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MODELING OF SEISMIC WAVES THROUGH GEOLOGIC METAMATERIALS

ABSTRACT:

This project conducted a modeling study on seismic invisibility cloaks that render geologic targets invisible to seismic waves, using the concept of seismic metamaterials. We present a parametric numerical study on the behaviors of seismic waves through cloaks with different design parameters as well as degrees of geologic heterogeneity. In addition, a seismic cloaking strategy is proposed for a future field-scale experiment at a real-world test bed. This feasibility study will guide future field experiment designs and ultimately allow us to conduct systematic field-scale tests employing Sandia's existing resources and field expertise. The ultimate goal is to develop methods and design parameters of seismic invisibility cloaks to protect against natural and man-made seismic waves. Seismic cloaking has potential applications in several areas of national security, energy, and natural hazard reduction.

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INTRODUCTION AND EXECUTIVE SUMMARY OF RESULTS:

While temporal and spatial invisibility cloaks have been studied for electromagnetic and acoustic waves at small scales, the idea of developing seismic cloaks to manipulate seismic waves in a specific area at geophysical scales has recently attracted much attention and potentially offers a nontraditional solution for earthquake protection [1]. The desired effects on seismic waves can be produced by using modified geologic media as seismic metamaterials such as reflection (Bragg's effect), band-gaps, wave-path control, attenuation by energy-dissipation, among others [2]. Theoretically, seismic cloaking can be achieved by modifying the constitutive properties of the geologic medium in a purposeful way such that the resulting medium acts as a seismic metamaterial with unique wave manipulation properties. In the context of seismic waves, "invisibility" refers to shielding, attenuating, absorbing or modifying seismic signals in a specific volume. Due to the difficulty of constructing real-size seismic metamaterials, previously studied cloaking designs were limited to scaled laboratory experiments and validated via numerical simulations. Except for a few proof-of-concept experiments, there is a paucity of realistically scaled field experiments to validate the method and understand the required design criteria for useful seismic metamaterial designs. A target-specific design strategy for seismic cloaks can be potentially developed by conducting field experiments where the cloaking design parameters can be systematically tested.

Seismic cloaking studies can be grouped in three categories: seismic metamaterials, above-surface resonators, and buried mass resonators [2]. Note that the study of seismic metamaterials is a rapidly growing field, with interest to a wide scientific community (civil and earthquake engineers, physicists, nanotechnology and metamaterial engineers, geophysicists, etc.) with scales ranging from nanometers to kilometers. For our work, however, we will focus on geophysical mesoscales (10s to 100s of m).

The first field-scale experiments of seismic cloaking were conducted in 2012 [3–4]. The two experiments used structured soft soil pierced by an array of cylindrical, air-filled vertical holes. This combination of soil and air-filled cylinders was the seismic metamaterial. The experimental setups consisted of a regular grid (15.57 m x 3.46 m) of 30 holes (0.32 m in diameter, 5 m in depth, grid spacing 1.73 m) and a grid (20 m x 40 m) of 23 holes (2 m in diameter, 5 m in depth, triangular grid spacing 7.07 m), respectively. The seismic waves were generated by 1) a monochromatic vibrocompaction probe (50 Hz, fixed) and 2) a weight drop of a 17 ton mass from a height of 12 m. To map the seismic energy's field, they use three-component velocimeters (deployment of ~20-30). Their results show a ~3-5 dB attenuation in seismic ground motion at the ground surface behind the array of boreholes and also demonstrated the shielding effect and the lensing of seismic surface waves.

For above-surface seismic cloaking, researchers have suggested forests of trees or steel towers that would interact with a passing seismic wavefield, acting as surface resonators [5 – 7]. Such a structure would serve as an alternative to boreholes or rigid inclusions. To test this idea, an experiment was conducted at the interface between an open field and a forest of pine trees where the seismic wavefield was recorded in a 120 x 120 m^2 area by using a dense seismic array made up of ~1000 geophones. The results indicated a strong attenuation of the Rayleigh wave when interacting with the forest over two large frequency bands. On the other hand, the attenuation occurred at frequencies higher than those required for seismic protection and the possible reflection of an incoming wave by the forest implies some risks due to sensitivity to the direction of both incoming waves and the relative location of target area [2]. Nonetheless, seismic cloaking via forests has potential for attenuation of man-made ground vibrations (i.e. traffic). Another proposed above-surface cloaking strategy is to use collections of buildings as resonators; in other words, to design cities as a giant seismic cloak [8–9]. A numerical study showed that when the buildings with different heights are strategically placed in the city, they can scatter most of the incoming seismic energy at low frequencies but act as a shield at higher frequencies which makes the design risky for nearby structures.

Prior to seismic cloaking, the concept of seismic barriers that use vertical trenches to block seismic wave propagation was proposed as early as the 1960s [10]; however, both the excessive depths of trench wall and the risk of resonance makes this concept impractical to reduce seismic ground motion. A recent study modified the two-vertical trench design and proposes a V-shaped seismic muffler that uses opposed sloping boreholes to reduce the seismic ground motion from an earthquake [11]. They tested the efficiency of their design via numerical modeling and a bench-scale (< 1 m^3) model, and found that seismic muffler walls formed by continuous air-filled trenches can significantly reduce the amplitude of seismic waves for the target area. In addition, there are other approaches to address dissipation of seismic ground motion such as localized resonators (i.e., buried tuned-mass dampers [12]), mass-in-mass lattices [13–14] and other absorbers [15–17]. These approaches use different sizes of resonators for each frequency band, imposing practical challenges for broadband protection.

In this work, to guide future field experiments and better understand the physics of metamaterials at geophysical scales, we conduct a parametric analysis on the behaviors of seismic waves through cloaks with variable design parameters and degrees of geologic heterogeneity. Further, we propose an experiment designed to demonstrate the wave suppression via seismic cloaking considering a real-world test bed.

DETAILED DESCRIPTION OF RESEARCH AND DEVELOPMENT AND METHODOLOGY:

In this study, we examine the effects of seismic cloaking designs and geologic heterogeneity on the performance of seismic cloaking by evaluating the spectral characteristics of seismic wavefields in geologic media with and without cloaks. Particularly, we consider seismic metamaterials as modified geologic media via a grid of borehole implantations, as well as above-surface resonators as a grid of trees.

We start by evaluating the efficiency of various geometric properties of the seismic metamaterial design on the wave suppression, such as the grid density, length, width and spacing of air-filled boreholes. Moreover, boreholes with different fill materials such as water, concrete and steel, are tested to increase the performance of seismic cloaking. The role of geologic heterogeneity is also investigated via stochastic seismic velocity models with different degrees of geologic roughness. In addition to the seismic metamaterials, we also present the bandgap characteristics of the above-surface resonators. Finally, we consider a real test site to develop an optimized cloaking design for a future field experiment.

Effects of Seismic Metamaterial Designs

Seismic waves in geologic metamaterials are simulated using a massively-parallel, in-house wave simulation code that solves the three-dimensional elastic wave equation using a finite difference scheme. Here, we consider seismic wave propagation at mesoscales. The numerical models are characterized as a homogeneous medium with a size of $120 \times 120 \times 50$ m. The computational domain is discretized as a uniform grid with a cell size of 0.15 m. Boreholes are represented as long square blocks. The shear velocity (v_s) of the homogeneous half space is set to 500 m/s and a compressional velocity (v_p) of ~866 m/s, which represents a sedimentary basin. The density (ρ) of the half space is 1513 kg/m^3. For seismic hazard reduction, the suppression of surface Rayleigh waves is one of the main concerns. Here, we assume that the Rayleigh wavespeed is nearly equal to v_s. A vertical seismic source at 50 Hz is generated by using a Ricker source time function. The source with a unit amplitude is positioned at (20 m, 60 m, 0 m) and placed 30 m away from the borehole grid that is centered at $x = 20$ m (Figure 1). The seismic wave fields are simulated for a 0.5 s time window.

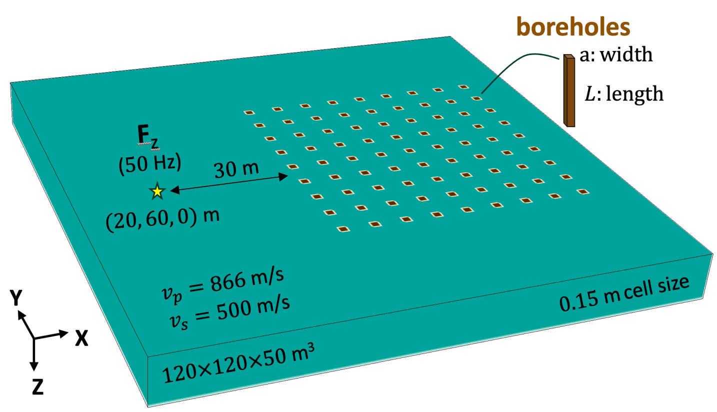

Figure 1. Computational model of the geologic medium with seismic metamaterials.

Spatial Density of Boreholes

We examine the behaviors of seismic waves through borehole grids with different spatial densities. First, we consider a regular 9×9 grid of boreholes with 1.5 m interspacing as seismic metamaterial (Figure 1). The width and length of the boreholes of the grid are 30 cm and 10 m, respectively. The sparse grid is constructed by simply eliminating every other borehole in the regular grid (Figure 2). Considering the characteristic seismic wavelengths (λ) that seismic engineering applications desire to control (1 to 50 Hz, [5]), the width of the boreholes is not ideal if we use the rule of thumb for the sub-wavelength scale that a metamaterial can be effective for controlling waves ($\sim\lambda/2$ to $\lambda/15$). However, we herein solely focus on the effect of the grid density for this experiment and will evaluate the impact of the borehole width for various wavelengths in detail next in our analyses.

Our results indicate that the patterns of the vertical particle velocity fields at the surface as a result of filtering through two different spatial densities of the borehole grid are distinct. Moreover, while the vertical displacements at an observation point at (100 m, 60.8 m, 0 m) do not show any visible differences, the spectral ratios of the vertical displacements (the cloaked case over the uncloaked case) along a radial profile in the x-direction indicate that the regular borehole grid results in wave suppression at a bandgap around 120 Hz. On the other hand, the sparse grid results in the same bandgap but with much less suppression.

Borehole width

The effects of the borehole width are examined by considering the sparse grid with 30, 60, 120 cm borehole width. The other parameters are kept the same as in the previous model. Figure 3a shows major differences in the pattern of the seismic wave fields. In addition, for this metamaterial design, an increased amplitude of the incoming wave is also visible at the observation point at 100 m away from the source location (Figure 3b). The spectral ratios indicate a dramatic improvement on the performance of seismic cloaking at both lower and higher frequencies (~ 100 to $150\ Hz$) by increasing the borehole width (Figure 3c).

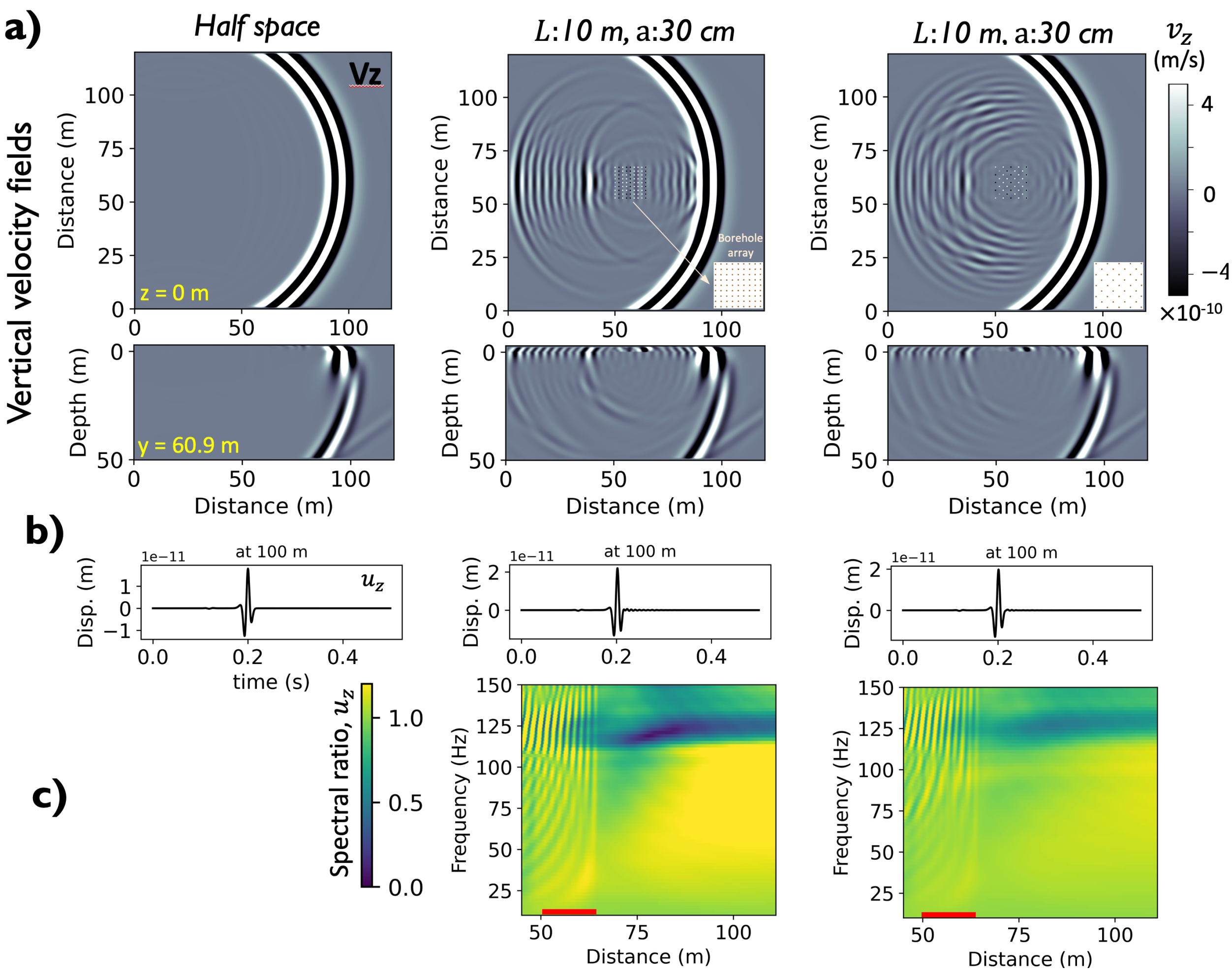

Figure 2. a) Vertical component of the surface velocity fields at 0.19 s. The inset map indicates the borehole grid. b) Vertical component of the displacement at the surface (100 m away from the source), c) Spectral ratios of the vertical displacement before and after cloaking along a radial profile at y = 60.9 m. The red line indicates the position of the borehole grid. The columns indicate the results of the half space, dense and sparse borehole grids, respectively.

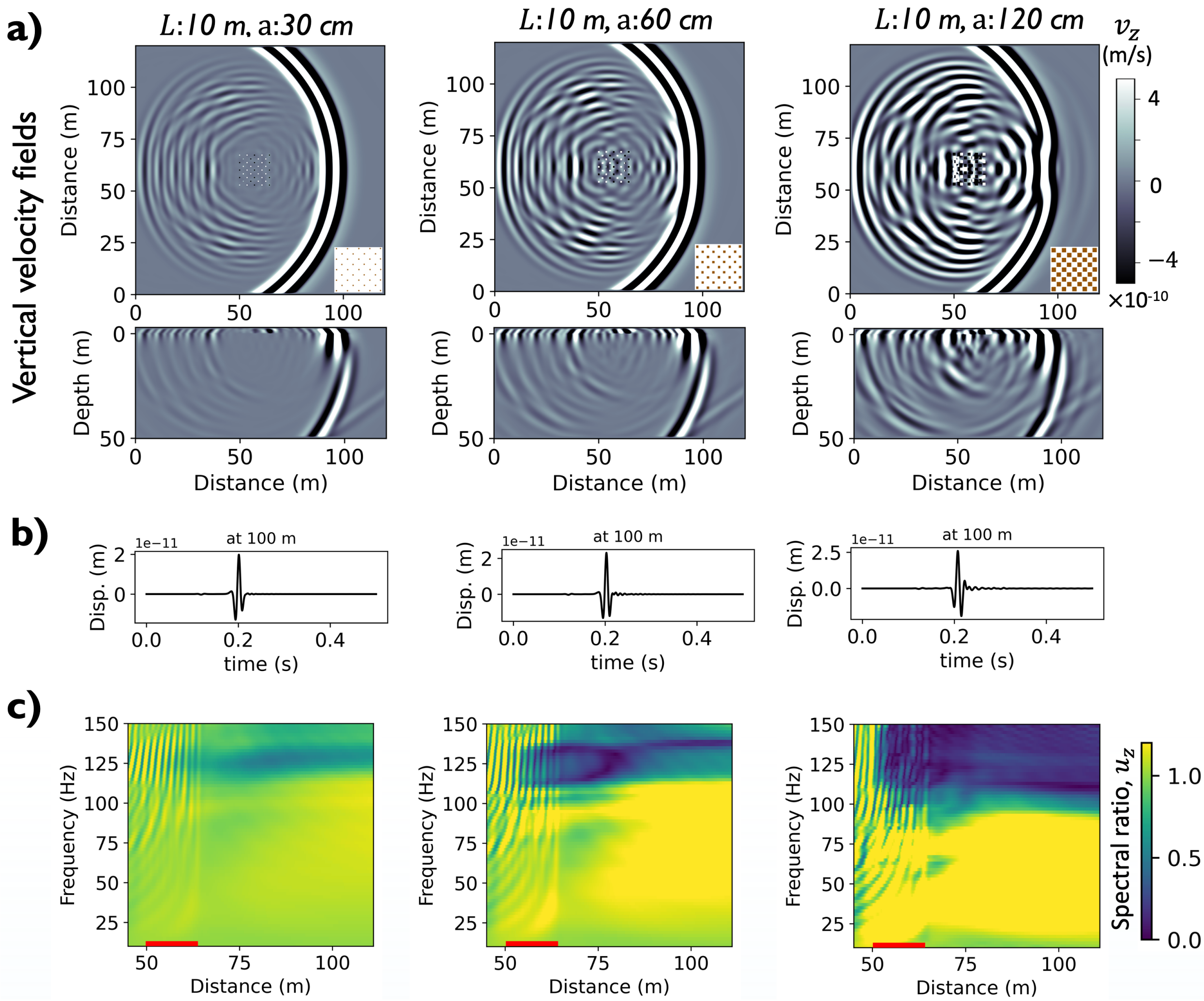

Figure 3. a) Vertical component of the surface velocity fields at 0.19 s. The inset map indicates the borehole grid. b) Vertical component of the displacement at the surface (100 m away from the source), c) Spectral ratios of the vertical displacement before and after cloaking along a radial profile at y = 60.9 m. The red line indicates the position of the borehole grid. The columns indicate the sparse borehole grids with 30, 60, 120 cm borehole widths, respectively.

Borehole length

We investigate the effects of the borehole length by considering the sparse grid with 3, 10, 20 m borehole lengths (Figure 4a). The width of the boreholes is 120 cm ($\sim\lambda/8$) while the other parameters are the same as used in the baseline case. It is evident that increasing borehole length results in both extending the bandgap and increasing wave suppression. Moreover, in the case of relatively small borehole width of 30 cm ($\sim\lambda/33$) in the regular grid, increasing borehole length does not have any impact on the performance of the seismic cloaking (Figure 4b).

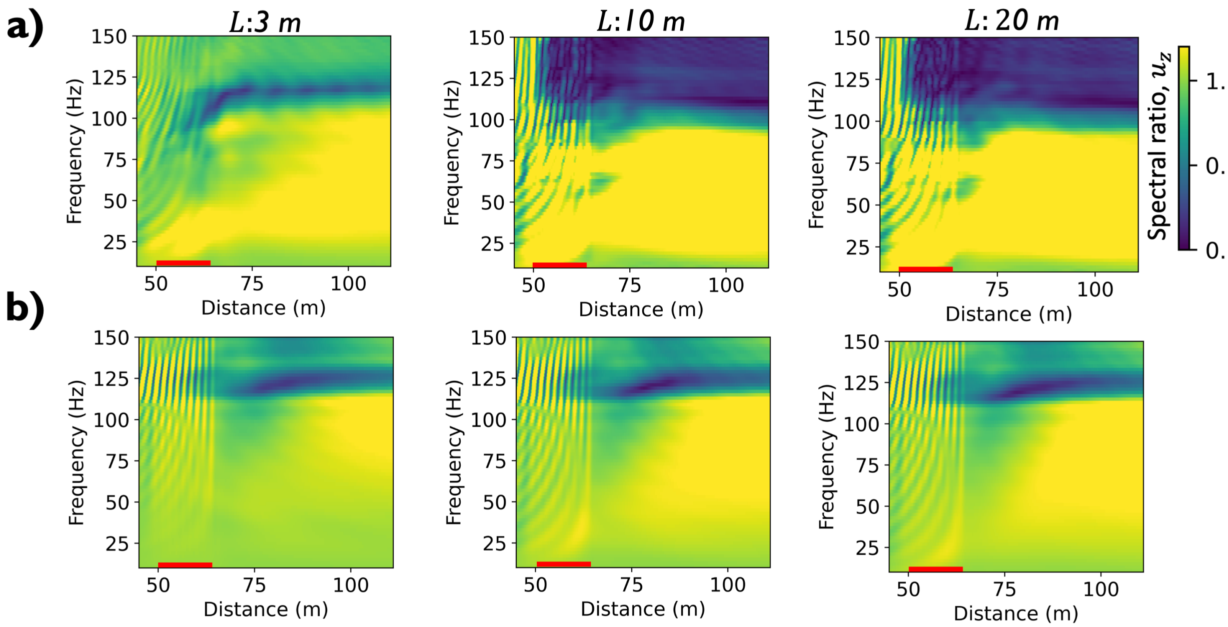

Figure 4. Spectral ratios of the vertical displacement before and after cloaking along a radial profile at y = 60.9 m for a) a sparse grid with 120 cm borehole width and b) a dense grid with 30 cm borehole width. The red line indicates the position of the borehole grid. The columns indicate the borehole grids with 3, 10, 20 m borehole lengths, respectively.

Borehole spacing

To analyze the impact of borehole spacing in a seismic metamaterial on the interacting seismic wavefield, we construct borehole grids with increasing borehole spacing and width. Particularly, we consider the spacing and width as a function of the wavelength of the seismic source (5 m). The borehole grids are centered at (y = 60 m) and are positioned 30 m away from the source. (Figure 5). We consider 120 cm ($\sim\lambda/8$) and 240 m ($\sim\lambda/4$) for both the borehole width and spacing, respectively.

The velocity fields at the surface indicate that both increasing the borehole spacing and width result in stronger shielding and filtering of the incoming waves (Figure 5). The vertical displacements at 100 m away from the source show that the strongest suppression can be achieved by using $\sim\lambda/4$ for both borehole spacing and width (Figure 5d). Moreover, the spectral ratios before and after the borehole grid implantation indicate that equal spacing and width of $\sim\lambda/8$ result in a bandgap effective down to ~75 Hz while the boreholes with $\sim\lambda/4$ width and spacing can suppress frequencies as low as ~35 Hz (Figure 6). Further, it can be also seen that the borehole grid with $\sim\lambda/8$ width and $\sim\lambda/4$ spacing can perform in the same bandgap almost as effectively as the grid with $\sim\lambda/4$ width and $\sim\lambda/8$ spacing (Figure 6b and 6c).

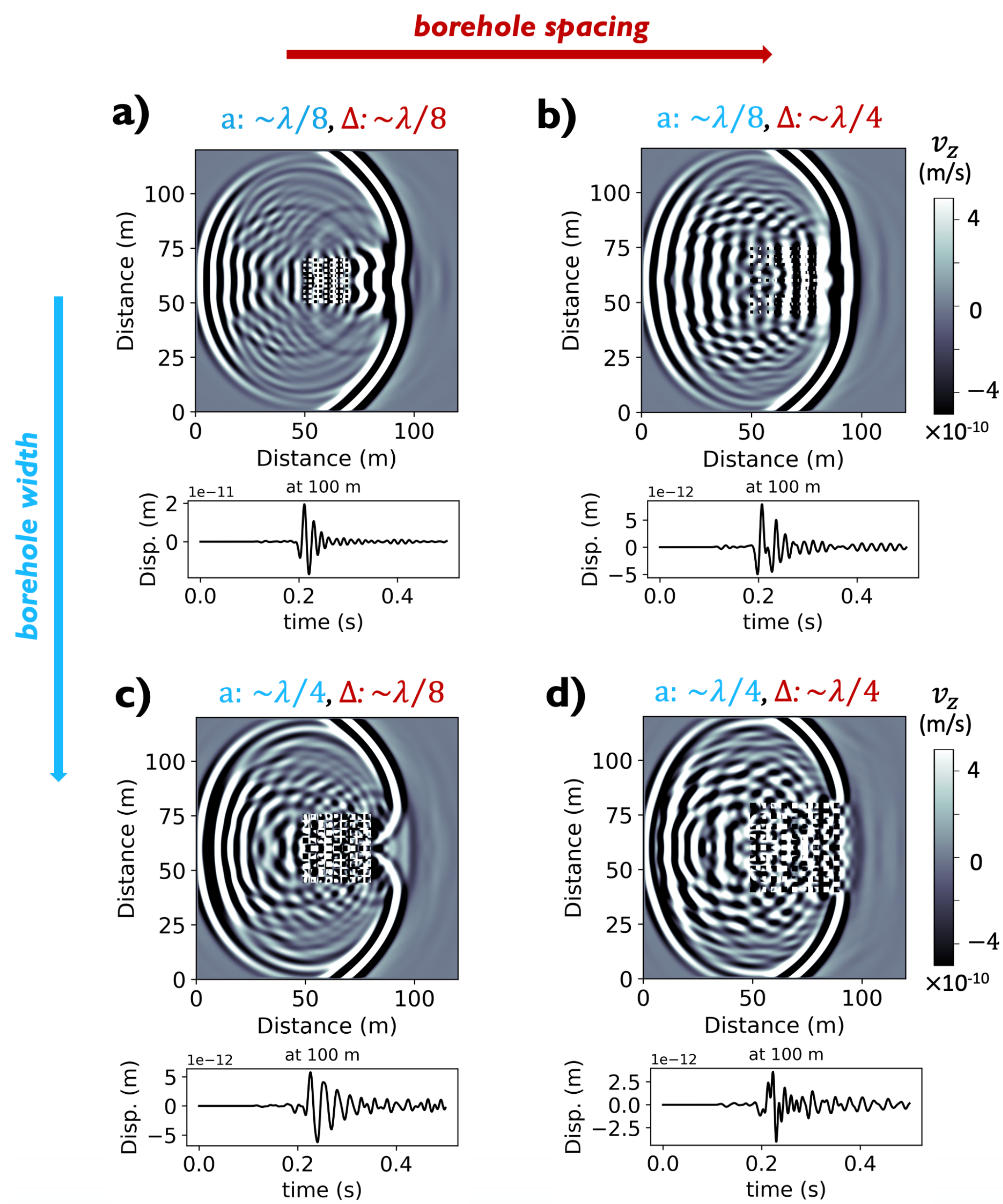

Figure 5. a) Vertical component of the surface velocity fields at 0.19 s and the vertical component of the displacement at the surface (100 m away from the source) for a borehole grid with a) $\sim\lambda/8$

width and $\sim\lambda/8$ spacing, b) $\sim\lambda/8$ width and $\sim\lambda/4$ spacing, c) $\sim\lambda/4$ width and $\sim\lambda/8$ spacing, and d) $\sim\lambda/4$ width and $\sim\lambda/4$ spacing.

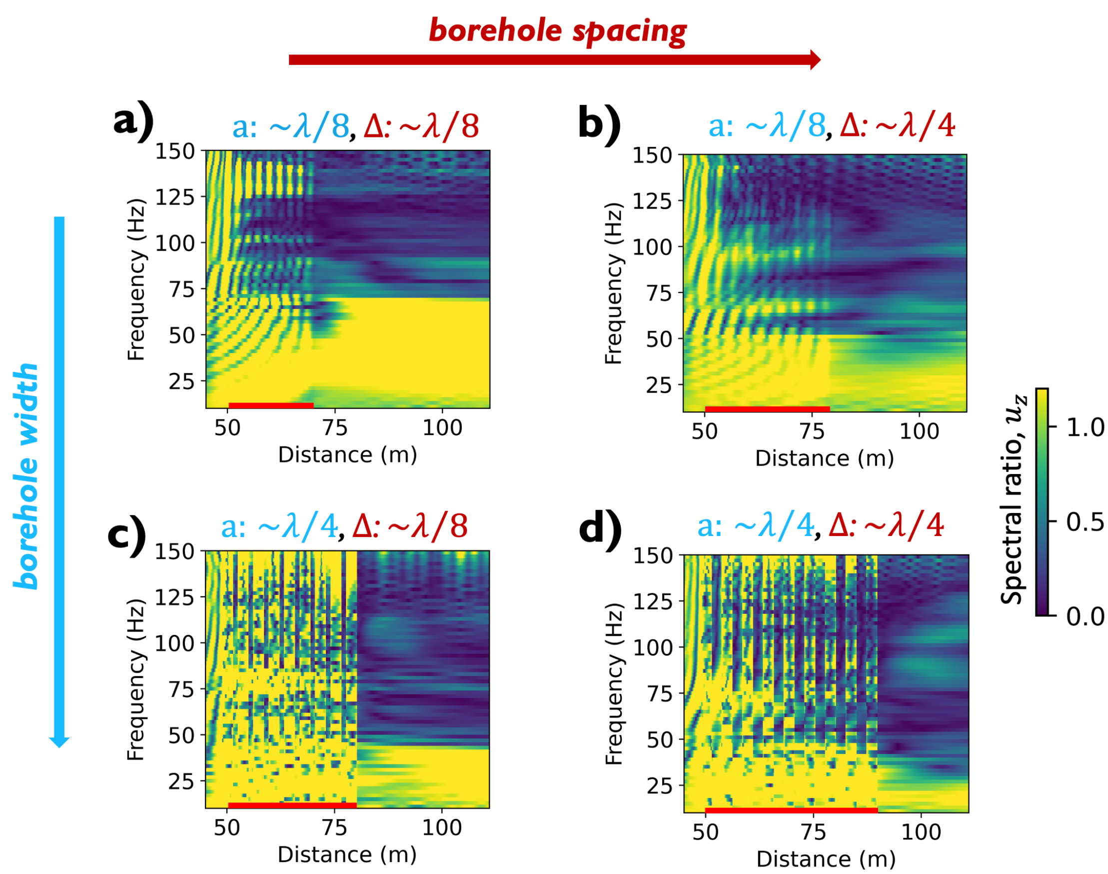

Figure 6. Spectral ratios of the vertical displacement before and after cloaking along a radial profile at y = 60.9 m for a borehole grid with a) $\sim\lambda/8$ width and $\sim\lambda/8$ spacing, b) $\sim\lambda/8$ width and $\sim\lambda/4$ spacing, c) $\sim\lambda/4$ width and $\sim\lambda/8$ spacing, and d) $\sim\lambda/4$ width and $\sim\lambda/4$ spacing. The red line indicates the position of the borehole grid.

Filled Boreholes

We evaluate whether other filling materials for boreholes can improve the efficiency of seismic cloaking. For this comparison, we choose various materials including water, concrete, and steel, whose properties are shown in Table 1.

	v_p (m/s)	v_s (m/s)	ρ (kg/m³)
air	350	0	1.2
water	1450	0	1000
concrete	4500	2267	2300
steel	5856	3130	7850

Table 1. Acoustic properties of the materials that are considered to fill the boreholes.

By considering the regular grid of boreholes with a width of 30 cm and a length of 10 m, the spectral differences in seismic waves due to the interaction with the seismic metamaterials are presented in Figure 7. The water-filled borehole grid results in multiple narrow bandgaps that appear to repeat with an almost fixed interval differing from the air-filled boreholes that are effective at a single bandgap around 120 Hz (Figure 2c). On the other hand, the concrete borehole grid can control almost the entire frequency range with a relatively low degree of suppression. Last, steel boreholes can attenuate incoming waves more effectively compared to water and concrete.

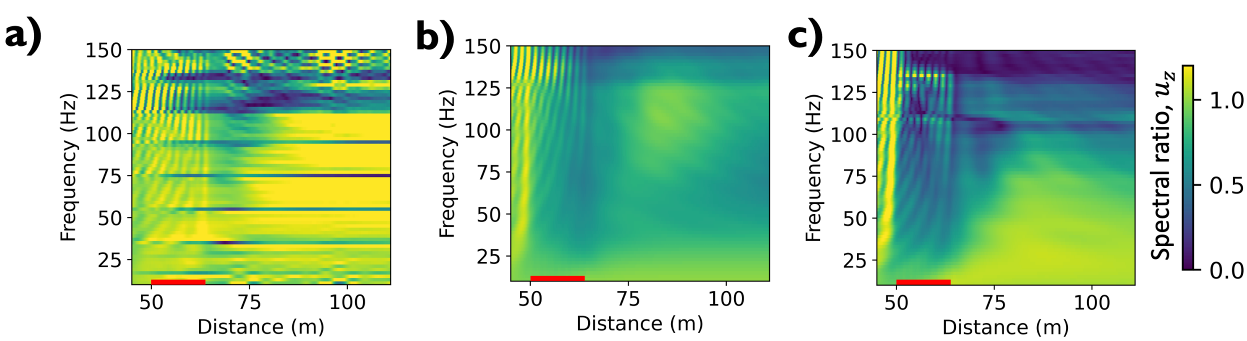

Figure 7. Spectral ratios of the vertical displacement before and after cloaking along a radial profile at y = 60.9 m for a borehole grid filled with a) water, b) concrete, c) steel. The red line indicates the position of the borehole grid.

Effects of Geologic Heterogeneity

To investigate the impact of the velocity variations in the host medium on the behavior of the seismic waves travelling through seismic cloaks, we consider stochastic velocity models with different levels of geologic roughness. The stochastic models are generated by adding 5% perturbations to a shear velocity of 500 m/s in each direction (Figure 8). We consider 25, 50 and 100 m correlation lengths to mimic decreasing geologic roughness.

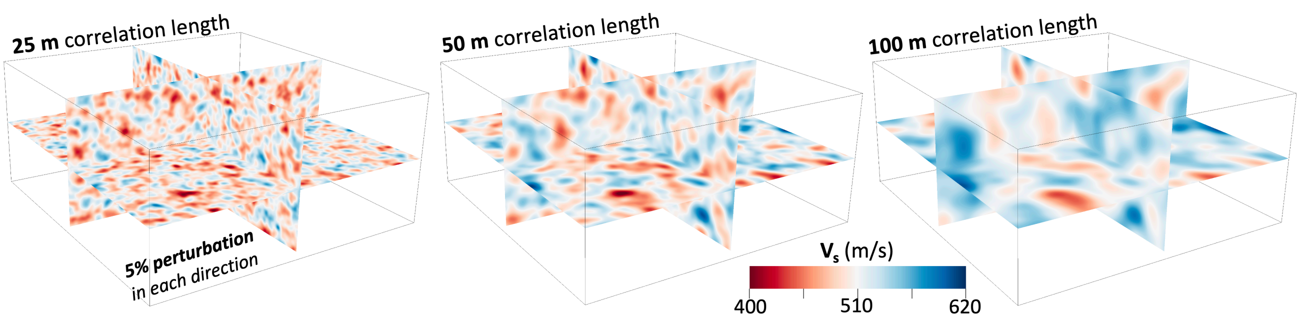

Figure 8. Stochastic seismic velocity models.

Figure 9a shows that the vertical velocity fields are strongly controlled by the heterogeneity of the host medium compared to those above a half space (Figure 2a). The spectral ratios of the vertical displacements before and after the borehole grid installation indicate major differences between the three stochastic models regarding the performance of the seismic cloak, such that the geologic heterogeneity not only has an impact on the bandgap in which seismic waves can be attenuated but also on the level of wave suppression (Figure 9c). The smoothest velocity model results in lower wave suppression over a wider range of frequencies along the radial distances behind the borehole grid whereas a more isolated bandgap with a higher amount of suppression is achieved in the case of the roughest velocity model. All cases indicate distinct spectral characteristics regarding the performance of the seismic cloaking, suggesting that the velocity model of the region of interest must be well known when designing seismic cloaks.

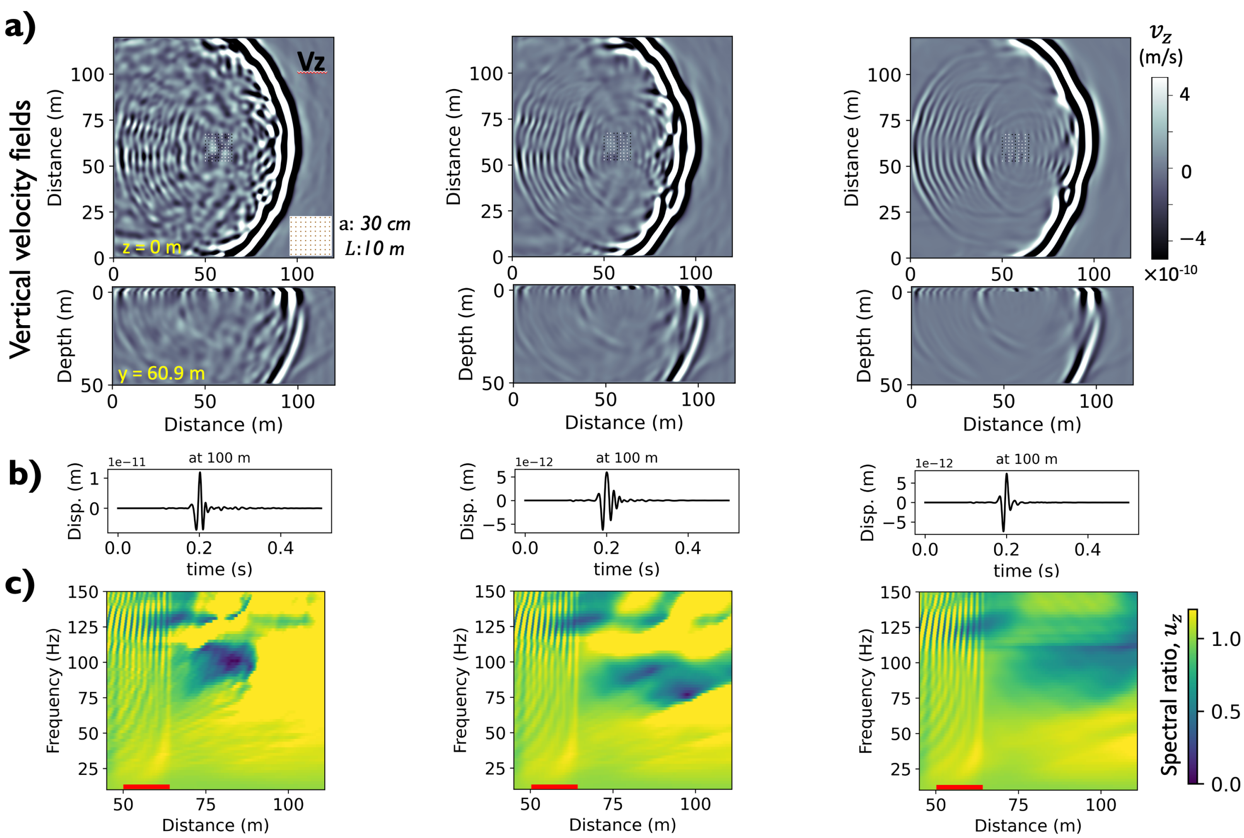

Figure 9. a) Vertical component of the surface velocity fields at 0.19 s. The inset map indicates the borehole grid. b) Vertical component of the displacement at the surface (100 m away from the source), c) Spectral ratios of the vertical displacement before and after cloaking along a radial profile at y = 60.9 m. The red line indicates the position of the borehole grid. The boreholes have a width of 30 cm and a length of 10 m The columns indicate the borehole grids with 30 cm. The columns indicate the results of the stochastic velocity models with 25, 50 and 100 m correlation lengths, respectively.

Above-surface Resonators

In addition to seismic metamaterials, we extend our analysis to above-surface resonators. For a fair comparison, we consider the previously-used dense and sparse grids (Figure 10) with trees to mimic natural above-surface resonators. The trees are represented as simple rods attached to the surface and their roots are neglected in our simulations. The v_p v_s and ρ are 2200 m/s, 1200 m/s and 450 kg/m^3, respectively.

Tree diameter and grid density

Figure 10 shows that the above-surface resonators result in multiple narrow bandgaps at as low as 50 Hz that are not regularly separated in frequency. The spectral ratios of the dense and sparse grid suggest that the grid density improves the efficiency of the wave suppression but does not change the bandgaps. Moreover, larger tree diameter extends the bandgaps and suppress the waves more strongly.

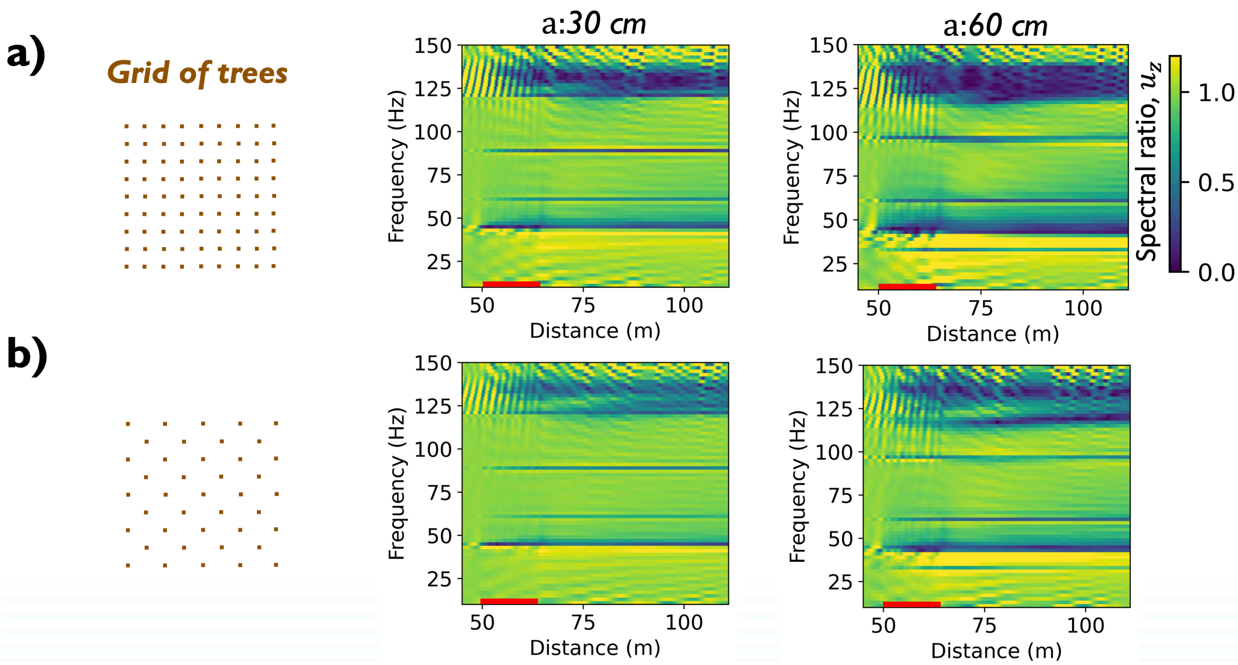

Figure 10. Spectral ratios of the vertical displacement before and after cloaking along a radial profile at y = 60.9 m for a) a dense and b) a sparse grid of trees with diameters of 30 and 60 cm, respectively. The length of the trees is 10 m. The red line indicates the position of the grid of trees.

Tree length

Considering the dense grid of trees, we compare the performance of the above-surface resonators with tree lengths of 3, 10 and 20 m. Figure 11 shows that taller trees increase the number of the bandgaps and result in wave suppression at lower frequencies. In addition, shorter trees can perform more effectively at higher frequencies with larger bandgaps.

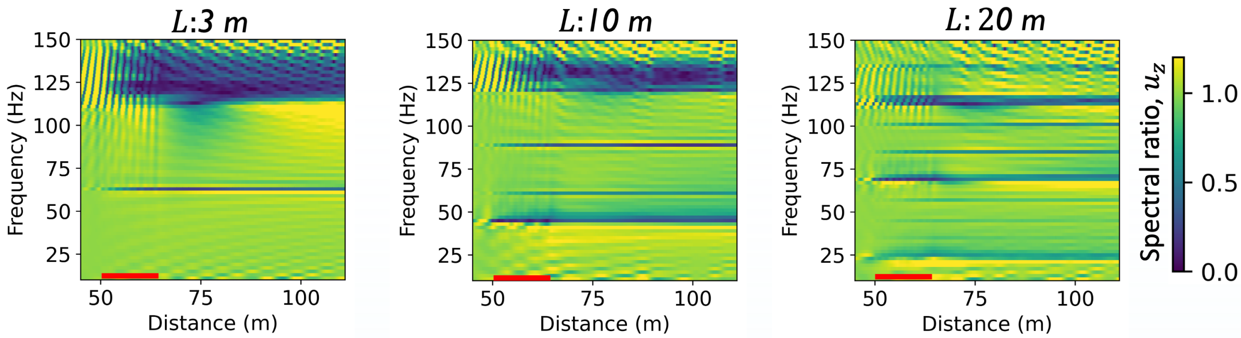

Figure 11. Spectral ratios of the vertical displacement before and after cloaking along a radial profile at y = 60.9 m for a dense grid of trees with lengths of 3, 10 and 20 m, respectively. The tree diameter is 30 cm. The red line indicates the position of the grid of trees.

A real-world experiment design – FACT site

Finally, we focus on designing a seismic cloak for future field testing by considering a real test bed. The Sandia Geophysics Department has a test bed 'the Facility for Acceptance, Calibration and Testing' (FACT) that can potentially be used to conduct future field experiments, to observe the changes in seismic wave propagation (scattering, shielding, etc.) due to seismic cloaks in a real-world geologic environment and systematically test the effect of each parameter in the cloaking design on the resulting wave fields. The velocity structure of the FACT site has previously been characterized by an internal seismic study. For our analysis, we consider two characteristic 1D shear velocity models of the site (Figure 12).

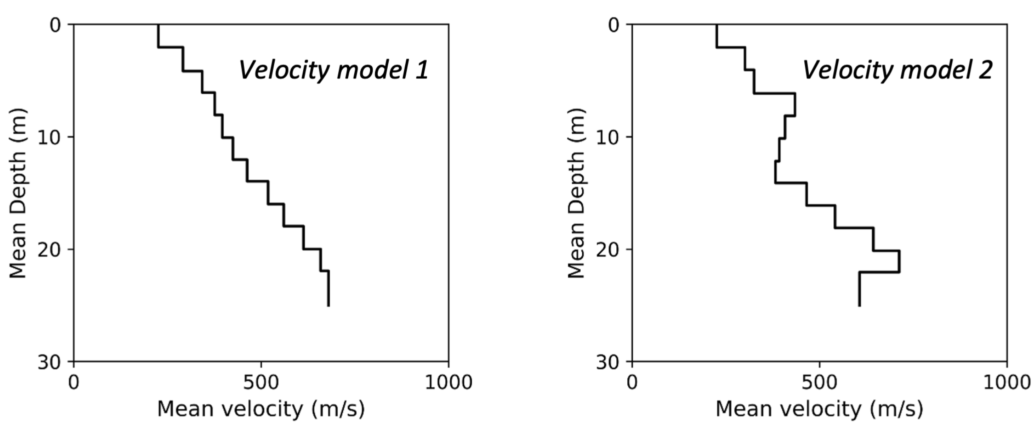

Figure 12. Two characteristic 1D shear velocity models of the FACT site.

Considering the restrictions on the size of the borehole implantations in the FACT site and the cost, we envisioned a 4 × 9 borehole grid as seismic metamaterials. The borehole width and length are 0.30 cm and 3 m, respectively. The source properties and the borehole grid position are the same as used in the previous models. In addition to the shear velocity models of the FACT site, we also construct two stochastic models with correlation lengths of 25 m and 100 m as previously described in the analysis of the geologic heterogeneity. The bounds of velocities are kept limited for stochastic models so that the same cell size can be used for the computational mesh.

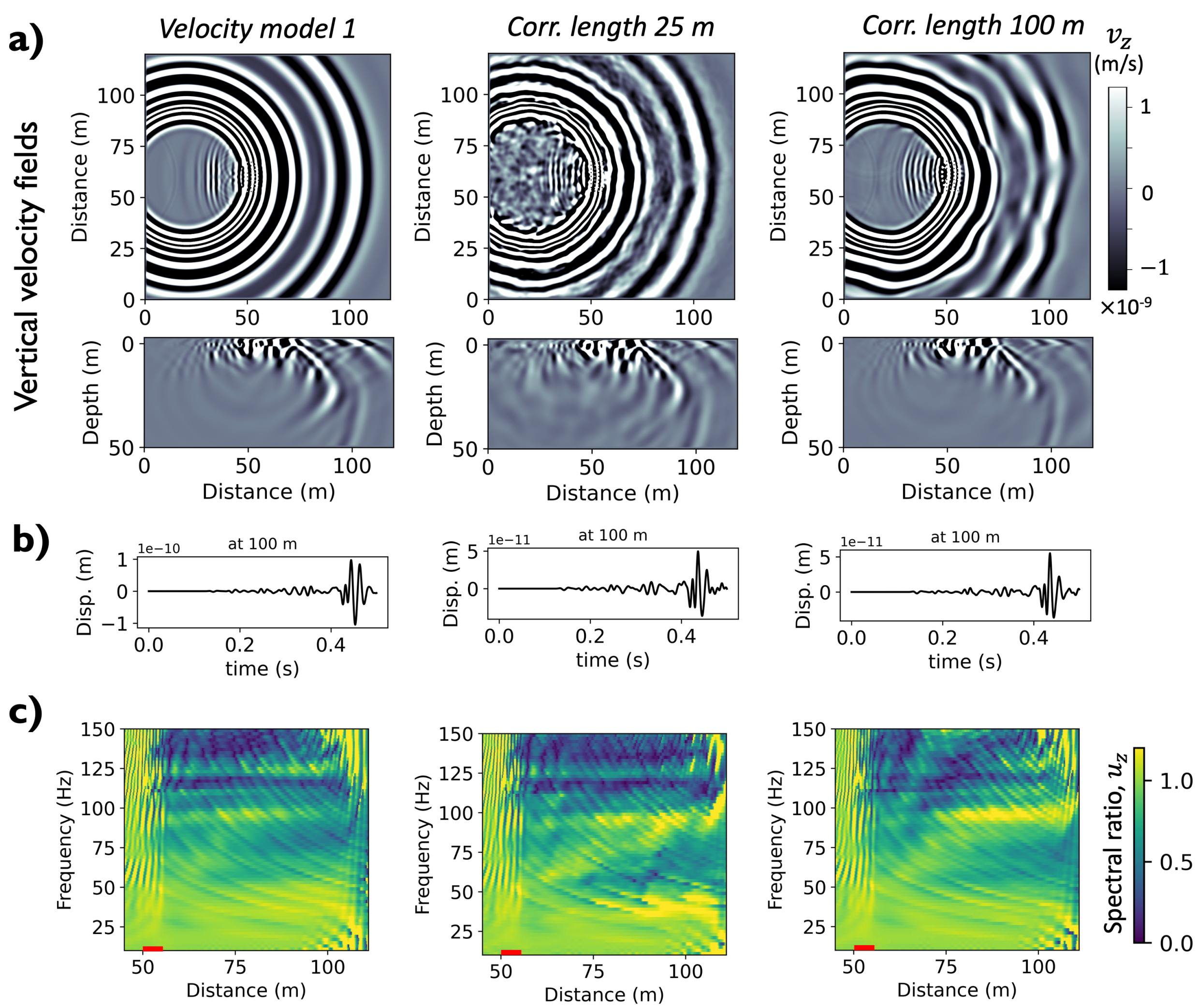

Figure 13. a) Vertical component of the surface velocity fields at 0.19 s. b) Vertical component of the displacement at the surface (100 m away from the source), c) Spectral ratios of the vertical displacement before and after cloaking along a radial profile at y = 60.9 m. The red line indicates the position of the borehole grid. The columns indicate the results obtained from the velocity model 1 (in Figure 12) with correlation lengths of 25 and 100 m, respectively.

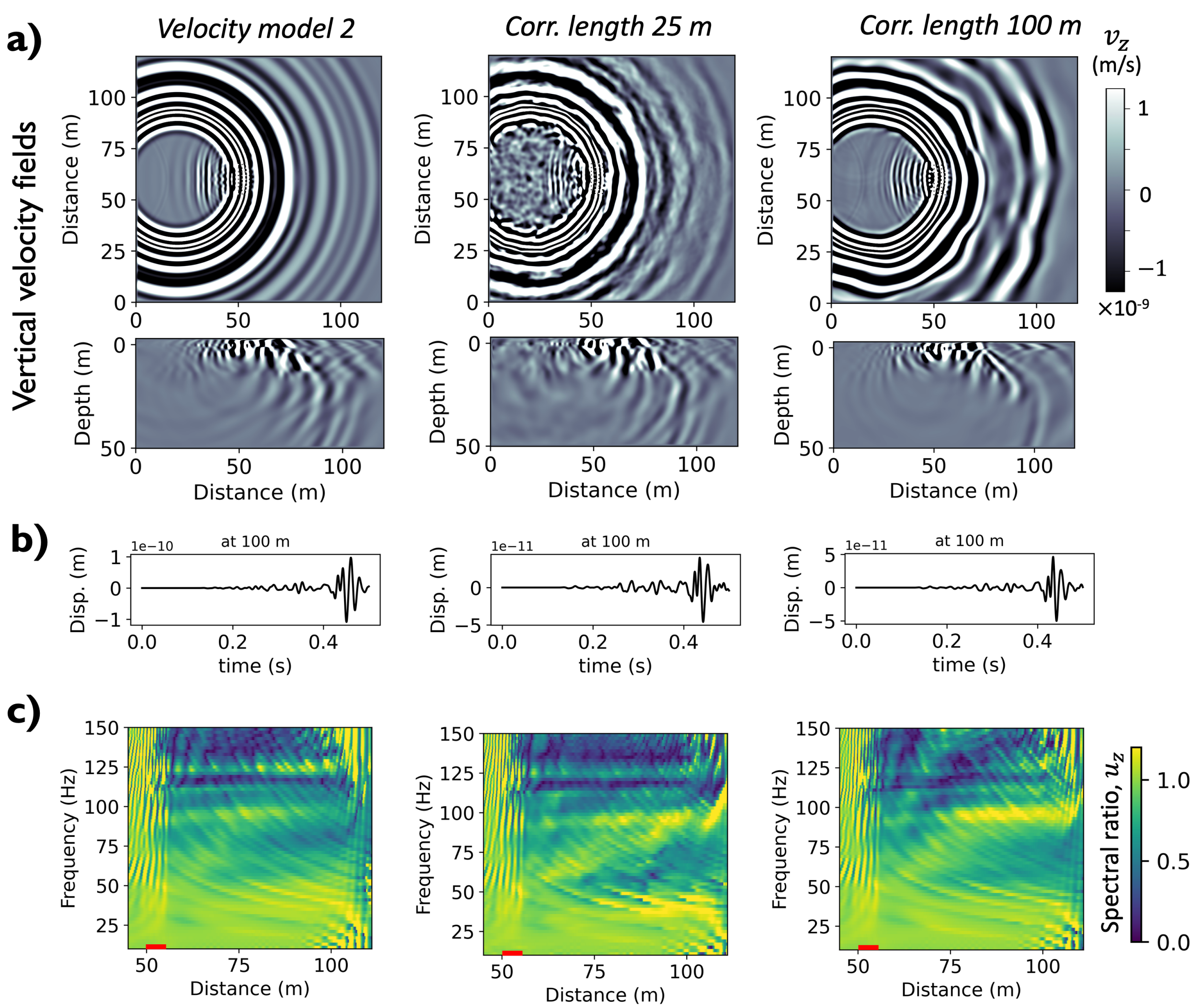

Figure 14. a) Vertical component of the surface velocity fields at 0.19 s. b) Vertical component of the displacement at the surface (100 m away from the source), c) Spectral ratios of the vertical displacement before and after cloaking along a radial profile at y = 60.9 m. The red line indicates the position of the borehole grid. The columns indicate the results obtained from the velocity model 2 (in Figure 12) with correlation lengths of 25 and 100 m, respectively.

The vertical velocity fields interacting with the borehole grid are shown in Figure 13 and 14. All velocity model scenarios indicate similar cloaking performance resulting in a strong suppression of seismic waves for the bandgap higher than ∼100 Hz and relatively less effective suppression at frequencies less than ∼50 Hz for the given seismic metamaterial design.

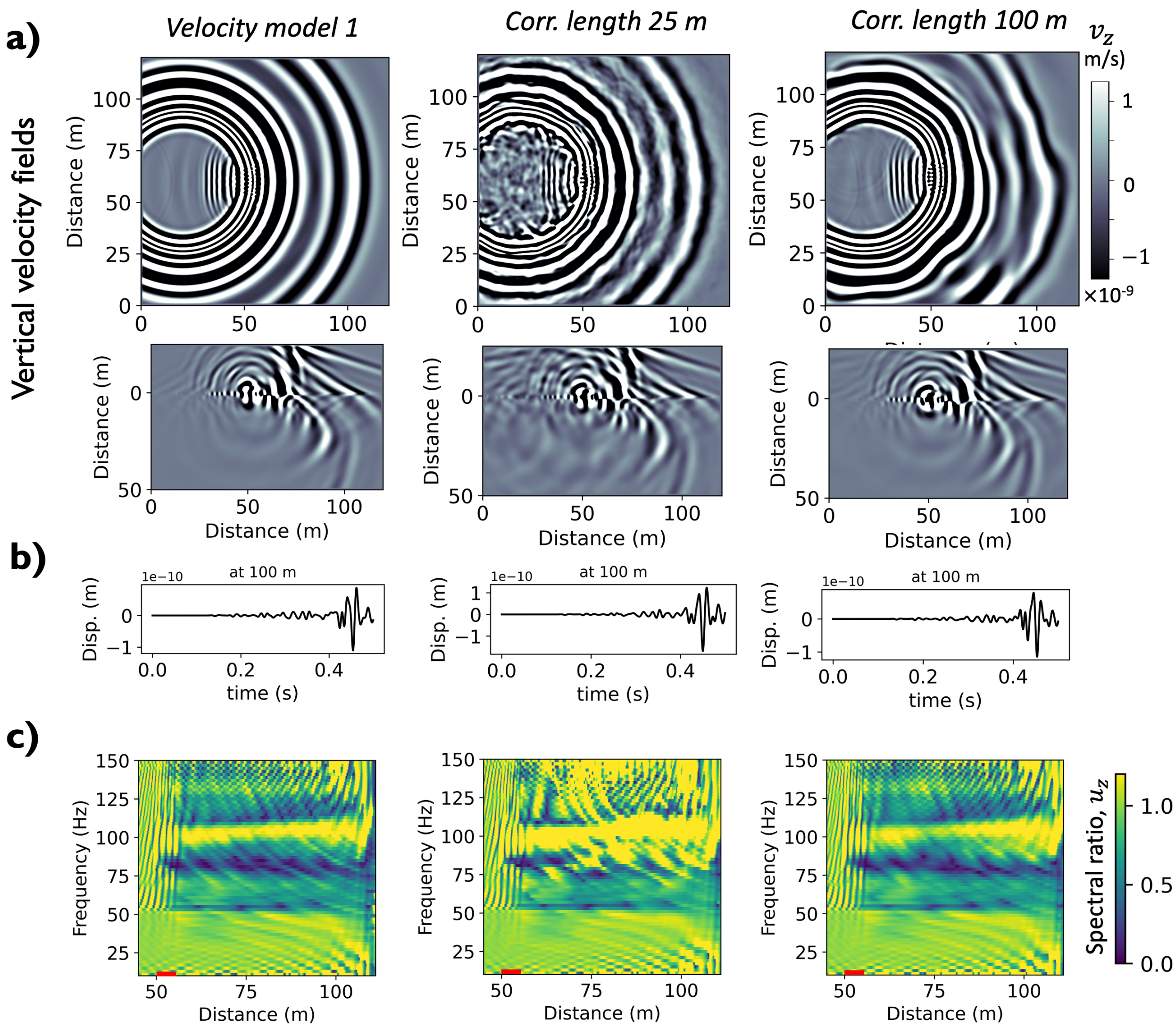

Figure 15. a) Vertical component of the surface velocity fields at 0.19 s. b) Vertical component of the displacement at the surface (100 m away from the source), c) Spectral ratios of the vertical displacement before and after cloaking along a radial profile at y = 60.9 m. The red line indicates the position of the grid of trees. The columns indicate the results obtained from the velocity model 1 (in Figure 12) with correlation lengths of 25 and 100 m, respectively.

In the case that the same experiment is numerically conducted by considering trees instead of boreholes in the grid (Figure 15), the spectral ratios indicate a stronger wave suppression between 50 and 100 Hz compared to the case of the boreholes. In addition, the above-surface resonators also result in similar spectral characteristics for each velocity model considered for the FACT site.

RESULTS AND DISCUSSION:

Our analyses investigate the effects of different metamaterial design parameters and degrees of geologic heterogeneity on the performance of seismic cloaking. Considering a meso-scale geophysical setting, the surface vertical displacement and velocity fields as well as their spectral characteristics have been evaluated to better understand the physics of seismic metamaterials. Seismic metamaterials are formed by modifying the elastic properties of the geologic media via implantations of air-filled boreholes. The effects of the borehole grid density on the performance of seismic cloaking were considered first. The numerical results indicate that the grid density increases wave suppression but it does not affect the frequency range at which the cloaking is most effective. The vertical component of the velocity field at the surface shows significant differences for the two different grid patterns (regular vs. hexagonal lattice). Moreover, increasing the borehole width (or radius) in a borehole grid intensifies the shielding and filtering of the incoming seismic wave field. Enlarging boreholes in the grid result in systematic improvement of the cloaking performance by both extending the effective band gap to lower frequencies and increasing wave suppression. While deeper borehole implantations broaden the band gap that can suppress the wave amplitudes behind the grid, there is a limit to the improvement of the cloaking efficiency; in other words, the band gap cannot continuously be extended to the lower frequencies even if very large borehole lengths are used. In addition, the results also indicate that increasing the length of the boreholes cannot be a strategy for enhancing the performance if the borehole widths are already very small compared to the source wavelength. For broadband seismic protection (≥ the frequency of the seismic source), our numerical results suggest that seismic metamaterials that consist of boreholes with at least a borehole width of $\sim\lambda/8$ are needed. Moreover, simply increasing the interspacing of boreholes in the grid rather than the boreholes width can be an effective strategy to improve cloaking performance for the seismic metamaterial designs considered here. Further, the different materials that fill the boreholes result in significantly different spectral characteristics of the resulting seismic wavefield. While filling boreholes with concrete or steel drastically increases the wave suppression at a wider band gap compared to the air-filled boreholes, the water-filled borehole grid results in multiple narrow band gaps that are almost regularly-spaced across the entire spectrum. The numerical results also highlight the significant impact of the host geologic medium on seismic cloaking. The stochastically-generated heterogeneous geologic models allow much different band gaps and strengths of wave suppression compared to those achieved by the same grid in a homogenous medium. This suggests that an accurate seismic velocity model is essential while designing a seismic cloak for a given field of interest. Distinct from seismic metamaterials, our analysis found that the above-surface resonators, in the forms of a grid of trees, act as a multi-band resonator that suppresses seismic waves at multiple narrow band gaps by transmitting seismic energy to the trees at isolated lower frequencies. This implies that in addition to broadband seismic protection, trees may be also more suitable for applications where the seismic waves are desired to be suppressed at specific frequency bands. Similarly, increasing grid density and diameter of the trees has stronger wave suppression ability at boarder band gaps. Moreover, taller trees in the grid result in a higher number of band gaps and filter the incoming seismic waves at lower frequencies compared to the grid with shorter trees.

Following the parametric analyses on the behaviors of the seismic waves passing through different cloaking designs and heterogenous media, we consider a real test bed (FACT site) for a future field experiment that utilizes cloaking concepts. The geometric properties of those seismic cloaks are chosen by considering the excavation restrictions of the FACT site and the cost. Our numerical simulations, which employ the seismic velocity structure of the site along with stochastic velocity models with varying geologic roughness, indicate that both seismic metamaterials (a grid of boreholes) and above-surface resonators (a grid of trees) can result in measurable cloaking effects on the incoming seismic wavefield generated by a vertical seismic source.

In this numerical study, we have constructed scenarios at mesoscales mainly focusing on the surface waves that commonly cause more damage than the body waves. The analysis can be further extended to buried seismic cloaks and other seismic source mechanisms in the future.

ANTICIPATED OUTCOMES AND IMPACTS:

Potential applications of seismic cloaking include several areas including national security, energy, and natural hazard reduction. This project systematically has tested different designs (density and geometry) of seismic metamaterials (boreholes) and natural above-surface resonators (trees) and degrees of complexities of host geologic media, and numerically demonstrated the feasibility of using seismic cloaks for wave suppression at mesoscales. Moreover, this parametric study provides insights regarding the key factors and controls on the cloaking designs for future field experiments.

Sandia Geophysics Department has a test bed that can readily be used to conduct seismic experiments (FACT site). This project provides a set of optimized cloaking design parameters for seismic field experiments at the FACT site. The proposed cloaking designs that numerically demonstrates seismic energy suppression with both seismic metamaterials and natural above-surface resonators reduce the risk of field experiments to be proposed in FY26. The numerical models in this study provide us a fundamental understanding of the physics of seismic metamaterials at geophysical scales and more importantly guide our envisioned field experiments in the FACT site.

The follow-on LDRD proposal will aim to conduct a series of seismic experiments at the FACT site. Seismic measurements will be made as we systematically change the seismic cloaking design. The initial seismic metamaterial will be formed by a line of holes. At progressive stages, the grid of holes will be extended with additional lines and the diameters will be enlarged. The experiments will utilize two types of sensors including densely-spaced 3-axis geophones and a Distributed Acoustic Sensing fiber optic system to monitor seismic waves through seismic metamaterials resulting in dense spatial sampling of the wavefield. Finally, thorough comparisons and technical analyses of both seismic data sets from progressive stages will help us to better understand the capabilities and the limitations of seismic metamaterials.

This proposal lies at one of the key elements of the Technical Themes in the Earth Science Research Foundation's research agenda: analyzing and experimenting to characterize, quantify, and manipulate Earth properties.

Because this research is fundamental in its focus on seismic protection and wave manipulation, many intersections previously identified between Earth Science and National Security apply. For example, seismic protection of specific areas via cloaking, such as nuclear power plants, infrastructure, military assets, is thus a likely application space for the proposed design process. Similarly, within the Energy and Homeland Security program space, we also see application of seismic protection for geologic storage repositories and critical underground infrastructure, in geothermal energy production, and in long-term waste disposal. In Climate Change, we see seismic protection as an important risk mitigation strategy; for example, earthquake protection of nuclear power plants and pipeline infrastructure, reducing the risk of hazards and negative environmental impact caused by a natural or anthropogenic seismic waves. Finally, seismic wave suppression has potential applications in reducing the impact of not only earthquakes but also other vibration sources due to human activities.

The primary outcome anticipated from the proposed field experiments is a quantitative theoretical foundation of seismic metamaterials in geologic settings at mesoscales. The main goal of the experiments is to observe the changes in seismic wave propagation (scattering, shielding, filtering, etc.) due to seismic cloaks in a real-world geologic environment and systematically test the effect of each model parameter in the cloaking design on the resulting wave fields. Currently this is poorly understood. In addition to addressing the lack of fundamental understanding and experimental evidence on seismic metamaterials, a process for designing seismic cloaks for seismic protection of real-life targets will be a novel capability at Sandia that will attract external collaborations whose primary relations lie in centers beyond 8000.

If our experiments are successful at demonstrating the seismic cloaking phenomenon, this will implicitly suggest that the seismic metamaterials can be scaled up (supporting the previous larger-scale experiments). Moreover, consistent numerical modeling, field evidence and technical analyses will ultimately enable us to propose a target-specific cloaking design and potentially attract collaborations for larger experiments. The fundamental science questions raised in this research are well-poised for a vigorous publication strategy that will impact both the geoscience and optimization communities within Sandia and beyond.

Conference presentation:

Beskardes, GD, and Leiph, P, (2024). A parametric analysis on the behaviors of seismic waves interacting with geologic metamaterials (Poster). *Seismological Society of America (SSA) Annual Meeting,* April 29 – May 3.

CONCLUSION:

Seismic cloaking for the manipulation of seismic wave propagation has received a lot of attention in the last decade due to its possible application to earthquake hazard reduction. Our project conducts a numerical study to systematically evaluate the effects of various cloaking design parameters and degrees of geologic heterogeneity on seismic wave propagation through seismic metamaterials (grid of boreholes). The numerical results suggests that the efficiency of seismic cloaking can be increased at a wider band gap by using larger and longer boreholes rather than increasing the number of the boreholes in the grid if applicable. Alternatively, increasing grid density of the borehole grid or filling boreholes with highly dense materials (e.g., concrete or steel) can be another strategy to have stronger wave suppression ability at broader band gaps if borehole geometry is restricted. Moreover, the natural above-surface resonators (grid of trees) result in multiple narrow band gaps for seismic wave suppression in the target region behind the grid. The geologic heterogeneity strongly affects the resulting seismic wave fields passing through the seismic cloaks and controls the band gaps and the degree of wave suppression. This emphasizes the necessity of characterizing the high-resolution seismic velocity structure of the area prior to the design of seismic cloaks. Further, we consider a real-world scenario and propose a seismic cloaking design for future field scale testing at the FACT site of Sandia's Geophysics Department. Based on the actual velocity model of the site and the allowable sizes of borehole implantations, we provide optimal seismic cloaking designs using both metamaterials and natural above-surface resonators for future field testing. The cloaking designs result in the seismic wave fields successfully demonstrating cloaking effects such as shielding and filtering that can be observed by seismic sensors in the area of interest. Our numerical study supports the findings of previous field scale tests and guides seismic cloaking designs for future real-world experiments.

REFERENCES:

[1] Mu, D., H. Shu, L. Zhao, and S. An (2020), A review of research on seismic metamaterials, *Advanced Engineering Materials* 22, 4, p.1901148.

[2] Brûlé, S., S. Enoch, and S. Guenneau (2020), Emergence of seismic metamaterials: Current state and future perspectives, *Physics Letters A,* 384, 1, p. 126034.

[3] Brûlé, S., E.H. Javelaud, S. Enoch, S. Guenneau (2014), Experiments on seismic metamaterials: molding surface waves, Phys. Rev. Lett. 112, 133901.

[4] Brûlé, S., E.H. Javelaud, S. Enoch, S. Guenneau (2017), Flat lens effect on seismic waves propagation in the subsoil, Sci. Rep. 7 (1), 18066.

[5] Colombi, A., P. Roux, S. Guenneau, P. Gueguen, R.V., Craster (2016), Forests as a natural seismic metamaterial: Rayleigh wave bandgaps induced by local resonances, Sci. Rep. 6, 19238.

[6] Colombi, A., D. Colquitt, P. Roux, S. Guenneau, R.V. Craster (2016), A seismic metamaterial: the resonant metawedge, Sci. Rep. 6, 27717.

[7] Roux, P., D. Bindi, T. Boxberger, A. Colombi, F. Cotton,I. Douste- Bacque, S. Garambois, P. Gueguen, G. Hillers, D. Hollis, T. Lecocq, and I. Pondaven (2018), Toward seismic metamaterials: The METAFORET project, *Seismological Research Letters,* 89, p. 582–593.

[8] Ungureanu, B., S. Guenneau, Y. Achaoui, A. Diatta, M. Farhat, H. Hutridurga, R. V. Craster, S. Enoch and S. Brûlé (2019), The influence of building interactions on seismic and elastic body waves, EPJ Applied Metamaterials, **6**, 18, doi: 10.1051/epjam/2019015.

[9] Brûlé, S., B. Ungureanu, Y. Achaoui, A. Diatta, R. Aznavourian, T. Antonakakis, R. Craster, S. Enoch, and S. Guenneau (2017), Metamaterial-like transformed urbanism, *Innovative Infrastructure Solutions,* 2, 1, p. 1–11.

[10] Woods, R. D. (1968), Screening of surface waves in soils, *Journal of the Soil Mechanics and Foundation Division,* 94, 951.

[11] Haupt, R. W., V. Liberman, M. Rothschild and C. G. Doll (2018), Seismic Cloaking Protection from Earthquakes, *2018 IEEE International Symposium on Technologies for Homeland Security (HST)*, p. 1–7, doi: 10.1109/THS.2018.8574152.

[12] S. Krödel, N. Thome, and C. Daraio (2015), Wide band-gap seismic metastructures, *Extreme Mechanics Letters,* 4, p. 111–117.

[13] Dertimanis, V.K., I. A. Antoniadis,and E. N. Chatzi (2016), Feasibility analysis on the attenuation of strong ground motions using finite periodic lattices of mass-in-mass barriers, *Journal of Engineering Mechanics,* 142, 9, p. 04016060.

[14] Wagner, P.R., V.K. Dertimanis, E. N. Chatzi, and J. L. Beck (2018), Robust-to-uncertainties optimal design of seismic metamaterials, *Journal of Engineering Mechanics,* 144, 3, p. 04017181.

[15] Cacciola, P. and A. Tombari (2015), Vibrating barrier: a novel device for the passive control of structures under ground motion, *Proc. R. Soc. A.* Vol. 471, 2179, The Royal Society, p. 20150075.

[16] Palermo G., S. Krödel, A. Marzani, and C. Daraio (2016), Engineered metabarrier as shield from seismic surface waves, *Scientific Reports* 6, p. 39356.

[17] El Ouahabi A.A., and V.V. Krylov (2018), Reduced-scale ultrasonic modeling of rayleigh wave transmission over seismic barriers formed by periodic arrays of vertical holes, *Noise Control Engineering Journal,* 66, p. 33–44.