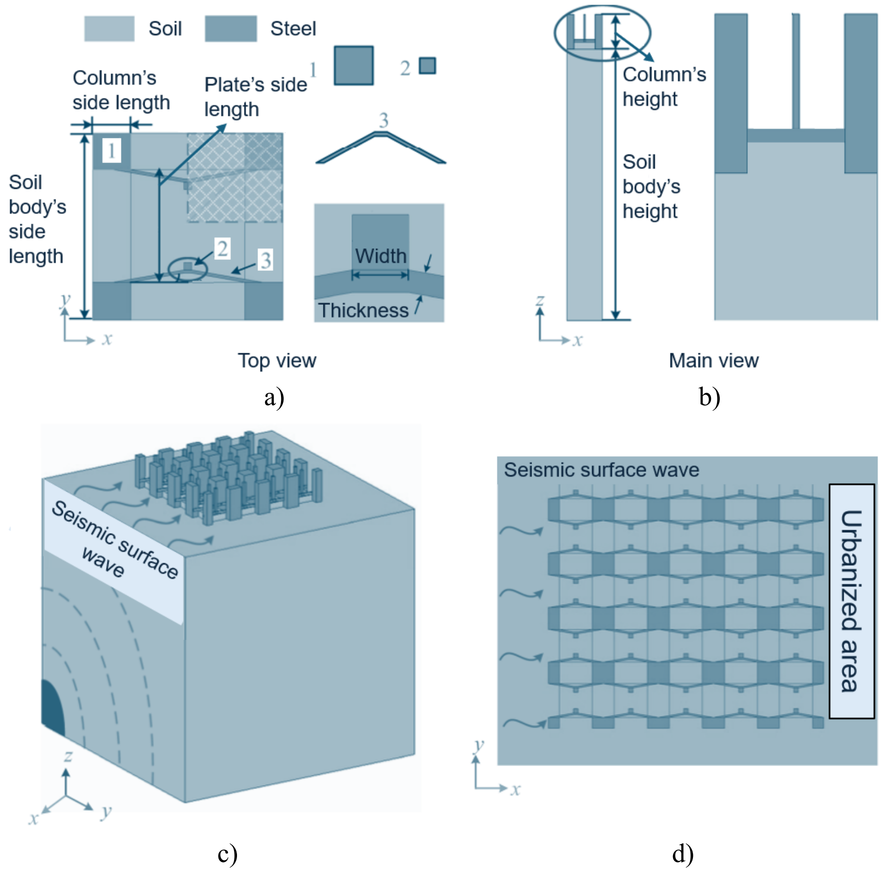
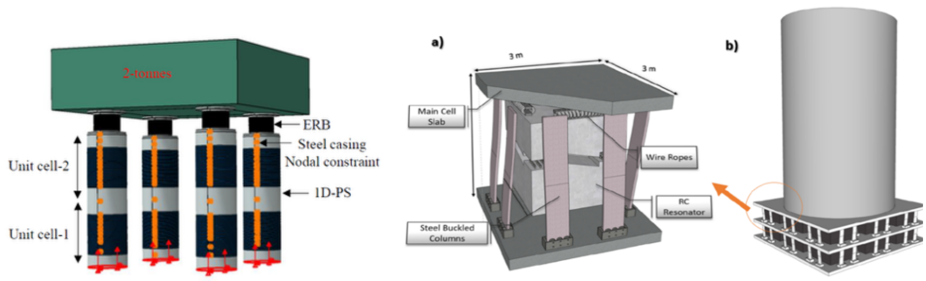


Figure 9: Combination of inertial amplification and local resonance mechanisms for SM solution (adapted from Li et al. [87]): a) unit cell design top view, b) main view of unit cell design, c) isometric view representation of SM deployment for seismic wave shielding, d) top view of SM arrangement with multiple unit cells

Metafoundation

Metafoundations consist of periodic unit cells (e.g., substrates and composite structures) arranged and placed at the foundation level of the structure [36]. Metafoundations open the possibility to implement innovative foundations integrating load-bearing and vibration isolation systems, while enabling wave attenuation effects for different ultra-low frequency excitations (< 5 Hz). Ungureanu et al. [89] analyzed a decameter-scale auxetic-like metamaterial plate as a foundation solution for seismic wave protection. Witarto et al. [90] numerically studied a 1D periodic foundation of reinforced concrete and polyurethane for earthquake protection, demonstrated in a small modular reactor building through large-scale testing. Cheng et al. [91] examined the material damping influence on layered periodic foundations, made of reinforced concrete panels and rubber blocks, for seismic isolation through dispersion and dissipation mechanisms. In this investigation, a six-story shear frame was evaluated for seismic performance considering fixed base foundation, traditional base isolation system, and layered periodic foundation. Sun et al. [92] designed a periodic foundation using inertial amplification mechanism for seismic mitigation performance considering the influence of the superstructure protected, supported by sensitivity and optimization analyses. Guo and Chen [93] investigated the Love wave attenuation capacity of a periodic array of soil-rubber-steel piles vertically buried into the substrate accounting for material anisotropy effects. Huang et al. [94] designed a 2D metamaterial elaborated from auxetic foam and hollow steel elements to attenuate ultra-low seismic frequency levels based on Poisson's ratio, elastic modulus, and density of the auxetic foam in numerical simulations. Gupta et al. [95] numerically designed a 2D metamaterial foundation using periodic steel-lead circular scatterers embedded in a rubber matrix, displaying wide and low-frequency BGs from 2.6 Hz developed through Bragg scattering mechanism. Kumawat et al. [96] combined a 1D periodic system with elastomeric rubber bearings, as displayed in Figure 10a, for passive base isolation of horizontal and vertical ground motions evaluated in FEM. Guner et al. [97] conducted a lab-scale experimental and numerical investigation to understand the compliance mechanism of a bistable metafoundation, which is installed at the foundation level of the structure of interest (Figure 10b). Special cases combine both metabarriers surrounding the structure with a metafoundation. Colombi et al. [98] designed an integrated solution based on a meta-foundation and a metabarrier, shown in Figure 11, evaluating the reduction of seismic waves vibration for a frequency range between 3.5 Hz and 8.0 Hz in a homogeneous elastic soil by 3D numerical simulations.



a) b)

Figure 10: Metafoundations developed for seismic protection of buildings: a) hybrid elastomeric rubber bearing with composite-based diatomic metastructures (Source: [96]) and b) compliance-based (Source: [97])

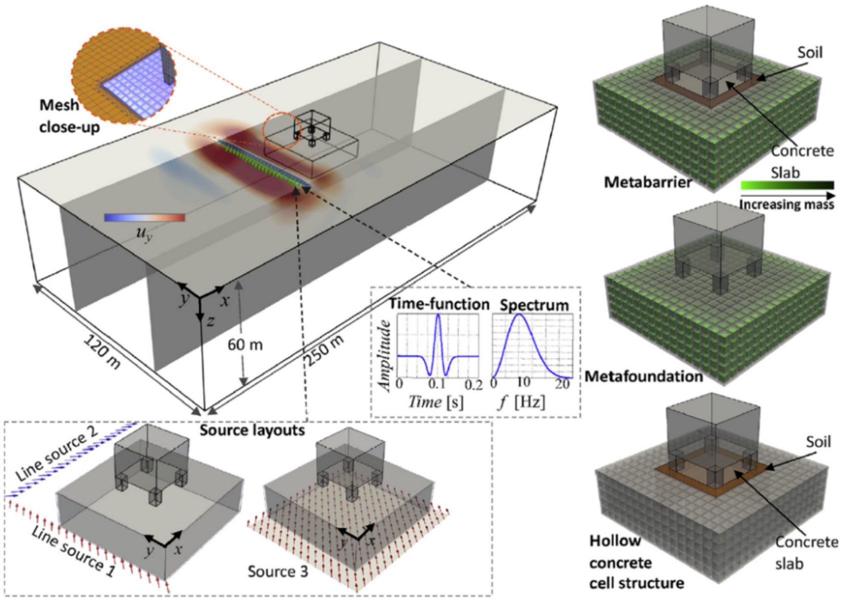


Figure 11: Combined metabarrier with metafoundation for seismic protection of civil structures. Source: [98]

4.3 Uncertainty quantification of seismic metamaterials

Due to the increasing interest of SMs in the research community, uncertainty quantification and sensitivity analysis of critical parameters (i.e., structural properties of resonators and soil parameters) have also been explored to understand the variability and influence in the vibration mitigation performance. Wagner et al. [99] presented stochastic models and parametric studies to investigate uncertainties of the design optimization problem for a mass-in-mass SM system subject to horizontal ground acceleration records. Wang et al. [100] conducted geometric quantification analysis due to additive manufacturing flaws in a quasi-zero stiffness locally resonant metamaterial for vibration isolation performance of seismic waves. Stochastic models are also found in metasurface literature. Zeighami et al. [75] performed an uncertainty quantification and global sensitivity analysis of soil density and shear modulus and resonator mass in a finite element model, considering dispersion relation and coefficient transmission as evaluation parameters.

5 Limitations of metamaterials for geotechnical application

Phononic metabarriers are typically characterized by large dimensions, often on the order of the wavelength of incoming seismic waves. This scale imposes significant limitations on their practical engineering applications, particularly in dense urban areas and city centers, where space is limited and construction constraints are more stringent.

The need for deep excavation and extensive structural modification can lead to high costs, logistical challenges, and potential disruption to existing infrastructure. Resonant metabarriers require meter-size resonators having very large resonating mass to open a relatively large BG within the frequency spectrum of seismic waves. Once these metabarriers are designed and installed on site, their resonance frequency is prescribed and cannot be modified. Retrofitting with SM at the foundation level of existing structures would have similar challenges presented by the prospect of installing base isolation systems technology in existing structures. In particular, metafoundation applications require supplementary design considerations to adequately address the structural demands imposed by the superstructure. To delve deeply into the complex interaction between the superstructure and metafoundation systems, 3D modeling of wave propagation involving computationally expensive approaches can pose obstacles for implementation in professional practice.

The attenuation performance of SMs have been validated in small-scale experiments in controlled environment and medium-scale experiments on the field while their real-scale experiment is still ongoing due to the complexity of soil-barrier dynamic interactions. Experimental validation of large-scale applications of SMs for protecting structural and nonstructural elements is another opportunity. Additional challenges that remain unknown is the potential for SMs in mitigating the effect caused by multiple hazards considering concurrent and cascading sequential events (e.g., earthquake-tsunami sequence).

Current limitations include standardization, policy, and guidelines to enable adoption by practicing engineers and construction industry [101]. The metamaterial architecture is complex and comes with challenges in simulation via commercially available geotechnical engineering software to simulate and analyze.

Although initial efforts investigating the impact of extreme climate conditions on geosynthetics and metamaterials as vibration mitigation solutions have been evidenced [29], there are still limitations to understand the lifecycle cost of metamaterials for civil infrastructure, especially for considerations in terms of the selected materials for creating the individual unit cells and scalability, evaluating fatigue and material aging effects, maintenance and long-term performance; and assessing sustainable environmental goals in terms of carbon sequestration.

6 Conclusions and Future Directions

This paper provided a state-of-the-art review of metamaterials for protection of civil infrastructure. Metamaterials can divert waves according to a design goal. The tuning of such waves at small scales has already been incorporated in non-civil engineering fields. In recent years, the potential for dissipating seismic waves has captured the interest of the earthquake engineering research community. This paper reviewed various innovations from the last 5 years including metamaterial inspired devices, embedding resonators in steel beams, redesigning foundations, and metastructures embedded in soil to create barriers at the surface or deep levels.

Future directions in this emerging field include research of design optimization via soft computing methods [102] based on machine learning and artificial intelligence could enhance the capabilities for the proposed SMs. For example, topology optimization studies varying the complex geometries to achieve design objectives or performance could create efficient systems [103–105]. The combination of the open-architecture configuration and the infill SMs of the geocell, controlled by active reconfigurable systems [106] to introduce dynamic changes in the soil, promises an efficient, inexpensive, *adaptive* geobarrier system for seismic wave attenuation for different frequency ranges. Existing SMs possess fixed internal architecture that cannot be altered after fabrication, and the wave dissipation properties work for a narrow range of frequencies. The ability to actively change the internal periodic structure after fabrication opens the possibility to become extremely efficient for a much wider range of external conditions. The control methods for programming and tuning these systems in real time would have great potential for large-scale applications.

Once the SMs are installed, the maintenance requirements and long-term performance will be critical. Current technology for structural health monitoring could be particularly useful to assess their performance. Recent work by Caballero et al. [107] experimentally tested the damage detection capabilities by observing the wave attenuation curves during the changes in mass and stiffness of metamaterials. Analytical and experimental tests of a diatomic metamaterial in [108] show the potential for scalability.

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