University Transportation Research Center - Region 2

Final Report

Mitigation of Transportation Induced Vibration Using Seismic Metamaterials

Performing Organization: State University of New York (SUNY)

February 2018

Sponsor:
University Transportation Research Center - Region 2

University Transportation Research Center - Region 2

The Region 2 University Transportation Research Center (UTRC) is one of ten original University Transportation Centers established in 1987 by the U.S. Congress. These Centers were established with the recognition that transportation plays a key role in the nation's economy and the quality of life of its citizens. University faculty members provide a critical link in resolving our national and regional transportation problems while training the professionals who address our transportation systems and their customers on a daily basis.

The UTRC was established in order to support research, education and the transfer of technology in the field of transportation. The theme of the Center is "Planning and Managing Regional Transportation Systems in a Changing World." Presently, under the direction of Dr. Camille Kamga, the UTRC represents USDOT Region II, including New York, New Jersey, Puerto Rico and the U.S. Virgin Islands. Functioning as a consortium of twelve major Universities throughout the region, UTRC is located at the CUNY Institute for Transportation Systems at The City College of New York, the lead institution of the consortium. The Center, through its consortium, an Agency-Industry Council and its Director and Staff, supports research, education, and technology transfer under its theme. UTRC's three main goals are:

Research

The research program objectives are (1) to develop a theme based transportation research program that is responsive to the needs of regional transportation organizations and stakeholders, and (2) to conduct that program in cooperation with the partners. The program includes both studies that are identified with research partners of projects targeted to the theme, and targeted, short-term projects. The program develops competitive proposals, which are evaluated to insure the mostresponsive UTRC team conducts the work. The research program is responsive to the UTRC theme: "Planning and Managing Regional Transportation Systems in a Changing World." The complex transportation system of transit and infrastructure, and the rapidly changing environment impacts the nation's largest city and metropolitan area. The New York/New Jersey Metropolitan has over 19 million people, 600,000 businesses and 9 million workers. The Region's intermodal and multimodal systems must serve all customers and stakeholders within the region and globally.Under the current grant, the new research projects and the ongoing research projects concentrate the program efforts on the categories of Transportation Systems Performance and Information Infrastructure to provide needed services to the New Jersey Department of Transportation, New York City Department of Transportation, New York Metropolitan Transportation Council , New York State Department of Transportation, and the New York State Energy and Research Development Authorityand others, all while enhancing the center's theme.

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The modern professional must combine the technical skills of engineering and planning with knowledge of economics, environmental science, management, finance, and law as well as negotiation skills, psychology and sociology. And, she/he must be computer literate, wired to the web, and knowledgeable about advances in information technology. UTRC's education and training efforts provide a multidisciplinary program of course work and experiential learning to train students and provide advanced training or retraining of practitioners to plan and manage regional transportation systems. UTRC must meet the need to educate the undergraduate and graduate student with a foundation of transportation fundamentals that allows for solving complex problems in a world much more dynamic than even a decade ago. Simultaneously, the demand for continuing education is growing – either because of professional license requirements or because the workplace demands it – and provides the opportunity to combine State of Practice education with tailored ways of delivering content.

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16. Abstract

Transportation systems create new technical and environmental challenges including noise and ground vibration, which affect ambient architectures, quality of life, and sustainability of the communities. Noise and vibration assessments become key elements of the environmental impact assessment process for mass transit projects, and noise and vibration are among the major concerns with regard to the effects of a transit project on the surrounding community.

The research objective of this project was to design an efficient and economic method to mitigate the vibration induced by transportation activities. Specifically, periodically arranged piles in the ground called seismic metamaterials were used, which attenuated the vibration through the scattering and local resonance phenomena. To achieve this, a computational-experimental framework including integrated modeling, simulation, optimal design, and experimental validation was developed. The effectiveness of the proposed seismic metamaterials to mitigate transportation induced vibration through three-dimensional numerical simulations was examined. A method was developed for the design and optimization of the structured seismic metamaterials with the desired vibration mitigation capability in the targeted frequency range, with proper combination of constituent phases. Scaled experimental investigations were performed to validate the effectiveness of the proposed optimal seismic metamaterials.

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Executive Summary

The increasing traffic intensity on roads, highways, and railways requires that major investments be made to make transportation systems more livable and sustainable, especially in the UTRC Region II area. This is due to the high density population in the NYC Metropolitan area where the high speeds and a large capacity of vehicles and trains are highly desired. Such transportation systems create new technical and environmental challenges including noise and ground vibration, which affect ambient architectures, quality of life, and sustainability of the communities. Noise and vibration assessments become key elements of the environmental impact assessment process for mass transit projects, and noise and vibration are among the major concerns with regard to the effects of a transit project on the surrounding community.

The research objective of this project is to design an efficient and economic method to mitigate the vibration induced by transportation activities. Specifically, we propose to use periodically arranged piles in the ground called seismic metamaterials, which attenuate the vibration through the scattering and local resonance phenomena. To achieve this, a computational-experimental framework including integrated modeling, simulation, optimal design, and experimental validation will be developed. First, we will examine the effectiveness of the proposed seismic metamaterials to mitigate transportation induced vibration through three-dimensional numerical simulations. Second, we will develop a method for the design and optimization of the structured seismic metamaterials with the desired vibration mitigation capability in the targeted frequency range, with proper combination of constituent phases. Third, scaled experimental investigations will be performed to validate the effectiveness of the proposed optimal seismic

metamaterials.

The framework integrating numerical simulations and experimental setup proposed in this project will provide a low-cost and efficient method to mitigate the transportation induced vibration, making significant contribution to the UTRC's Focus Area 7: Promoting livable and sustainable communities through quality of life improvements. The successful completion of this project will result in major breakthroughs in modeling and designing seismic metamaterials in multidisciplinary areas, which would expand the conventional boundary of vibration mitigation approaches for transportation and many other applications.

1. Introduction

1.1 Overview and objectives

Undesired noise and vibration are prevalent in our daily life. They could arise from the use of tools and machine, construction, transportation, and low amplitude earthquake (Figure 1). The undesired noise and vibration often harm human life and animal activities. In addition, the long-term and cycling vibration could cause crack and subsidence of surrounding buildings. It is well recognized that noise and vibration are not only an annoyance, but also have adverse health, social, and economic impacts. To avoid the undesired noise and vibration, a lot of basic technologies have been proposed in the past decades. In general, these technologies can be divided into two categories, i.e., active control and passive control. [1, 2] For active control, a second wave is specifically designed to interact with the vibration source, resulting in destructive interferences between these two waves and wave attenuation (Figure 2). [3, 4] This technology is particularly useful to control low-frequency noise and vibration but is unmanageable for high frequency due to the limitation of free space and zone of silence techniques. In this regard, passive control is more effective to control noise and vibration without the need for active control. [1, 5, 6] Soft materials based on wave energy dissipation or hard materials for wave reflection are often employed for passive control (Figure 3). It has been demonstrated that both active and passive noise and vibration control methods are effective under certain circumstances; however, they still suffer from some drawbacks. For example, for active control, the frequency range is very limited, thereby limiting their potential applications in complex noise and vibrational environments. For passive control, there is a conflict between the wave energy dissipation and mechanical robustness. For example, soft materials coated on the surface of submarines have the capability to control acoustic wave effectively, but the mechanical performance is very poor. This conflict is particularly prominent for noise and vibration control in mechanically challenging environments.

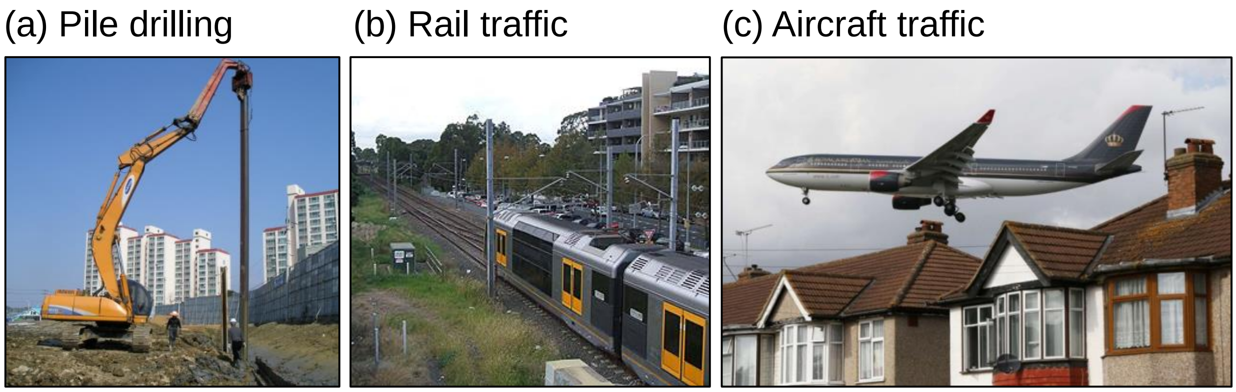

Figure 1. Possible vibration sources. (a) Pile drilling, (b) rail traffic, and (c) aircraft traffic. (Images source: https://www.thestar.com/news/world/2013/10/09)

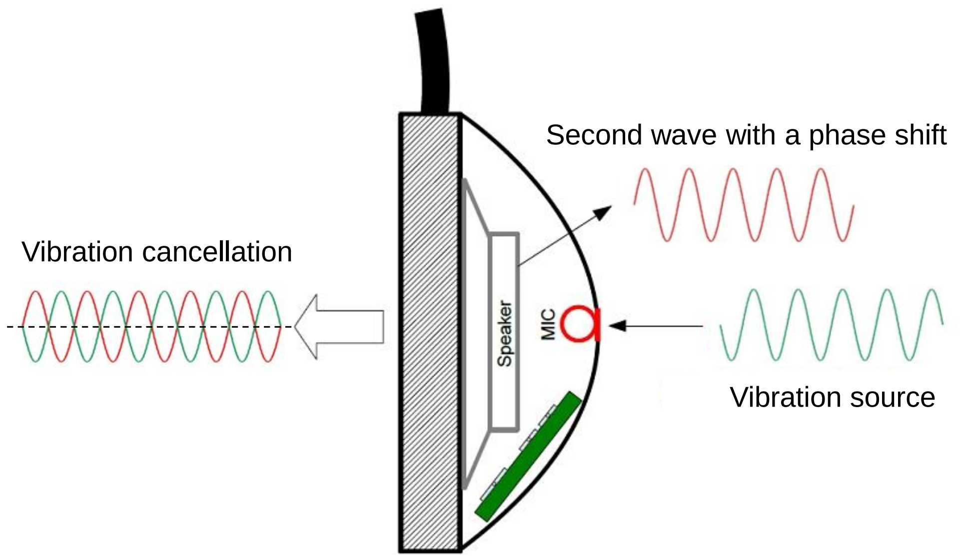

Figure 2. Schematic of active vibration control method.

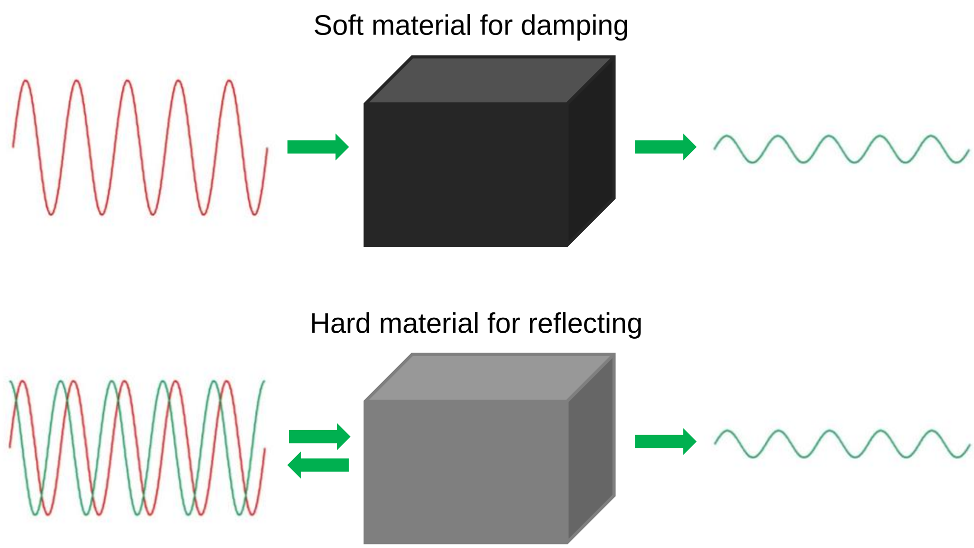

Figure 3. Schematic of passive vibration control.

Recently, architected materials with spatially modulated elastic constants and densities have been proposed to control noise and vibration. [7-10] When the wavelength of the propagating mechanical wave is comparable to the structural periodicity, destructive interferences arise at the interfaces of the compositions. As a result, the incident wave will be totally reflected and redirected to elsewhere. Despite remarkable achievement in this area has been obtained, challenges remain. For example, most of the previous studies are focused on exploring new physical mechanisms while little attention has been devoted to exploring the potential applications. Specifically, in engineering practice, broadband and multiband wave filtering capabilities are highly desired. In addition, improved mechanical performance including stiffness, strength, and fracture toughness are essential in structural components where load-carrying ability and vibration mitigation are simultaneously pursued. These pose a great challenge for the coupled architecture-material design strategy.

The objective of this work is to control undesired low frequency vibration (below 10 Hz) using periodic structures by integrative numerical and experimental approaches.

1.2 Background and motivation

The vibration induced by traffic, construction, industrial activities, blasting or natural earthquake not only damages civil infrastructures and affects high precision facilities, but also lowers the comfort level of residents. Therefore, vibration isolation is of great concern for both researchers and civil engineers. To decrease or eliminate the effects of vibration on infrastructures and facilities, two types of vibration isolation methods have been proposed, which are active vibration isolation and passive vibration isolation. Regarding the passive vibration isolation, open or filled trenches and piles are employed as wave barriers [37-38]. Trenches are often used to isolate vibrations for shallow structures, while piles are much more widely utilized due to their ability to be exempted from the influence of high groundwater level and to enhance the capacity of the ground as well.

The effectiveness of pile barriers for waves has been investigated intensively in the past decades. Liao and Sangrey [39] experimentally studied the effects of pile barriers to reduce the ground vibrations and they found that the impedance mismatch between the piles and the soil has a great impact. However, full scale experiments of piles as wave barriers are limited due to the trade-off between costs and effectiveness. Therefore, many analytical and numerical methods have been proposed to solve the problem of pile barriers. Avilés and Sánchez-Sesma [40] analytically investigated the two-dimensional (2D) and three-dimensional (3D) problem of pile barriers for the foundation and they concluded that stiff piles have better screening effectiveness than flexible piles. Takemiya [41] studied the effectiveness of honeycomb wave impeding barriers using a 3D finite element method (FEM) and a dramatic reduction effect was achieved. The 3D boundary Element Method (BEM) has also been implemented to study the vibration isolation of piles as wave barriers against that of trenches [42-44]. A 3D BEM–FEM coupling model for the time-harmonic dynamic analysis of piles and pile groups in soil was proposed by Padrón et al. [45]. In their model, the piles were modeled using finite elements, while the soil was modeled using boundary elements. They concluded that this method was much more efficient than other numerical methods. Most of these theoretical studies concentrated on formulating different analytical and numerical methods to analyze the effectiveness of piles as wave barriers. However, only single or several rows of piles were investigated for an incident wave propagating along specific directions due to the complexity of wave propagating in piles and soil.

Recently, periodic composites have attracted much interest owning to their capacity to tailor the propagation of mechanical waves. One fundamental property of these periodic composites is the existence of complete band gaps (CBGs) – frequency ranges within which mechanical waves are totally reflected or trapped inside regardless of the incident angle [46-47]. Inspired by this, Huang and Shi [48] considered the pile-soil system as a 2D periodic composite and numerically studied the mechanism of dynamic attenuation of pile barriers. Xiang et al. [49] fabricated a scaled model frame and a periodic foundation, on which the shake table test was conducted, and they found that the vibration can be attenuated significantly. More recently, seismic metamaterial has been designed to reduce the amplitude of seismic waves at the free surface and good agreement between the numerical and experimental results was observed [50]. It should be pointed out that the aforementioned researchers assume that the height of piles is infinite in their simulation. However, the height of piles is finite and highly correlated with the elevation of the structures to be isolated in engineering practice.

Historically, the study of wave propagation in periodic structures can reach back to Rayleigh's treatment of wave propagations in his book The Theory of Sound. [11] After then, studies on wave propagation have evolved into an emerging multidisciplinary that encompasses physical mechanisms and applications from both condensed matter physics and acoustical engineering. Among these, periodic structures and materials with spatially modulated elastic constants and densities have attracted extensive research interests due to their capabilities to manipulate the propagation of sound and heat. [12-15] The introduction of structural periodicity leads to modification of phonon dispersion relations, providing avenues to tailor group velocities. One of the remarkable features in phonon dispersion relations is the existence of complete wave band gaps: frequency ranges where the propagation of phonons is suppressed irrespective of incident angles.

The technical word, phonon, coming from the study of vibrations of atomic crystal lattices, now has been widely adopted in studies on mechanical wave propagation. After the discovery of the first complete phononic band gap by Sigalas and Economou in 1993, [16] a new term, phononic crystal, was then coined by Kushwaha and his colleagues, differentiating it from its counterparts in electronics and optics, photonic crystals. [10] However, the first observation of noise and vibration attenuation using periodically architected materials was not reported until 1995 when a research group in Spanish studied the acoustic wave propagation in a sculpture. [17] They found that this sculpture enables the attenuation of sound waves in the audio frequency range. Intrinsically, the formation of the band gaps in phononic crystals is due to the destructive interferences of the propagating wave, which are intrinsically dedicated by the geometric arrangements and material properties of the compositions. [18-21] In this regard, the complete band gaps are called Bragg-type band gaps.

The emergence of complete Bragg-type band gaps requires that the structural periodicity must be of the same magnitude as the effective wavelength in the periodic structures. This could pose a great challenge to design compact phononic crystals for audio frequency range since the size of the desired phononic crystals will be very large for low-frequency waves. In 2000, Liu and his colleagues developed a new type of periodic structure where low-frequency band gaps are observed. [22] This new structure was termed acoustic metamaterials. [18, 23, 24] Indeed, there is no clear boundary between these two types of mechanisms. As it will be shown in Chapter 2, there could be overlapping between these two kinds of band gaps. [25] As a result, the overlapping band gap is larger than conventional pure locally resonant band gaps. Now, the progress in the field of phononic crystals and acoustic metamaterials has since proliferated into a rich subject with numerous applications, including wave filtering, [26-28] acoustic cloaking, [29-31] heat management, [15, 32, 33] energy harvesting. [34-36]

Despite the extensive research interests and enticing potential applications, current phononic crystals and acoustic metamaterials still, suffer from some drawbacks. For example, for the mitigation of transportation induced vibration and noise, low frequency (below 10 Hz) phononic crystals are highly desirable. The objective of this report is to propose a new method to manipulate the low frequency wave propagation.

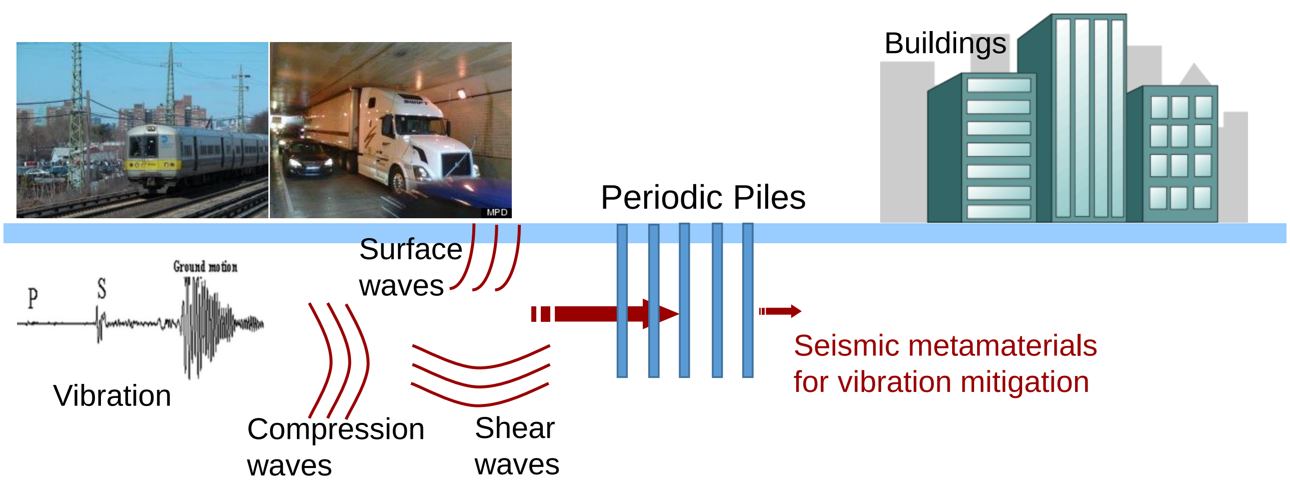

Figure 4. Isolation of vibration induced by transportation using seismic metamaterials.

2. Numerical and experimental methods

2.1 Experimental setup

Experiments were performed on the designed seismic metamaterials, which consist of sand and steel cylinder. Here we consider two cases: a cylinder with square lattice symmetry and triangular lattice symmetry (Figure 5). The lattice constant is set as 10 cm and the diameter of the steel cylinders is 7.7 cm. The typical experimental setup of the sample is given in Figure 6. The sample was directly connected to an electro-dynamic shaker controlled by a Spider Vibration Controller system. The sinusoid signal with a sweeping frequency from 5 Hz to 800 Hz and constant amplitude was generated by the controller and then amplified by a signal amplifier to drive the shaker and excite the sample. Two accelerometers, one was directly attached to the shaker and the other was mounted on the far end of the sample, were used to capture the input and output acceleration signals, respectively. Each sample was tested three times under the same experimental conditions. The transfer function from the input excitation to the output acceleration was computed.

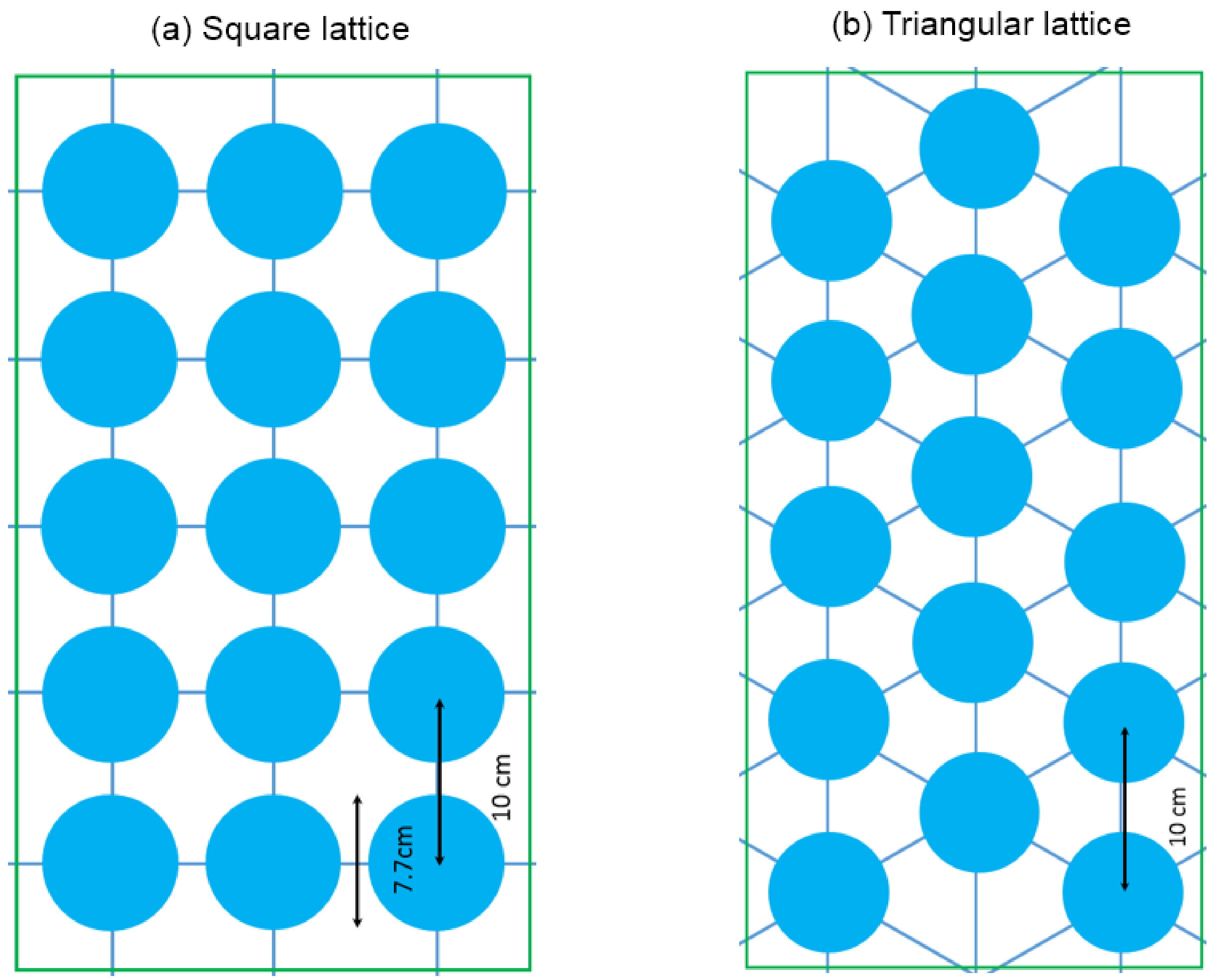

Figure 5. Schematics of (a) square lattice and (b) triangular lattice.

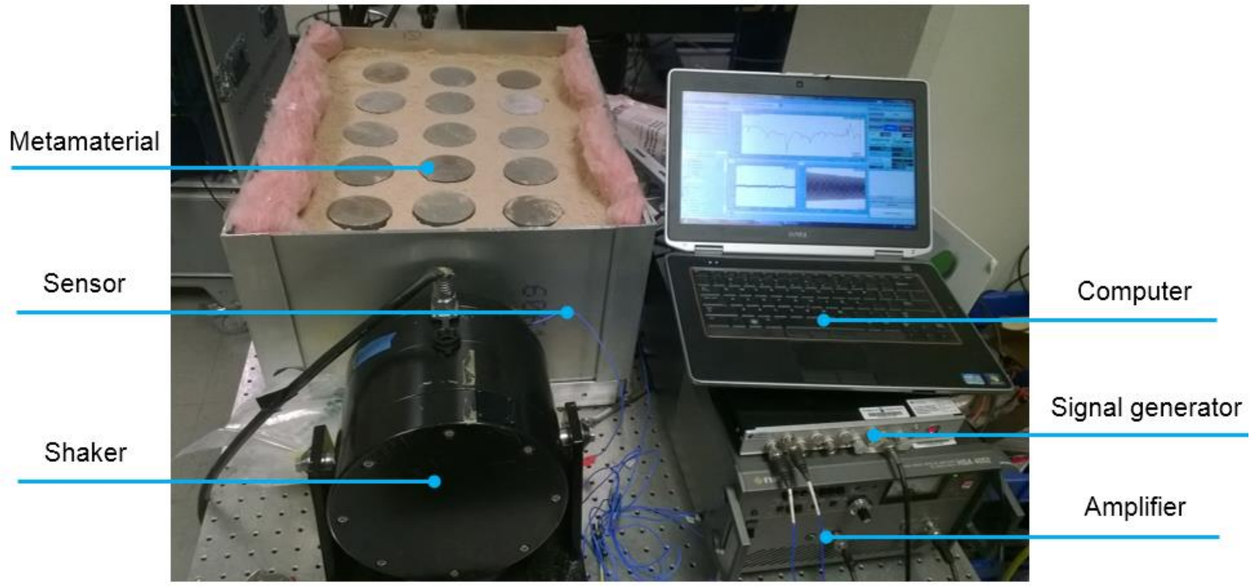

Figure 6. Experimental setup for low amplitude wave transmission test

2.2. Numerical simulation details

2.2.1 Construction of the first irreducible Brillouin zone

The periodicity of the proposed seismic metamaterials with a square topology can be described by two lattice vectors $\mathbf{a_1}$ and $\mathbf{a_2}$ (Figure 7). The reciprocal lattice primitive vectors can be calculated as:

$$\mathbf{b_1} = 2\pi \frac{\mathbf{a_2} \times \hat{\mathbf{z}}}{\mathbf{a}_1 \cdot (\mathbf{a_2} \times \hat{\mathbf{z}})} \text{ and } \mathbf{b}_2 = 2\pi \frac{\hat{\mathbf{z}} \times \mathbf{a}_1}{\mathbf{a}_1 \cdot (\mathbf{a_2} \times \hat{\mathbf{z}})} . \quad (1)$$

By connecting the perpendicular bisectors of the reciprocal lattice, the corresponding Brillouin zone can be constructed. Due to the presence of the rotation and mirror symmetries of the unit cells, the first irreducible Brillouin zone is considered in the phononic dispersion relations simulation. Following the same procedure, we can construct the first irreducible Brillouin zones for seismic metamaterials with triangular topology.

2.2.2 Bloch wave analysis for periodic metamaterials

The governing equation of elastic wave propagating in the seismic metamaterials is given by:

$$-\rho\omega^2\mathbf{u} = \frac{E}{2(1+\nu)}\nabla^2\mathbf{u} + \frac{E}{2(1+\nu)(1-2\nu)}\nabla(\nabla\cdot\mathbf{u}) \quad (2)$$

In Equation (2) **u** is the displacement vector and ω is the angular frequency. E, ν, and ρ are Young's modulus, the Poisson's ratio, and the density of the constituent material, respectively.

The phononic dispersion relations are constructed by performing eigenfrequency analysis. The Bloch's periodic boundary conditions are applied at the boundaries of the unit cell such that:

$$\mathbf{u}_i(\mathbf{r}+\mathbf{a}) = e^{i\mathbf{k}\cdot\mathbf{a}}\mathbf{u}_i(\mathbf{r}) \quad (3)$$

where **r** is the location vector, **a** is the lattice translation vector, and **k** is the wave vector.

The governing equation (2) combined with the boundary condition (3) leads to the standard eigenvalue problem:

$$(\mathbf{K}-\omega^2\mathbf{M})\mathbf{U} = 0 \quad (4)$$

where **U** is the assembled displacement vector, and **K** and **M** are the global stiffness and mass matrices assembled using standard finite element analysis procedure. The unit cell is discretized using tetrahedral elements. In our simulations, we have used a discretization of 40 elements for the minimum wavelength. Equation (4) is then numerically solved by imposing the two components of the wave vectors and hence calculates the corresponding eigenfrequencies. The phonon dispersion relations are obtained by scanning the wave vectors in the first irreducible Brillouin zone.

2.2.3 Frequency domain analysis for transmission spectrum of finite-size structures

The transmission spectrum of the proposed lattice metamaterial was calculated by performing a frequency domain analysis. To model the elastic wave incident normally to the left-hand-side surface of the seismic metamaterials, a low amplitude harmonic displacement is applied on the left-hand side (Figure 8). Perfectly matched layers (PMLs) are applied at the two ends of the homogeneous parts to prevent reflections by the scattering waves from the domain boundaries. The frequency range for the transmission simulation is 5~ 800 Hz. Here we have used a discretization 40 elements for the minimum wavelength. For the purpose of fair comparison, the simulated transmission is defined as the ratio of output displacement amplitude to the input displacement amplitude.

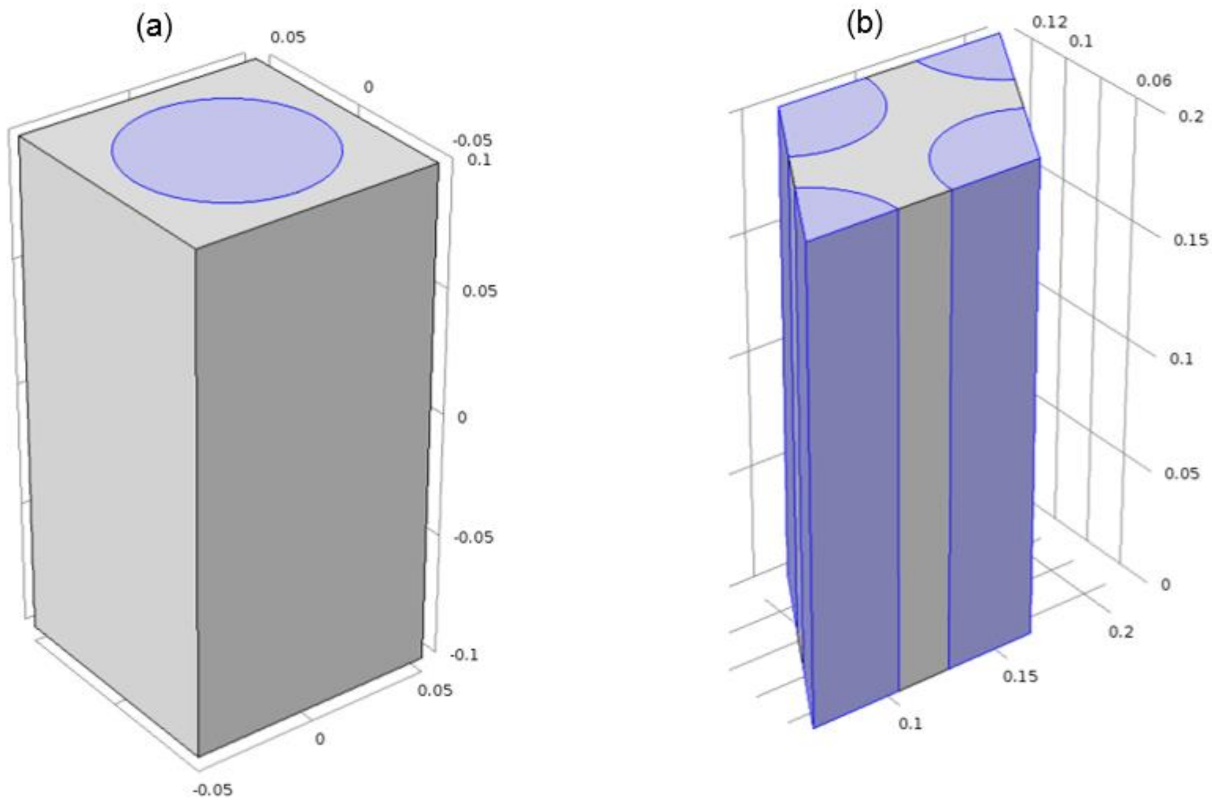

Figure 7. (a) Unit cell for square lattice and (b) Unit cell for triangular lattice.

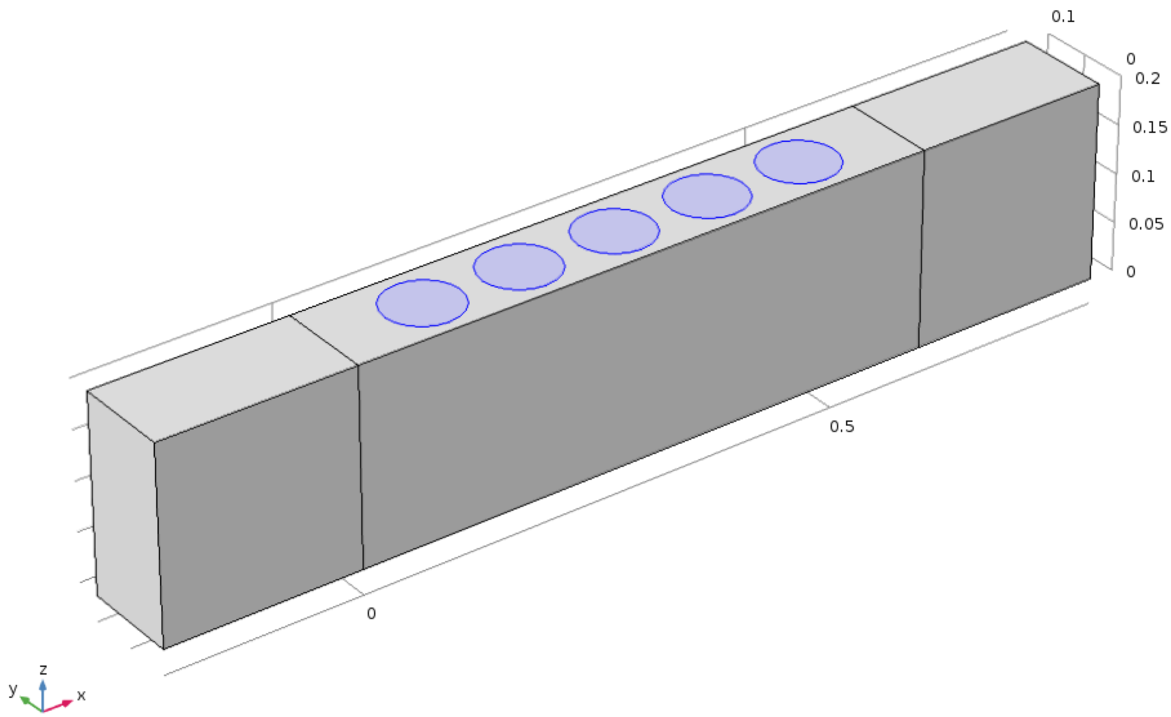

Figure 8. FE model of seismic metamaterials with square lattice symmetry. Periodic boundary condition is applied in the y-direction.

3. Results and discussion

3.1 Comparison between experiments and numerical modeling

The simulated phononic dispersion relation and transmission for square lattice are presented in Figure 9 (a) and (b), where two large complete band gaps can be directly observed. The positions of two strong attenuation zones agree well with the simulated band gaps. The measured transmission line was presented in Figure 9 (c). Though the transmission amplitude of the two attenuation zones is different from the simulated ones, the simulated complete band gaps are well captured by the experiments. The simulated dynamic responses of the seismic metamaterial at different frequencies are plotted in Figure 10. One can notice that, at the frequency of the complete band gaps, the input wave can propagate through the seismic metamaterial freely. While the incident wave was totally reflected when the incident frequency lies in the band gap.

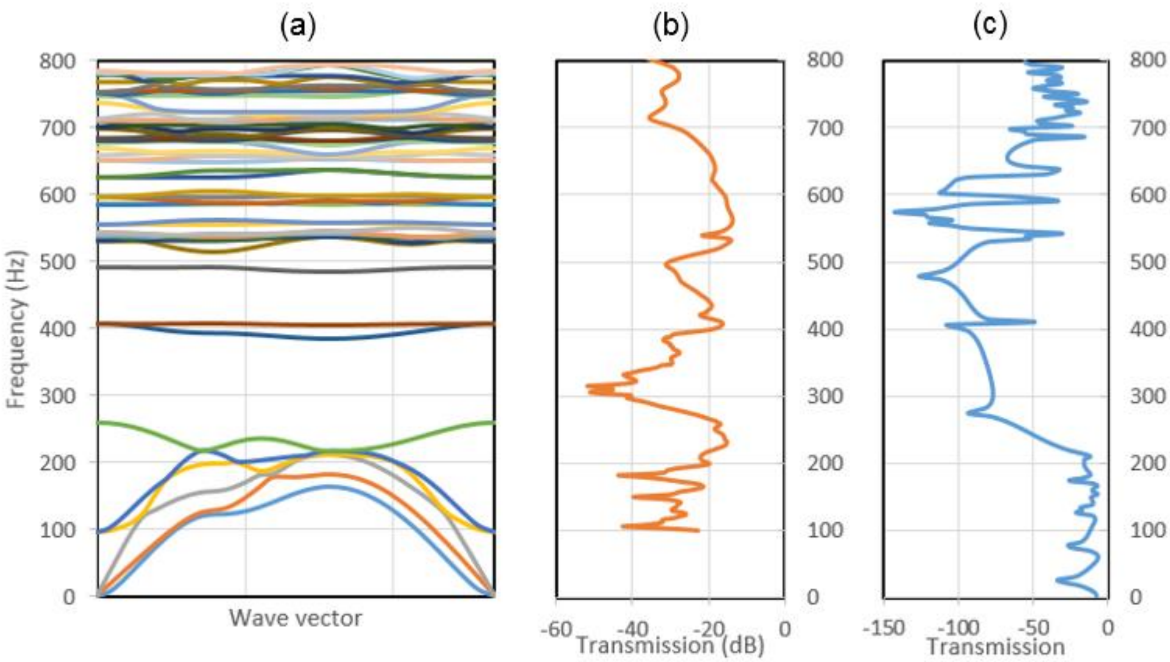

Figure 9. Comparison of simulations and experiment for square lattice. (a) Phononic dispersion relation (b) Measured transmission (c) Simulated transmission

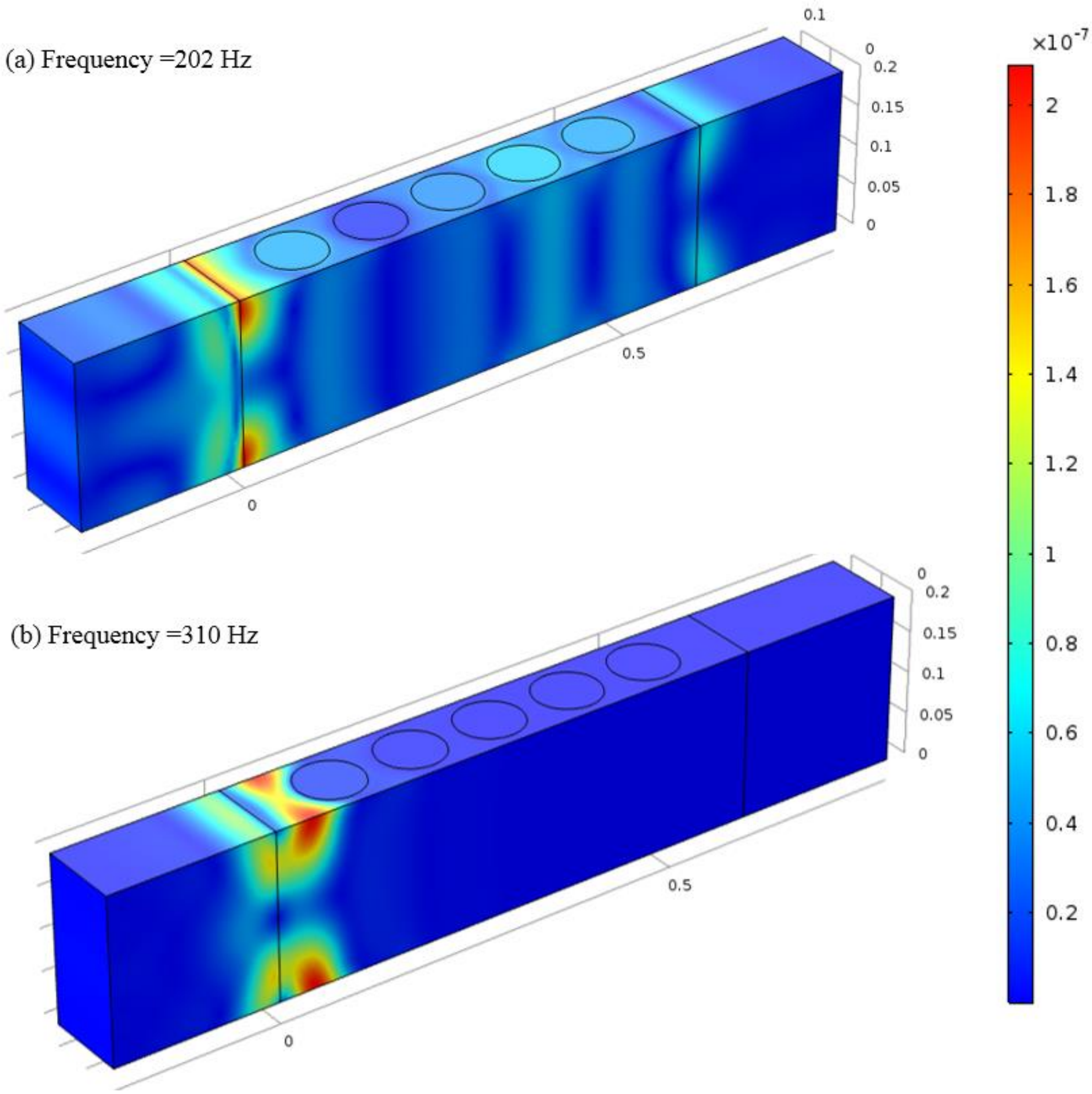

Figure 10. The simulated dynamic response of the seismic metamaterial at different frequencies. (a) Frequency f= 202 Hz and (b) frequency f=310 Hz.

Following the same experimental and numerical procedure, we studied the wave propagation in the proposed seismic metamaterials with triangular lattice symmetry. As shown in Figure 11, there is one large complete band gap in the simulated phononic dispersion relation, which was also well captured by the experiment. The comparison between numerical simulations and experiments suggests that the proposed metamaterials have broadband vibration mitigation capability, which can be perfectly captured by the proposed experimental scheme.

For comparison purposes, other three types of lattice symmetry, namely, square lattice, honeycomb lattice and hexagonal lattice are also calculated and compared. Figure 12 shows the band structures of seismic metamaterials with a square lattice, a honeycomb lattice and a hexagonal lattice, respectively. Two complete band gaps appear in the band structure of the periodic composite with a square lattice. However, no complete band gaps appear in the band structure of the periodic composite with a honeycomb lattice.

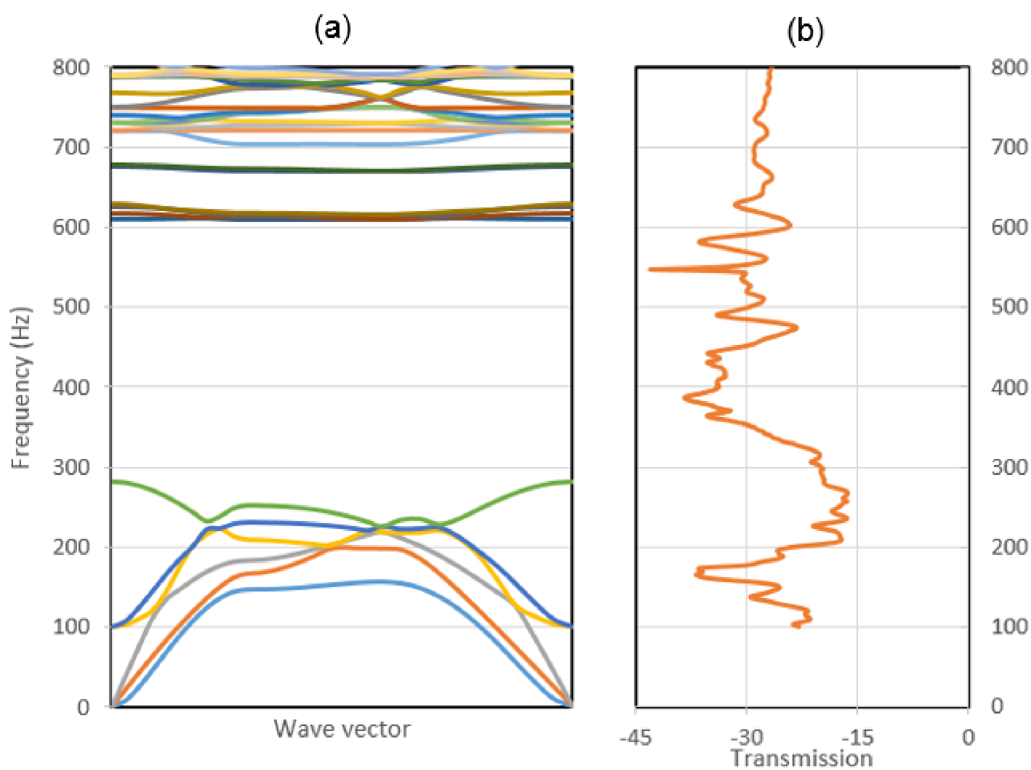

Figure 11. Comparison of simulations and experiment for triangular lattice. (a) Phononic dispersion relation and (b) Measured transmission.

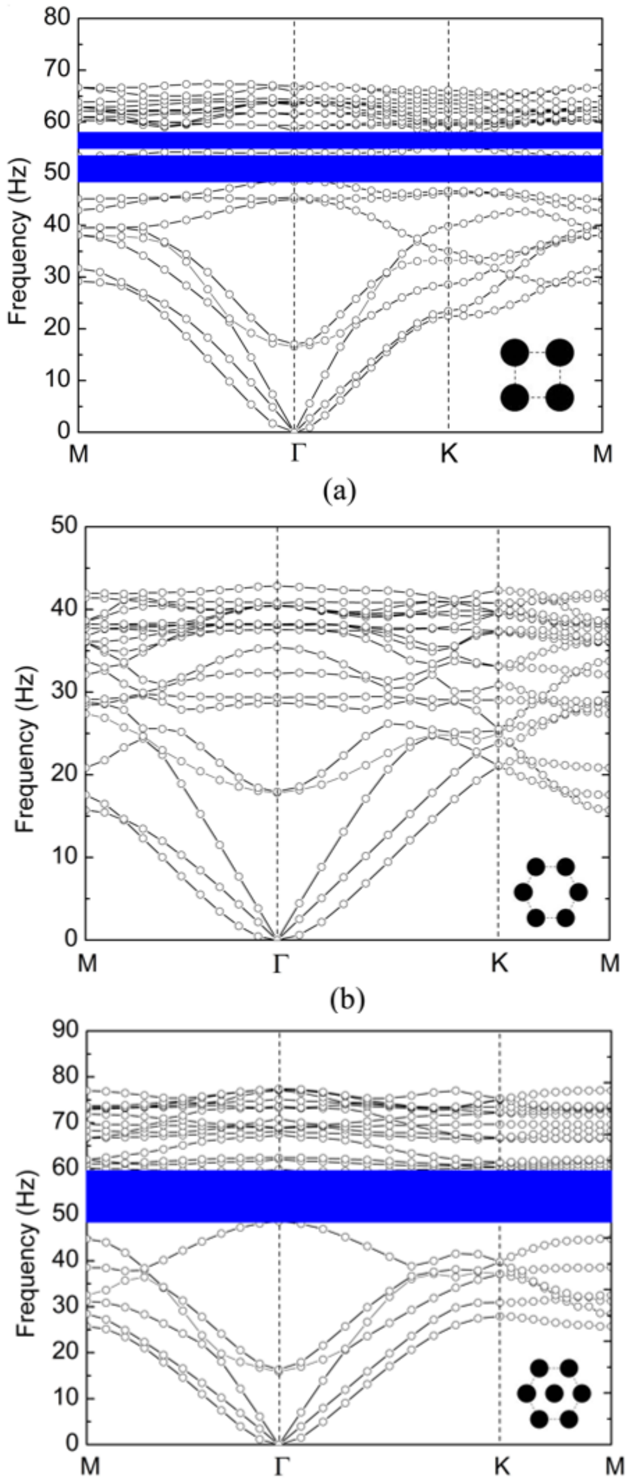

Figure 12. Band structures of the periodic piles with different lattice symmetries. (a) Square lattice. (b) Honeycomb lattice. (c) Hexagonal lattice.

3.2 Effect of layered feature-dispersion relation

We have numerically and experimentally captured the attenuation of waves in the proposed seismic metamaterials. One can notice that there is a strong requirement for the volume fraction of steel cylinders (larger than 50%) and large dimensions of the seismic metamaterials for low frequency vibration control. One common solution is to design new structures for low frequency vibration control, such as locally resonant based structures, which poses a great challenge for the fabrication and installation of the proposed new structures. Here, we hope to exploit the layered feature of the soil to control the low frequency vibration. Figure 13 shows the proposed seismic metamaterials with the layered soil of different heights from shallow, 6 meters to deep 18 meters.

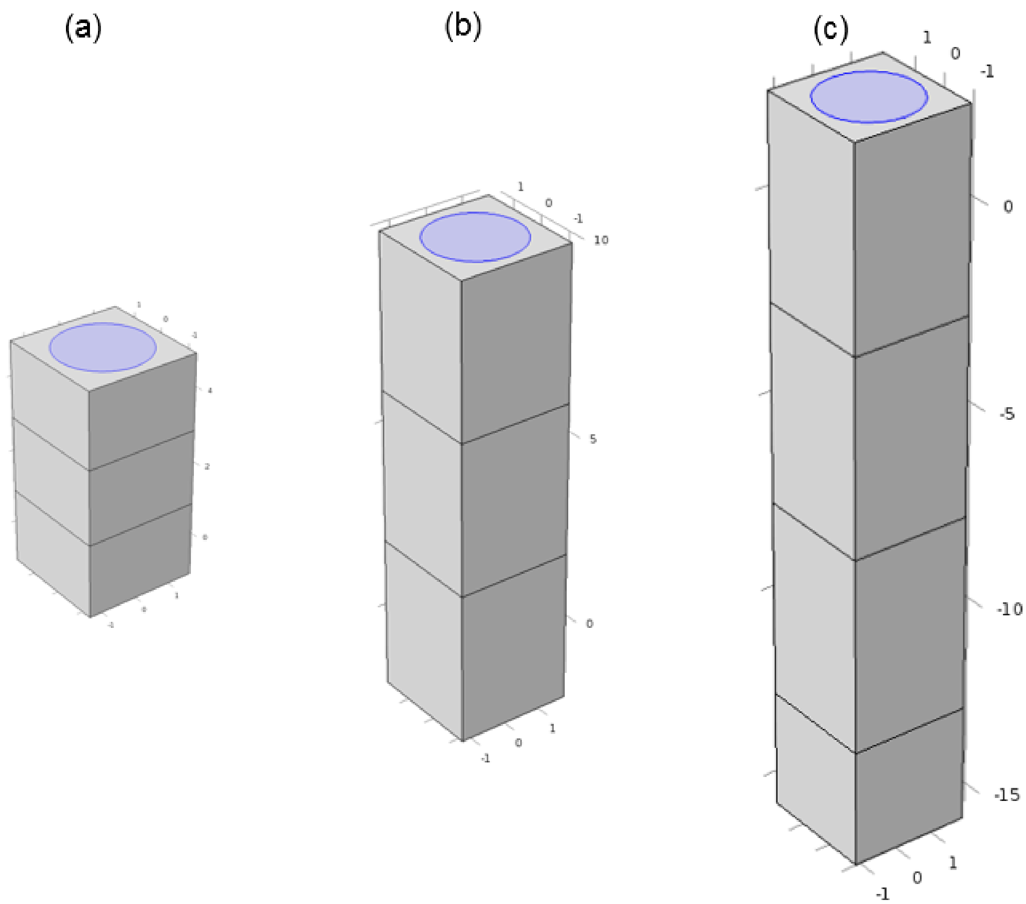

Figure 13. FE models of seismic metamaterials with different heights. (a) h=6m, (b) h=12 m, and (c) h=18 m.

Figure 14 shows the simulated dispersion relation for shallow piles with a layered feature of soil. One can notice that for regular structure (a), there are two complete band gaps within the frequency range of 26 Hz ~ 32 Hz, which is impractical for low frequency vibration control. While for the seismic metamaterials with the layered feature, there are multiple low frequency partial band gaps (below 10 Hz), indicating that they have great potential to be employed as the wave barriers to mitigate transportation induced vibration or seismic waves.

The simulated transmission lines are plotted in Figure 15, where two significant transmission dips can be observed at high frequency range. While compared with the homogeneous structure, there are attenuation zones that can be observed. The dynamic responses of the layered structures at two frequencies are plotted in Figure 16. One can notice that most of the dynamic wave energy is localized in the first layered of the soil, thereby preventing the propagation of the input waves.

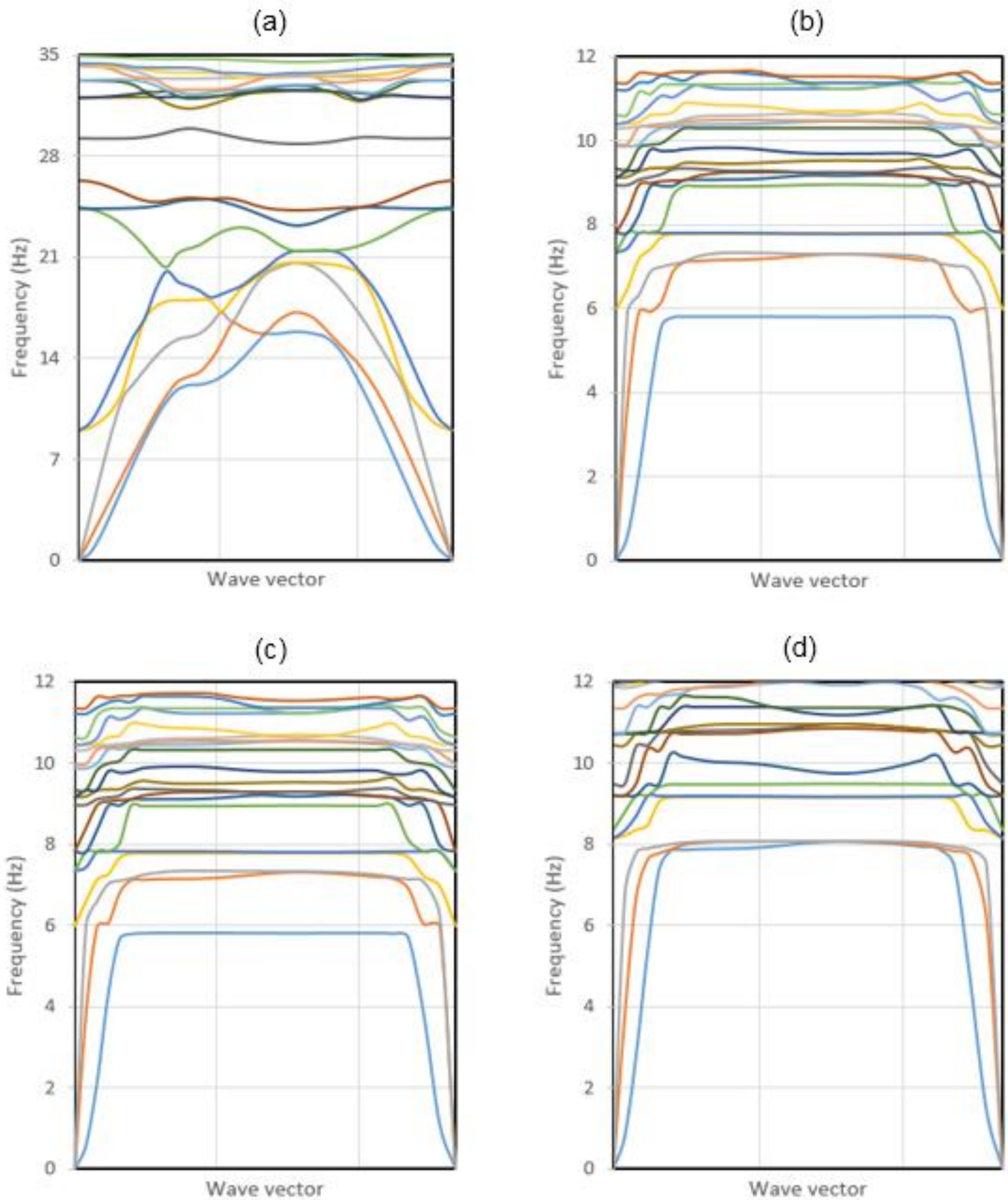

Figure 14. Phononic dispersion relations of (a) homogeneous structures with h=6 and vf=0.5 (b) h=6, vf=0.5, E1:E2:E3= 1-10-100 (c) h=6, vf=0.5, E1:E2:E3=1-100-10. (d) h=6, vf=0.5, E1:E2:E3=10-1-100. Here h indicates the total height of the pile, vf indicates the volume fraction of the pile, and Ei is the Young's modulus of each layer.

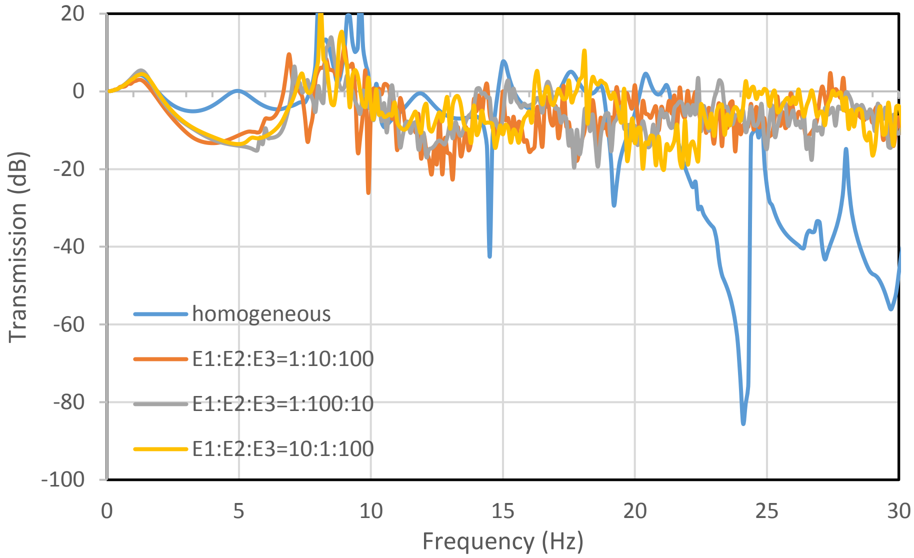

Figure 15. Transmission of seismic metamaterials with a height of 6 m.

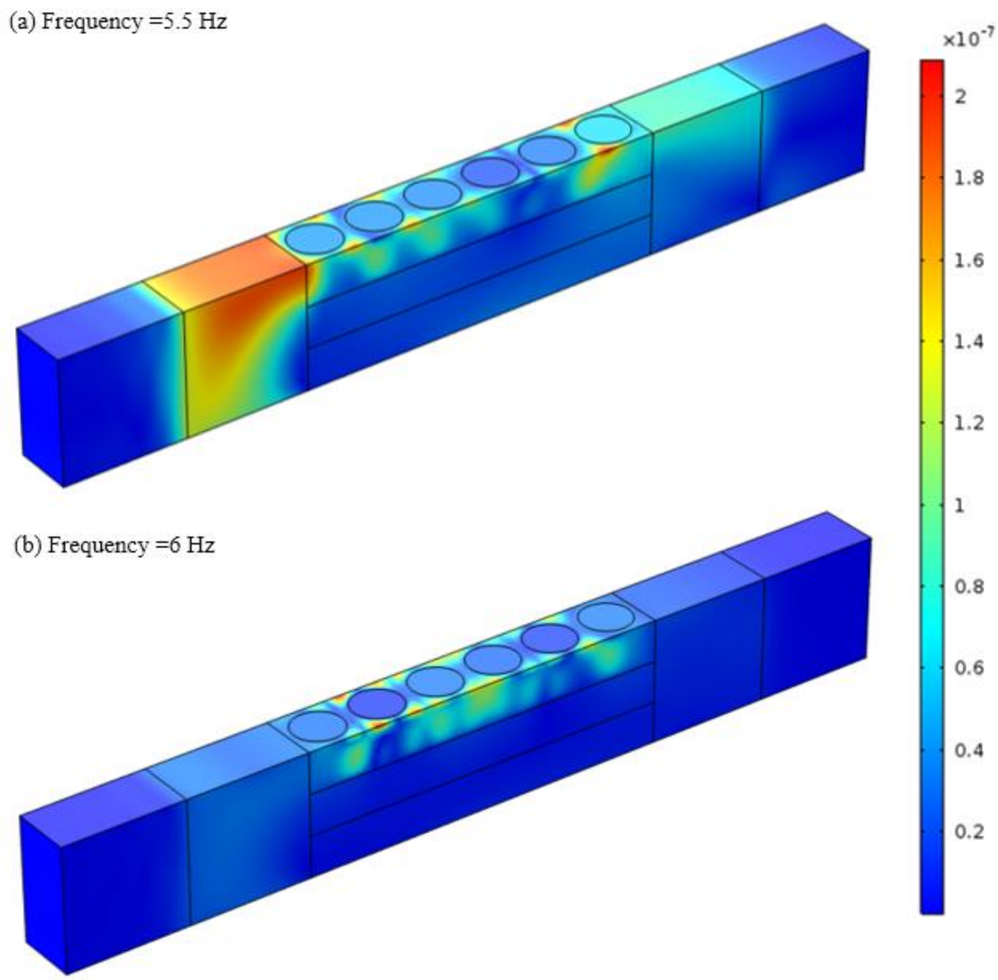

Figure 16. The simulated dynamic response of the seismic metamaterial at different frequencies. (a) Frequency f= 5.5 Hz and (b) frequency f=6 Hz. The color bar is displacement and unit is meter.

Simulated dispersion relations and transmission lines for an increased height of pile (h=12 m) are plotted in Figure 17 and 18. One can notice that for the homogeneous structure, there is one complete band gap. While for the layered structures, there are multiple partial band gaps can be observed. The dynamic responses plotted in Figure 19 indicate that the input wave energy is localized in the first layer of soil, similar to shallow piles. The localized wave energy can be dissipated by the viscoelastic property of soil.

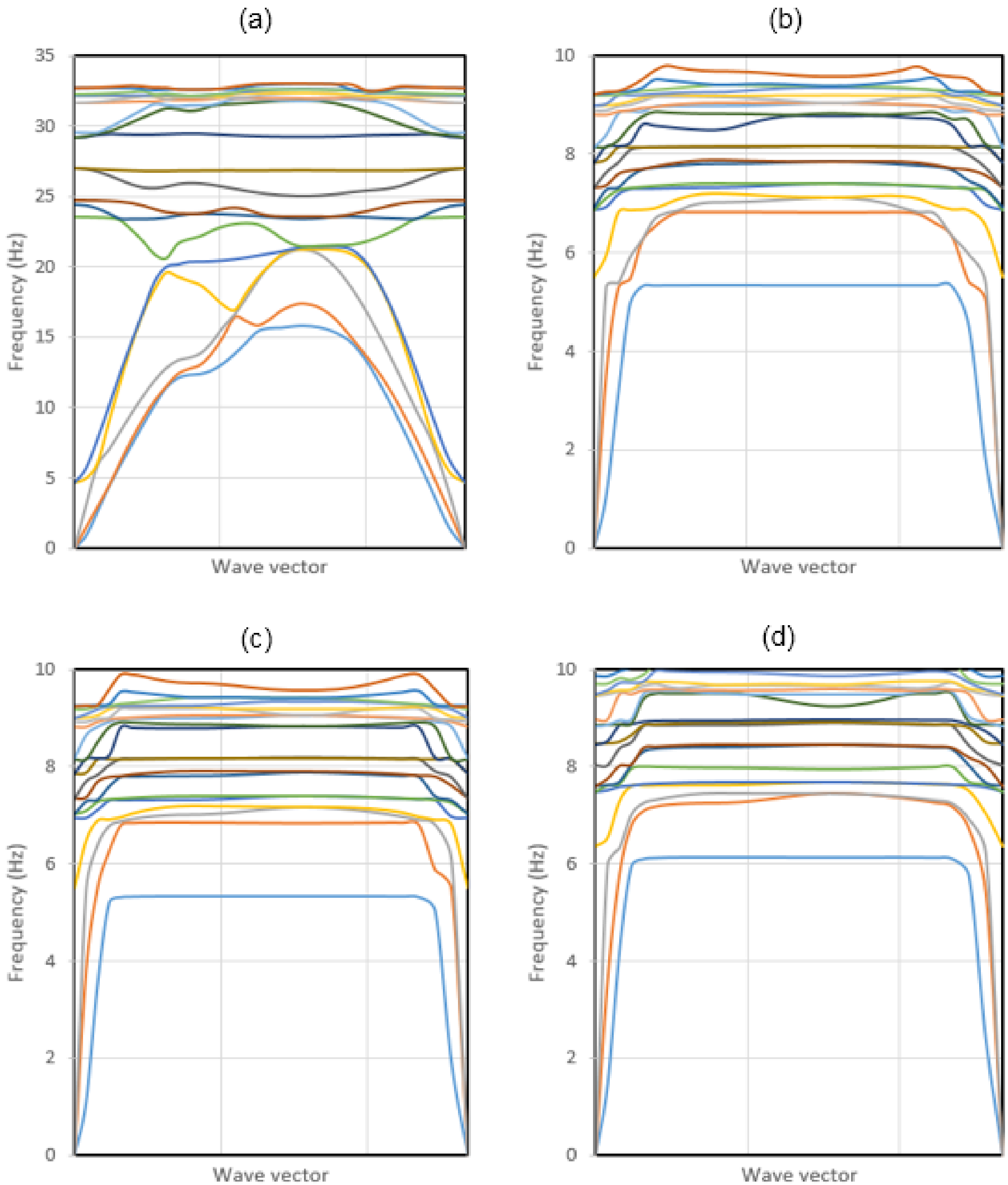

Figure 17. Phononic dispersion relations of (a) h=12, vf=0.5, homogeneous (b) h=12, vf=0.5, E1:E2:E3=1-10-100 (c) h=12, vf=0.5, E1:E2:E3=1-100-10 (d) h=12, vf=0.5, E1:E2:E3=10-1-100. Here h indicates the total height of the pile, vf indicates the volume fraction of the pile, and Ei is the Young's modulus of each layer.

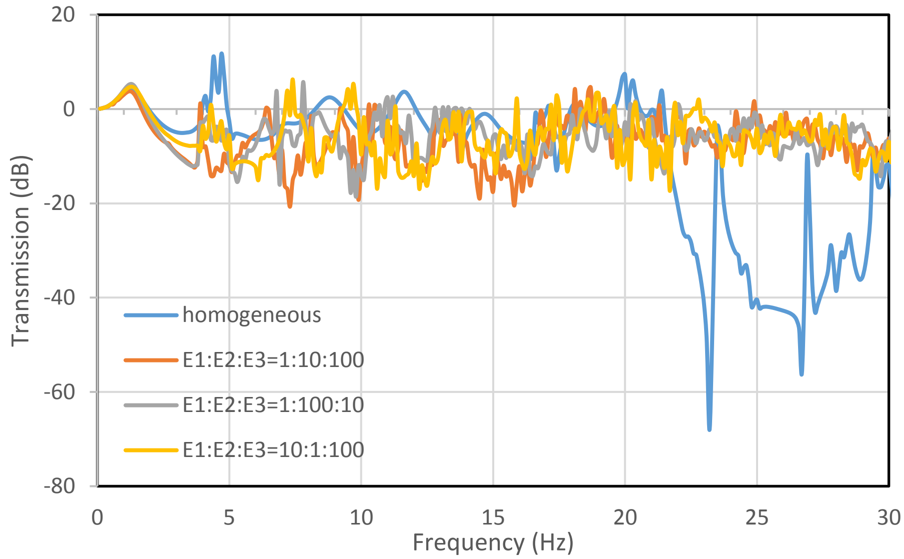

Figure 18. Transmission of seismic metamaterials with a height of 12 m.

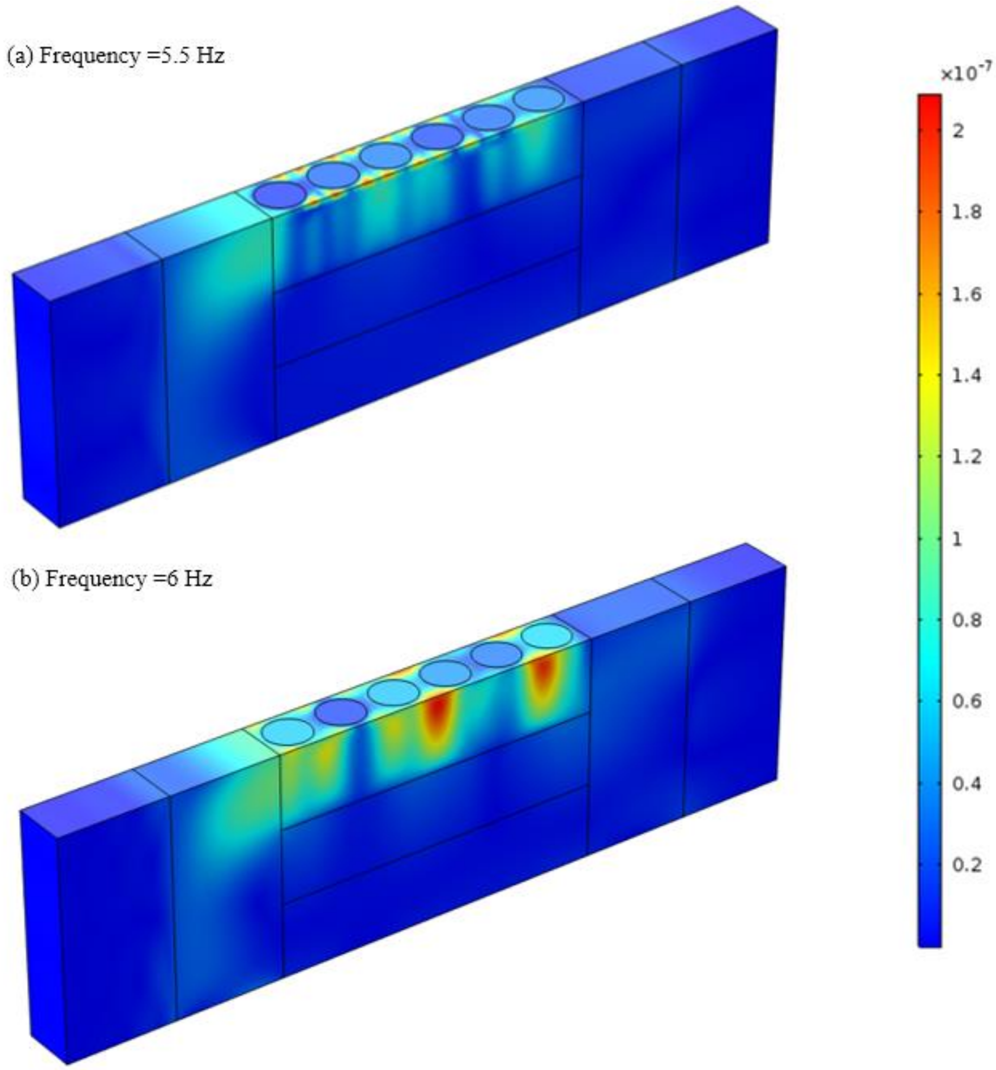

Figure 19. The simulated dynamic response of the seismic metamaterial at different frequencies. (a) Frequency f= 5.5 Hz and (b) frequency f=6 Hz. The color bar is displacement and unit is meter.

We further study the phononic dispersion relations of the seismic metamaterials with deep piles. Besides the obvious different heights, we consider the interaction between pile and bedrock. Specifically, we consider two cases: the pile was clamped by the bedrock and pile was free to move. The dispersion relations of these two cases are plotted in Figure 20. For the unclamped structure, no band gaps can be observed in the dispersion relation, indicating that pile height has a great impact on the emergence of band gaps and hence the vibration control property. Remarkably, for the clamped structure, there are two complete band gaps. One is a regular complete band gap that lies in a relatively high frequency range, while the other one is called cut-off band gap. This cut-off band gap is particularly useful for low frequency vibration control.

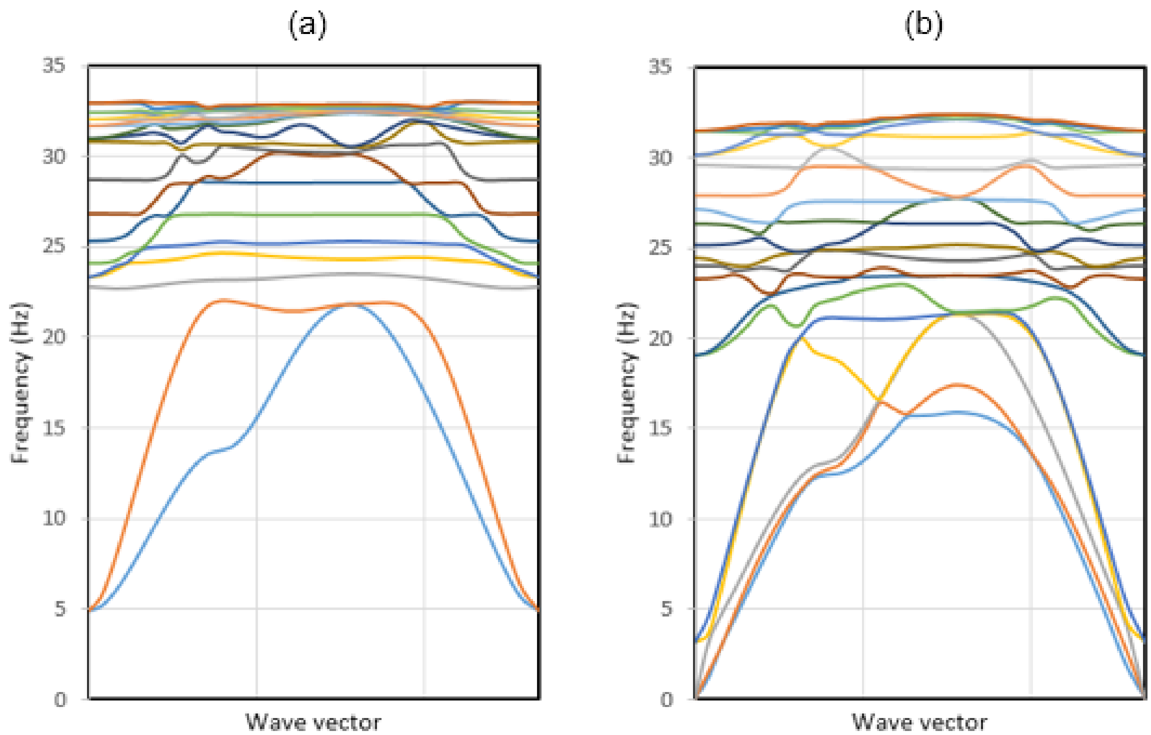

Figure 20. Phononic dispersion relations of (a) h=18, vf=0.5, homogeneous, clamped (b) h=18 vf=0.5, homogeneous, unclamped.

4. Conclusions

In summary, we have experimentally and numerically investigated the low frequency vibration control using rationally designed pile-soil seismic metamaterials. We observe that the periodic piles with square and triangular lattice symmetries have wide complete band gaps. While these wide complete band gaps have a strict requirement on the volume fraction of steel piles and dimensions of the structure, which may pose a great challenge for the potential applications. Our new proposed structures consisting of different layers of soil have low frequency band gaps, which can be used for transportation induced vibration or low frequency seismic waves. Besides the layered feature of the soil, we further harness the interplay between deep piles and bedrock to design structures for ultralow frequency vibration control. These results provide design guidelines for civil engineers to isolate undesired vibration.

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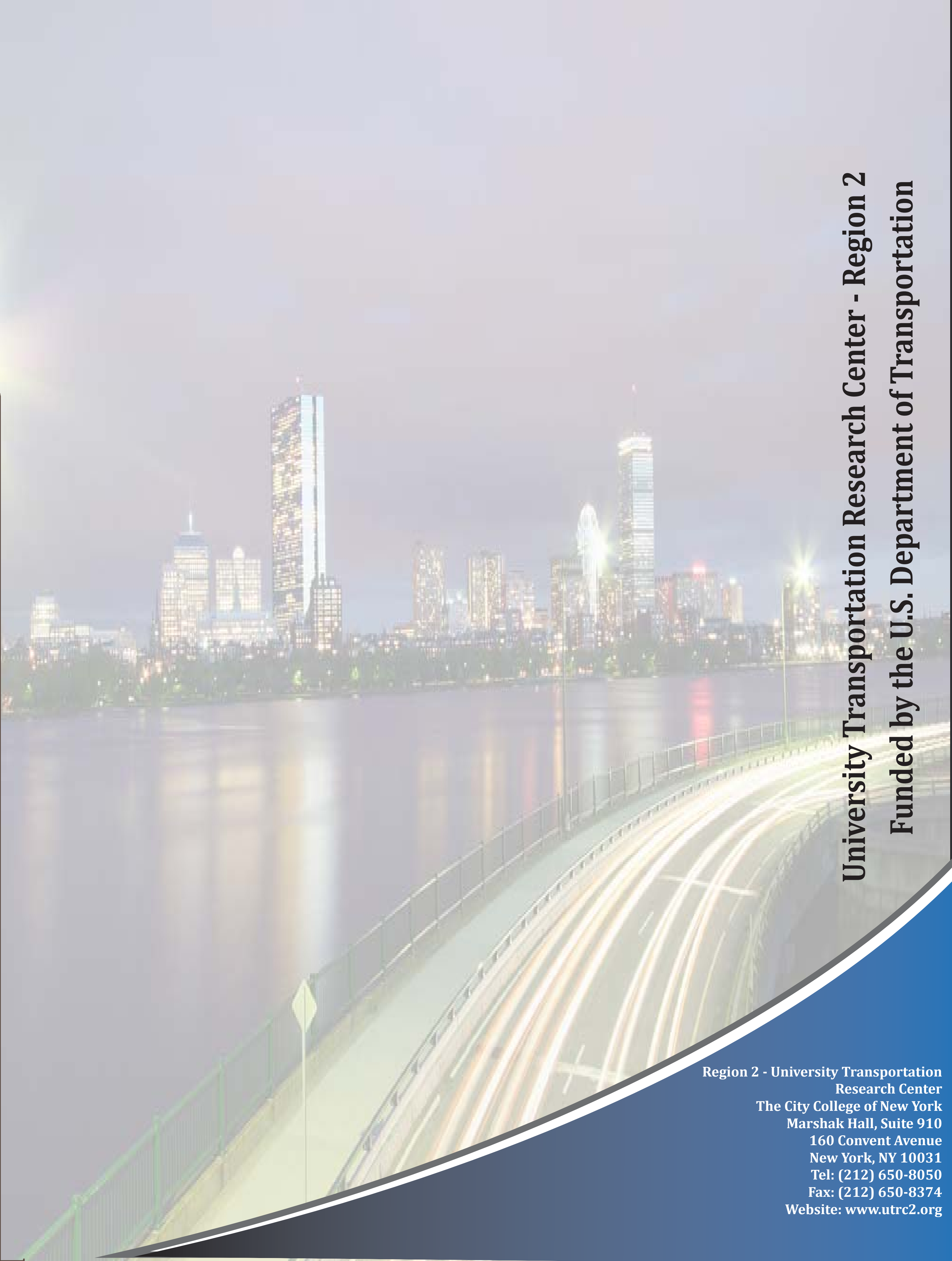

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