Transactions, SMiRT-25
Charlotte, NC, USA, August 4-9, 2019
Division X

SITE MITIGATION FOR CRITICAL INFRASTRUCTURE USING SEISMIC METAMATERIALS

J. Cipolla, A. Shakalis, P. Ghisbain[1]

[1] Thornton Tomasetti, Inc., 40 Wall St, New York, NY, 10005

ABSTRACT

Cost and regulatory pressures in the nuclear power industry have motivated the development of standardized reactor plants and structures. However, customization, and attendant costs, of these plants for local seismic conditions is mandatory for many sites. This situation represents a significant risk for the widespread adoption of modular or standardized nuclear facilities.

In this paper, we will discuss a seismic strategy adapted from mitigation approaches used in underwater shock protection of naval ships. Modern warships benefit from the use of commercial equipment and machinery, because such equipment has lower cost and higher technical performance than military-standard equipment. However, this commercial-off-the-shelf (COTS) equipment typically cannot withstand severe shock environments, or cannot demonstrate shock performance within programmatic cost and schedule constraints. Naval designers, therefore, have begun creating ship structures that mitigate underwater shock levels for COTS equipment, so that the ship may use this industrial standard equipment without modification.

Our experience with metamaterial seismic barriers indicates that a similar approach shows promise for nuclear facilities. Metamaterials are specially designed composite structures whose properties cannot be found naturally. Metamaterial technology has been particularly successful in exotic and demanding wave propagation applications, such as optics, electromagnetics and acoustics. Here, we demonstrate through numerical simulations how specially designed metamaterial barriers lower the spectral metrics of surface-wave earthquake excitations inside a protected region, enabling the installation of standardized facilities.

EXECUTIVE SUMMARY

To effectively meet regulations and mitigate costs, standardized reactor plants and structures are desired. However, seismic hazards necessarily create additional measures and customization, which inhibits the ability to modularize or standardize nuclear facilities. Seismic Metamaterials use properties not found naturally to dissipate or refract seismic surface waves, thereby lowering seismic risk by lowering peak ground accelerations on-site. This reduction of the seismic hazards surrounding the facility allows for a standardized development within the protected region.

INTRODUCTION

Cost and regulatory pressures in the nuclear power industry have motivated the development of standardized reactor plants and structures. However, customization, and attendant costs, of these plants for local seismic conditions is mandatory for many sites. This situation represents a significant risk for the widespread adoption of modular or standardized nuclear facilities. Seismic metamaterials is an emerging study in the field of metamaterials. Currently, the field is predominantly focused on resonant and dissipative approaches. Metamaterials are specially designed composite structures whose properties cannot be found naturally. Metamaterial technology has been particularly successful in exotic and demanding wave propagation applications, such as optics, electromagnetics and acoustics. Two seismic metamaterials (SMM) are studied; the common resonant SMM, and a refractive SMM, borrowing from technologies used in acoustics and electromagnetics. This report demonstrates through numerical simulations how specially designed metamaterial barriers lower the spectral metrics of surface-wave earthquake excitations inside a protected region, enabling the installation of standardized facilities.

OBJECTIVES

The intent of this paper is to expound on the current state of seismic metamaterials (SMM) research and to show preliminary results from studies adapting acoustic metamaterials to seismic approaches. Both resonant and refractive SMM are introduced and studied, with the goal of reducing peak ground accelerations, thereby allowing for less strict and potentially standardized code-based criteria for facility design.

BACKGROUND

Existing Standards: Seismic Risk and Standards for Nuclear Facilities

Standards that supplement typical design codes, (i.e., International Building Code, ASCE 7, ACI 318) for seismic structural design and analysis for nuclear facilities include ASCE 4 and ASCE 43. These two standards dictate the evaluation of and analysis of nuclear structures. In a typical structural design for seismic threats, the ground motion response spectrum is required.

Often, to mitigate the response of a structure due to a seismic event, tuned damping is used and integrated in to the structure to allow for dissipation of the incident seismic energy. Seismic regions also dictate stricter and more conservative values for lateral loads on the structure.

Seismic analysis methods also vary depending on the complexity of the structure; often, a static or static coefficient analysis can be used to get an ‘envelope’ of analysis responses. Dynamic analyses and Soil-Structure Interaction (SSI) can be used for higher fidelity, more accurately capturing the structural response and potentially lowering the perceived seismic loads. The tradeoff is in the amount of information required, wherein SSI and other dynamic analyses necessarily require more information about the facility. Static coefficient analyses are conservative, but its lower fidelity implies simpler calculation, which is more useful in the early design phases.

Seismic designs are governed by peak ground accelerations. The intent of the metabarrier is to lower these accelerations to reasonable thresholds, thereby lowering the design loads and permitting the design of a structure with a lower perceived seismic risk. Furthermore, the fragility of the structure, useful in Probabilistic Risk Assessments, is reduced.

BACKGROUND

Existing Technologies: Prior Research in Seismic Metamaterials

Seismic Metamaterials (herein SMM) is an emerging field in the study of specifically tailored materials (metamaterials). Metamaterials are specially designed composite structures whose properties cannot be found naturally. Metamaterial technology has been particularly successful in exotic and demanding wave propagation applications, such as optics, electromagnetics and acoustics. In acoustics, metamaterial waveguides have been devised to redirect or focus incident waves.

SMM have previously been devised as large arrays of tuned dampers [5], forests [3][4], or embedded piles [1]. SMM are commonly implemented as resonant structures, which require a significant amount of mass to be mobilized so to mitigate the surface wave response. As these metamaterials are realized on a large scale, the designs and large masses required are realizable. The use of embedded piles shows promise as a way to dissipate an incident surface wave without the necessity for (intentionally) moving parts, and can be considered analogous to devices created for similar purpose in acoustics [7].

Common devices in acoustic and optical metamaterials incorporate refraction or redirection of incident waves. In a similar application in the notional seismic metamaterial, the refractive index of the surrounding soil can be modified to redirect the incident waves. Moving forward, there are two governing approaches to the design of an effective SMM barrier: dissipation through resonant metamaterials, and redirection through the use of engineered refractive indices. Each approach is considered in detail in the following sections of this report.

Existing Procedures: Prior Soil-Structure Interaction Modelling in FLEX/TRANAL

FLEX [11] is an explicit dynamic time-domain FEA solver which incorporates reduced integration elements. Wave propagation modelling and soil structure interaction has been conducted in FLEX since the 1980s, and its predecessor TRANAL was the software of choice for earlier works in soil-structure interaction research published by SMiRT 7 [9]. Of particular use in modelling and simulation of the SMM is the use of nonlinear kinematic cap models for the soils subjected to loading [10], which is to be used in our future metabarrier research. The procedures outlined in earlier works remain similar in modern modelling of SSI in FLEX. PZFlex is a recent addition to FLEX including piezoelectric elements for modelling of transducers, along with wave propagation and extrapolation tools. PZFlex has been extensively used in the study of acoustic metamaterials [8]. Recent modelling (including this work) has adapted the acoustic modelling to seismic waves [2][6].

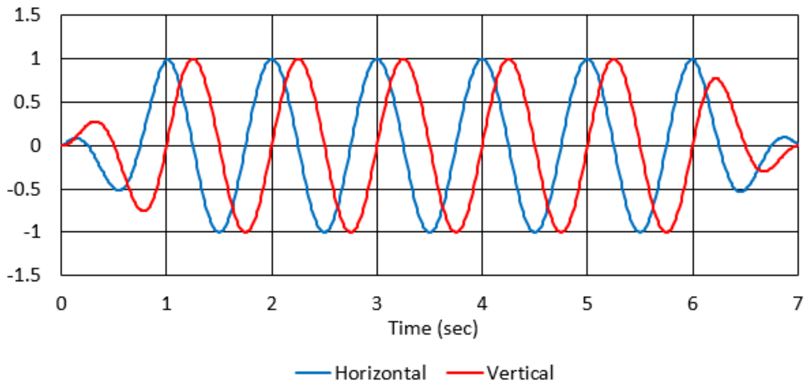
METHODOLOGY

Modelling Assumptions

To simulate the surface wave threat and the effect of SMM barriers, the finite element software PZFlex (recently rebranded OnScale) was employed. The software implements a structured grid explicit dynamic time domain FE solver for wave propagation. Dissipative (resonant) and redirecting SMM designs are modeled. PZFlex reduced order quadrilateral elements, which including relevant degrees of freedom (i.e., displacement) and hourglass control (required for reduced order schemes) were chosen for the wave propagation modelling. The material chosen for the soil substrate was linear, isotropic, and homogeneous, with P-wave speeds of 1000m/s, S-wave speeds of 200m/s, and a density of 2000kg/m^3.

In both models, impedance based boundary conditions are available and applied; impedance boundaries are commonly used in acoustic modelling to more accurately represent (compared to simple symmetry boundaries) the medium beyond the region of interest. Furthermore, each model is set with the same initial conditions and loadings; the left edge of the modeled soil receives a velocity excitation, while the rest of the model is initially at rest.

The velocity applied follows a Rayleigh wave profile (Figure 1); its amplitude is highest nearest to the surface, and soil velocities decrease to zero as depth increases. The effect is a propagating surface wave, otherwise known as ground roll, which is a particularly damaging aspect of the seismic threat. For a more tractable comparison, a similar motion is observable with ocean waves. Dissipative (resonant) and redirecting SMM designs are modeled and studied in Cases 1 and 2.



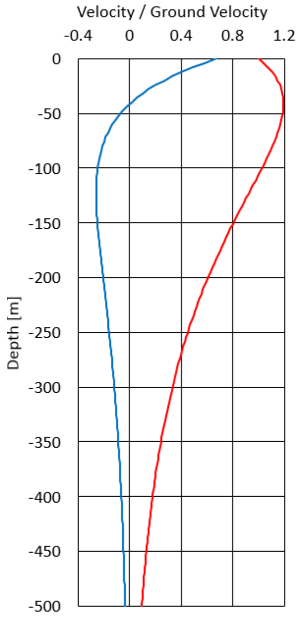


Figure 1 - Input Excitations.
A velocity boundary condition is applied vertically and horizontally with a 90 degree phase shift (above) along one edge of a homogeneous soil medium; a surface wave profile is used (left), wherein velocities are maximized near the surface. This profile ensures the creation of a propagating surface wave in the model.

METHODOLOGY

Case 1 – Resonant SMM

The first case modeled a resonant SMM (oscillator), modeled as a dampened spring-mass system. The oscillator housings were assumed as rigid sub-assemblies in the modeled soil, with a lumped mass and linear spring elements to create the resonant SMM desired. A total of 10 oscillators were used, spaced 20m apart. The oscillators are tuned to the incident frequency of the model, and include 5% damping in each direction of travel. A representation of the oscillator is shown below. The Resonant SMM Model also included several 'targets', a location where the nodal displacements were recorded ahead and behind the SMM array.

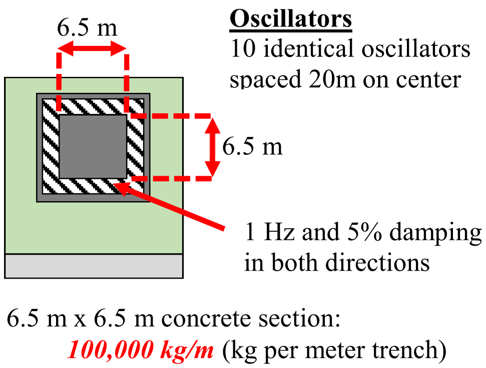


Figure 2 - A notional Resonant SMM.

Case 2 – Refractive SMM Barriers

A refraction-based approach is also considered. By altering the elastodynamic properties of the soil, a wave-guiding barrier with physically realizable material properties can be devised. A region of the model is designated for this barrier, with material properties defined externally for element regions, and read in to PZFlex. The resulting model is a homogeneous soil with an 80m wide and 40m deep embedded barrier. Shallower barriers require further extremal materials (i.e., higher refractive indices).

The refractive index of the barrier differs from the surrounding soil; since the barrier is a solid continuum structure, local dispersive effects are not of great concern. The changed refractive index allows for a passive (i.e., no moving parts) redirection of the incident surface wave. The region's acoustic impedance varies throughout the barrier. Unlike the tuned oscillators, this barrier would effectively be broad-band, subject only to the 'feature size' of the property variation within the barrier. Similar effects are recorded in acoustic metamaterials, wherein feature size dictates the operational frequency range of the metamaterial.

Figure 3 - A Seismic Metamaterial Barrier adjacent to a facility.

RESULTS

Case 1 – Resonant SMM

The resonant SMM successfully displays characteristics of a single-degree-of-freedom (SDOF) frequency response. Furthermore, the incident surface wave has its peak displacements drop by 30%. Shallow wave energy (i.e., work done by the wave within 20m of the surface) is reduced by 55%, as shown in Figure 6. Normalized velocity magnitudes are shown as contours in Figure 4. Comparing the second and third images shows earlier waves not being mitigated to the same extent as later waves. This is due to the oscillators; as the oscillators 'ramp up' to their resonant peak, later excitations are more easily dissipated while earlier ones effectively excite the system. A clear frequency dependent response of the tuned oscillators is shown in Figure 5. As with the typical TMD used in structural applications, the Resonant SMM displays lowered efficiency as the operating frequency of the oscillator and the incident frequency differ.

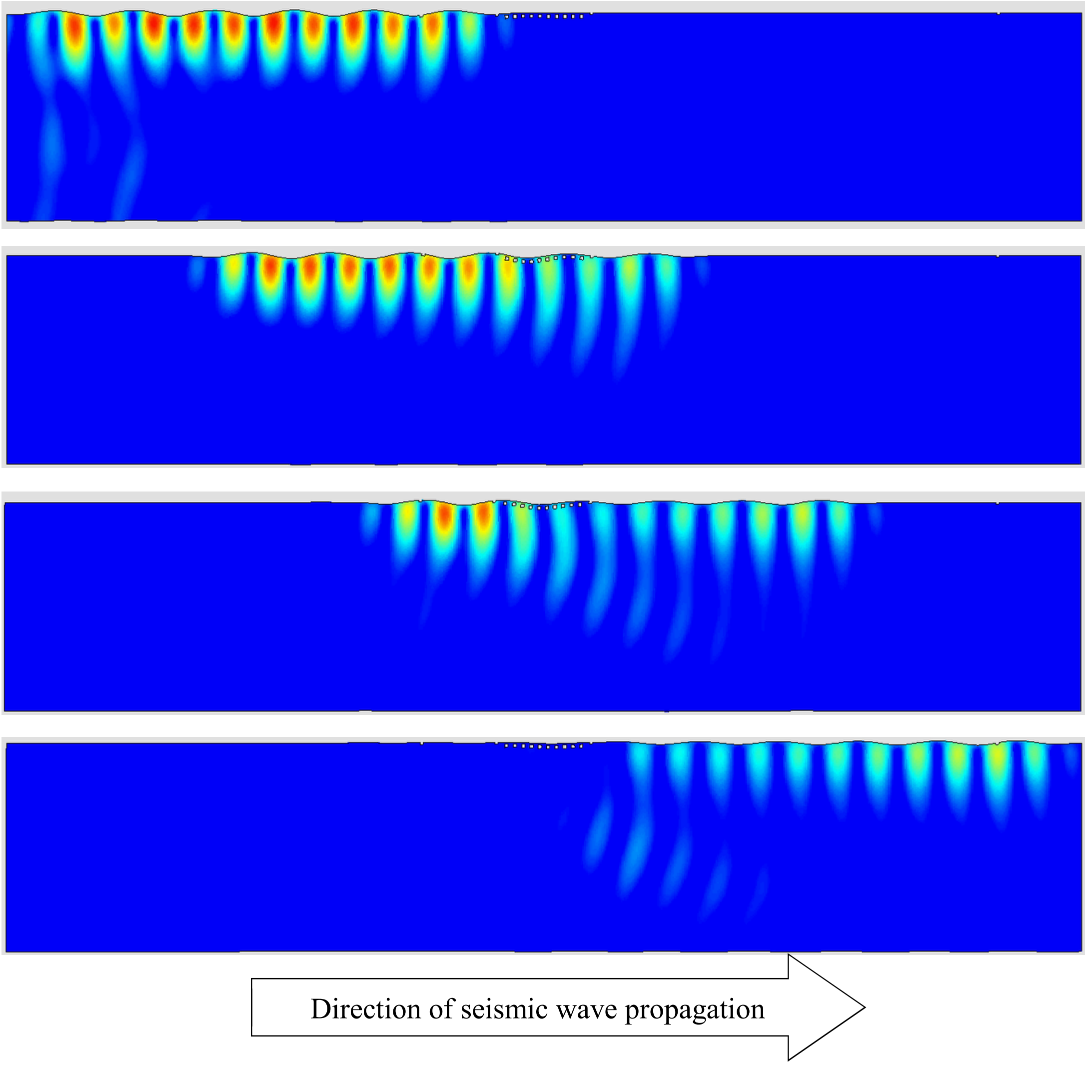


Figure 4 - Velocity Magnitude Contours; Resonant SMM Barrier reduction of incident Rayleigh wave. Note: Comparing the second and third images shows earlier waves not being mitigated to the same extent as later waves. This is due to the oscillators; as the oscillators 'ramp up' to their resonant peak, later excitations are more easily dissipated while earlier ones effectively excite the system.

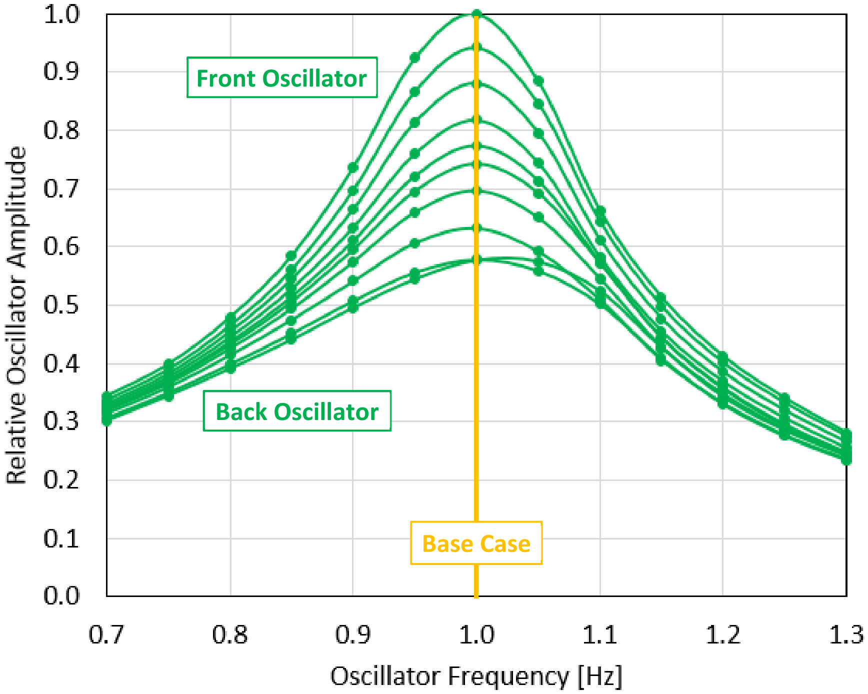


Figure 5 - Frequency Response of the Tuned Oscillators to 1Hz excitation.
Note: Front oscillator (nearest to source) has higher response than Back (furthest) oscillators. A clear frequency dependence is shown for all oscillators in the Resonant SMM array.

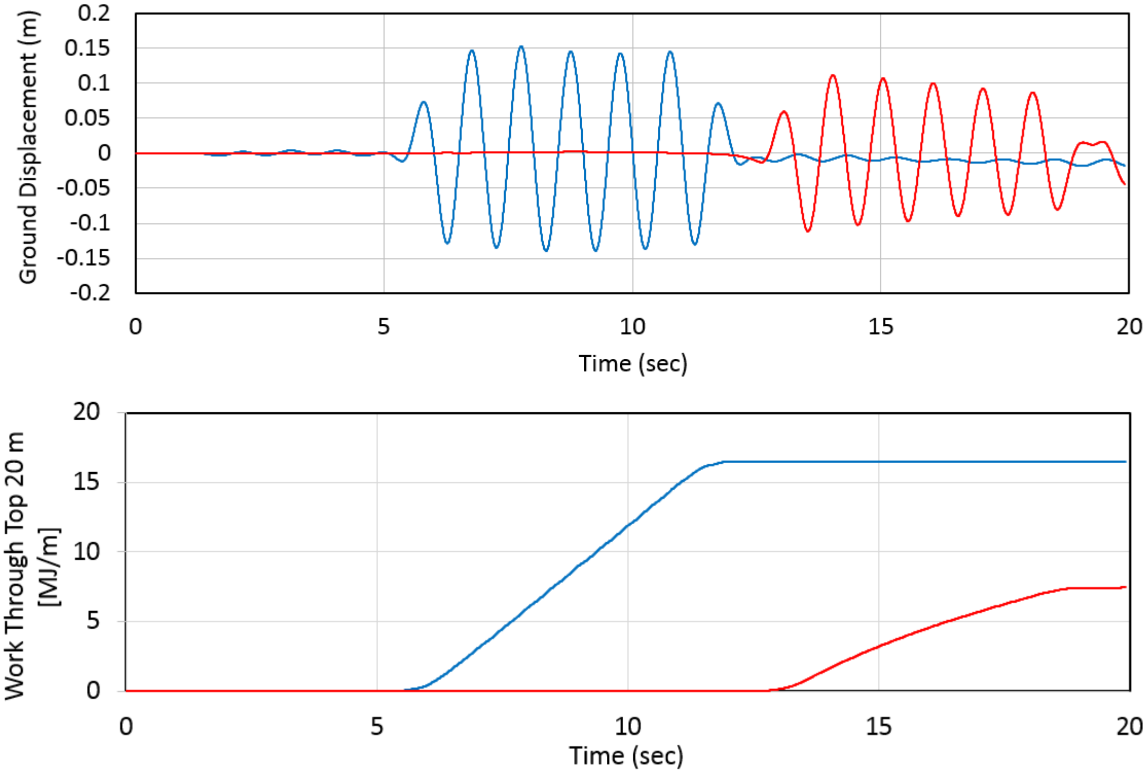


Figure 6 - Nodal Responses upstream (blue) and downstream (red) of the barrier.
Note: A 30% reduction in vertical ground displacement, as well as a 55% reduction in work done (Energy Imparted) can be observed. The Resonant SMM successfully dampens incoming surface waves.

RESULTS

Case 2 – Refractive SMM Barriers

The refractive SMM is devised by altering acoustic impedances in a trench within the soil medium. The model is effectively plane-strain; a unit width is considered. The modelled trench is 80m wide and 40m deep. The alteration of impedances allows for a redirection of the incident surface wave. The subsequent ground displacement is compared between ‘pristine’ (i.e, no SMM Barrier) and SMM cases. The Refractive SMM successfully redirects the incident Rayleigh wave excitation, reducing peak ground vertical displacement by nearly 70%. Peak vertical velocities and accelerations see a reduction of nearly 80%, as shown in Figure 7.

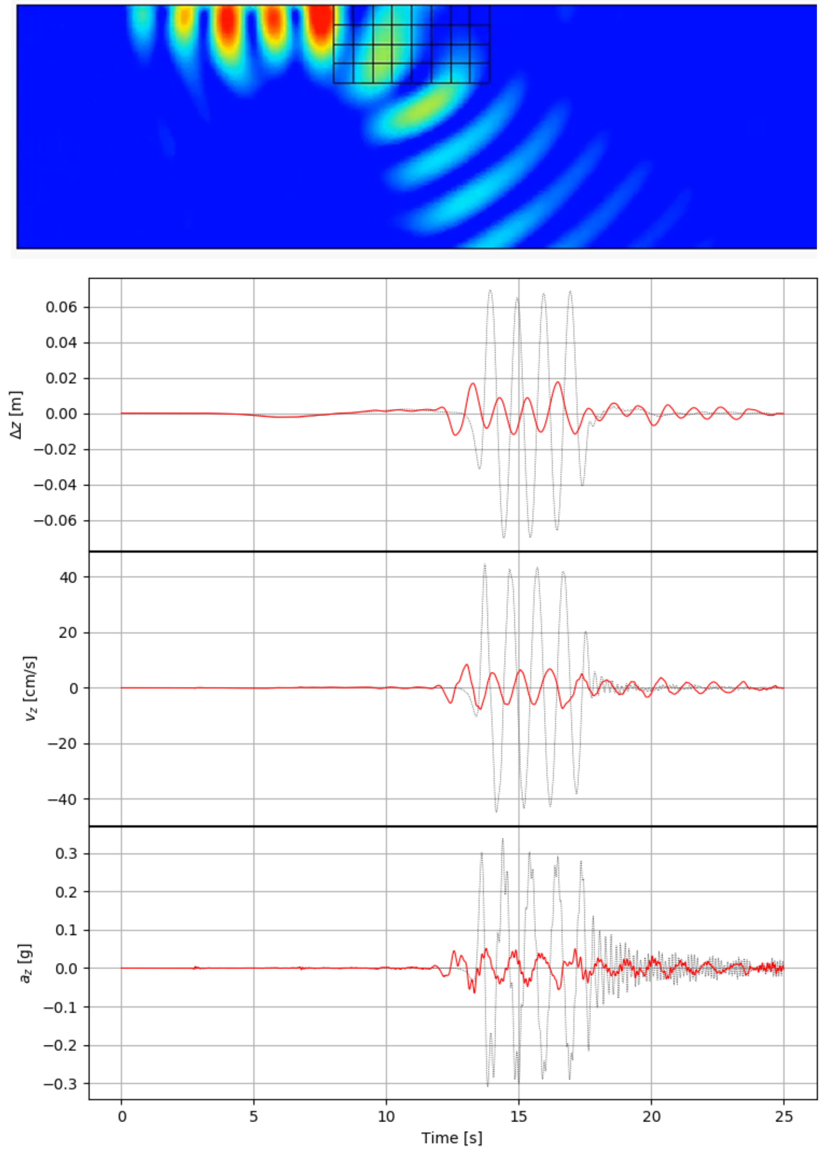
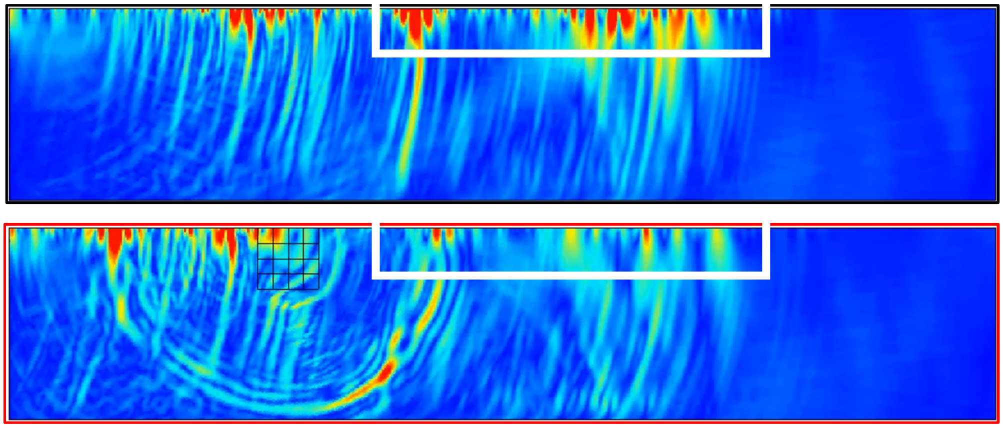


Figure 7 - Velocity Magnitude Contour; Resonant SMM in gridded region.
Plots: Vertical Displacements, Velocity, and Acceleration of a node in the region downstream of the SMM barrier.
No barrier case: Gray. With barrier case: Red.

RESULTS

Case 2 – Refractive SMM Barriers (Continued)

The refractive SMM also adequately reduces incident velocity and acceleration magnitudes in the case of non-monochromatic signal; the velocity-time histories for the San Fernando (1971) earthquake are applied in lieu of the 1Hz sinusoidal excitation. The resulting reduction in peak acceleration and peak velocity magnitudes are equivalent to lowering the Mercalli intensity of this seismic event from VII to V. This significant reduction is achieved with a small 40m x 40m excavation as shown by the gridded region in the second image.



	v_x *[cm/s]*	v_z *[cm/s]*	*Peak Accel. [g]*	*Mercalli Intensity*
None	*14.03*	*26.09*	*0.33*	***VII***
Refractive SMM	*4.52*	*8.97*	*0.09*	***V***

Figure 8 - San Fernando (1971) Velocity Magnitude Contour; without (top) and with Refractive SMM (bottom). Note mitigated velocity at surface.

PRIMARY CONCLUSIONS

Both SMM devices create a significant drop in seismic response in the protected region. The effects of the resonant SMM are frequency dependent, as expected, while the refractive SMM has provided further broad band response to more realistic excitations, (i.e., Actual earthquake time-histories). The SMM field is still emerging and these technologies are under further development. The ability of either SMM technology to mitigate ground accelerations opens the possibility for site-specific mitigation of seismic hazards.

The effectiveness of the stiffness-based refractive barriers leads to a methodology by which a site, protected by refractive barriers, may be engineered to a level which enables the use of standardized, rather than site-specific, facilities and equipment. Significant reductions in design, engineering, qualification and certification can result.

Future steps include studies in to the directional-dependence of the refractive SMM, (w.r.t. source location), other excitations, including bulk pressure and shear waves, as well as soil inhomogeneity and nonlinearity.

REFERENCES

[1] Brûlé, S., Javelaud, E.H., Enoch, S., Guenneau, S. (2014). “Experiments on Seismic Metamaterials: Molding Surface Waves,” *Physical Review Letters* 112 (13), 133901.

[2] Cipolla, J., Milner, D., Mould, J., Nikodym, L., Reed, H., Robeck, C., Salari, R. (2017) “Metamaterials in Seismic Mitigation”, *3rd Workshop on Seismic Metamaterials*, Bologna, May 15-17, 2017.

[3] Colombi, A., Colquitt, D., Roux, P., Guenneau, S. and Craster, R.V. (2016). “A seismic metamaterial: The resonant metawedge,” *Scientific Reports 6,* 27717.

[4] Colombi, A., Roux, P., Guenneau, S., Gueguen, P., and Craster, R.V. (2016). “Forests as a natural seismic metamaterial: Rayleigh wave bandgaps induced by local resonances,” *Scientific Reports 6,* 19238.

[5] Finocchio, G., Casablanca, O., Ricciardi, G., Alibrandi, U., Garescì, F., Chiappini, M., and Azzerboni. B. (2014). “Seismic metamaterials based on isochronous mechanical oscillators,” *Appl. Phys. Lett. 104,* 191903.

[6] Reed, H., Shakalis, A., Seilor, E., Cipolla, J., Kelly, A. (2018). “Uncertainty Quantification of the Performance of Seismic Waveguides through Reduced Order Model Interpolation,” *World Conference of Computational Mechanics 2018*

[7] Sánchez-Pérez, J., Caballero, D., Sanchez-Dehesa, J., Meseguer, F. (1998). “Sound Attenuation by a Two-Dimensional Array of Rigid Cylinders,” *Physical Review Letters 80*, 5325-5328. 10.1103.

[8] Shakalis, A., Lobaza, K., Reed, H., Cipolla, J., Robeck, C., Kelly, A., Salari, R. (2017). “The effect of inertial distribution on dispersive modes in pentamode metamaterials for use in acoustic cloaking,” *The Journal of the Acoustical Society of America 142*, 2615

[9] Vaughan, D.K., Isenberg, J., Kot, C.A., Srinivasan, M.G. (1983). “Nonlinear Soil-Structure Interaction Analysis of the HDR Containment Building,” *SMiRT 7*

[10] Vaughan, D.K., Isenberg, J. (1984). “Soil-Structure Interaction in Explosive Testing of Model Containments,” *Nuclear Engineering and Design 77*, 229-250.

[11] Vaughan, D.K. (1983, plus updates through 2019) “FLEX Users Guide,” Report UG8298, Thornton Tomasetti, Santa Clara, CA.