Seismic Barrier Protection of Critical Infrastructure

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Abstract - Each year, on average a major magnitude-8 earthquake strikes somewhere in the world. In addition, 10,000 earthquake related deaths occur annually, where collapsing buildings claim by far most lives. Moreover, in recent events, industry activity of oil extraction and wastewater reinjection are suspect to cause earthquake swarms that threaten high-value oil pipeline networks, U.S. oil storage reserves, and civilian homes. Earthquake engineering building structural designs and materials have evolved over many years to minimize the destructive effects of seismic surface waves. However, even under the best engineering practices, significant damage and numbers of fatalities can still occur.

In this paper, we present a novel concept and approach to redirect and attenuate the ground motion amplitudes caused by earthquakes by implementing an engineered subsurface seismic barrier – creating a form of *metamaterial*. The barrier is comprised of borehole array complexes and trench designs that impede and divert destructive seismic surface waves from a designated 'protection zone'. The barrier is also designed to divert not only surface waves in the aerial plane, but includes vertical 'V' shaped muffler structures composed of opposing boreholes to mitigate seismic waves from diffracting and traveling in the vertical plane.

Computational 2D and 3D seismic wave propagation models developed at MIT Lincoln Laboratory suggest that the borehole array and trench arrangements are critical to the redirection and self-interference reduction of broadband hazardous seismic waves in the vicinity of the structure to protect. The computational models are compared with experimental data obtained from large bench-scale physical models that contain scaled borehole arrays and trenches. These experiments are carried out at high frequencies, but with suitable material parameters and bore-hole dimensions. They indicate that effects of a devastating 7.0-magnitude earthquake can be reduced to those of a minor magnitude-2 or -3 eathquake within a suitable protection zone. These results are very promising, and warrant validation in field scale tests.

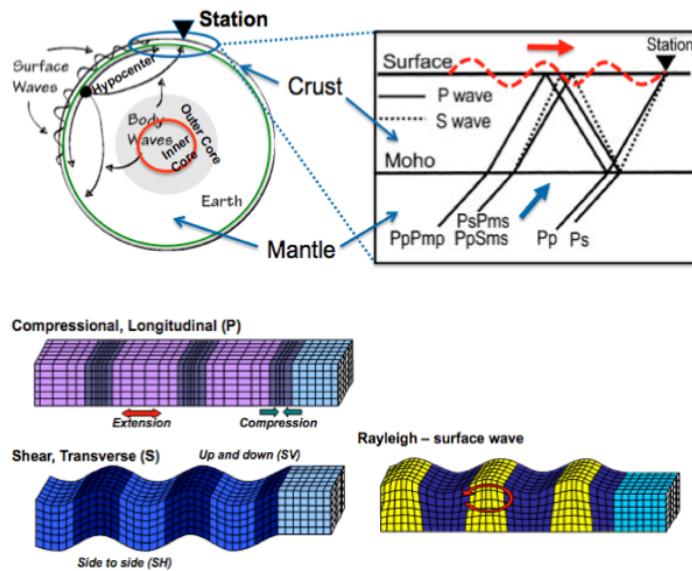*Keywords* – seismic, metamaterials, borehole structures, earthquake mitigation

I. Introduction

Damage caused by earthquakes to critical structures such as nuclear power plants, regional hospitals, military installations, airport runways, pipelines, dams, and other infrastructure facilities exacerbates the disaster and adds tremendous cost and time of recovery. Even low energy earthquakes resulting from human activity can cause significant damage as well. For example, wastewater reinjection practices used by the oil industry resulted in over 900 earthquakes in 2014-2015 in the state of Oklahoma, with a recent 2016 quake of magnitude 5.8. These continual earthquake swarms, although many small, threaten extremely high value above and below ground pipelines that control oil supply, storage, and transport in the U.S., and is a major economic and environmental concern.

Figure 1 (left) describes pictorially the different kinds of seismic waves, including body waves and surface waves. From the civil engineering standpoint, the most destructive are surface waves (Rayleigh, Love, shear). To protect against them, a large body of earthquake engineering has been developed, and effective building practices are being routinely applied to new construction.However, existing high value structures are unlikely to be retrofitted, thus posing significant risk to lives, economy, and the environment. Here, we propose a novel concept to redirect and attenuate the ground motion of earthquake surface waves by implementing an engineered below-ground seismic barrier around such high value structures. As shown schematically in Figure 1 (right), the structures proposed employ borehole arrays and trench components to act as broadband seismic wave barriers that conceptually create a *cloaking* device that significantly reduces the energy that would otherwise reach an area we desire to protect, such as a power plant, oil pipeline complex, or other critical structures.
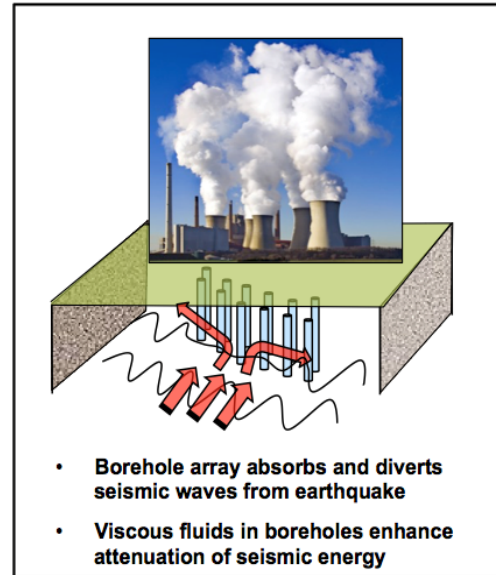
Figure 1. *Left:* Typical seismic wave types caused by earthquakes. Statistically, surface seismic waves (Rayleigh – ground roll, Love, Shear) can cause significant damage and destruction to man-nade structures in critical infrastructure. *Right:* Notional borehole array concept that diverts and absorbs hazardous seismic waves prior to reaching critical infrastructure.

II. Prior Investigations

Several "earthquake cloaking" concepts have been proposed recently. The main limitation of the all the published approaches so far is the narrow-band resonant nature of the structures, which do not address the typical bandwidth of a real-life tremor. Furthermore, there are limitations to scalability to low frequencies (large structures) as well as applicability to shear waves.

(Colombi, et al,, *Scientific Reports* 2016, 6, 19238.) suggested that tall above-ground structures, such as trees or steel towers, can be placed strategically to absorb some of the ground vibrations and dissipate seismic energy. However, from the previous measurements and calculations, only energy at discrete resonant frequencies can be dissipated with this approach. Furthermore, in order to access frequencies below 1-10 Hz, the height of the above ground structures would have to be several hundred meters, which is impractical.

A second approach (Kim and Das, *Modern Physics Letters B* 2013, 27) suggested that burying large resonator tanks underground would convert the incident seismic energy into acoustic energy and, thereafter, into heat. Our analysis of this approach with 3-dimensional finite element modeling found that only energy at discrete resonances can be dissipated. Furthermore, seismic shear waves cannot couple into acoustic air filled resonator structures, thus reducing bthe utility of this approach precisely

for the more damaging type of waves. Finally, because of great impedance mismatch between hard ground and air, coupling of the resonances into the underground tanks would be extremely inefficient, as most of the energy would be reflected.

A third approach (Krödel, S, et al. *Extreme Mechanics Letters* 2015, 4, 111-117) proposed burying seismic dampers into the ground for energy dissipation. Once again, this approach is narrowband and requires multiple resonant dampers, each working in a separate frequency band, to cover a practical range of frequencies. In a scaled experiment in a tank of sand, researchers found that many dozen different-size resonators would be required to cover the relevant frequency spectrum. Scaling such approaches to full size would be impractical.
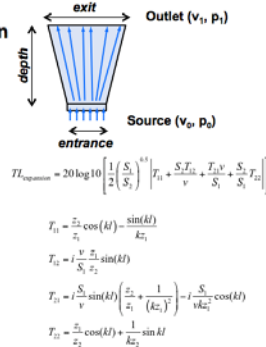
Finally, in the only controlled experiments performed in earth to date (Brule, et al., *Physical Review Letters* 2014, 112), a team from Institute Fresnel and Menard Construction company have excavated an array of several dozen holes in a sedimentary basin outside of Grenoble, France. The team has studied elastic wave attenuation through the array of these holes at a source frequency of 50 Hz, provided by a vibrocompactor. This experiment has generated a large amount of excitement in the popular media as it was the first and the only large scale demonstration of elastic wave diversion in soil. A modest attenuation of 3-5 dB was achieved by the borehole array. The major limitation of this

experiment is its reliance on the phononic crystal approach, which is inherently narrowband and, often, direction-dependent. Furthermore, scaling this phononic crystal design to frequencies below 1 Hz and to hard soil conditions that are prevalent in most locations would result in impractically large sizes for the array structure.

III. 'V' Shaped Opposing Borehole Muffler Structure

By contrast to the previously explored approaches, our design involves a broadband borehole array structure, combining attenuation from scattering theory as well as reflective muffler designs to enable not only aerial plane seismic wave diversion, but also vertical-depth plane protection. As described below, the muffler structures attenuate both shear waves and surface waves, over the frequency ranges relevant to earthquakes in both the aerial and vertical orientation planes.

- Develop Intuition of energy dissipation in tapered geometry from acoustic muffler theory
  - Tapered funnel with a subwavelength opening
- Energy attenuation as a function of entrance, exit and angle dimensions
- Simple analytical expressions rely on transfer matrix approach
  - Combine transmission through subwavelength aperture + expansion through the muffler

$$TL_{expansion} = 20\log10\left[\frac{1}{2}\left(\frac{S_1}{S_2}\right)^{0.5}\left|T_{11} + \frac{S_2 T_{12}}{v} + \frac{T_{21}v}{S_1} + \frac{S_2}{S_1}T_{22}\right|\right]$$

$$T_{11} = \frac{z_2}{z_1}\cos(kl) - \frac{\sin(kl)}{kz_1}$$

$$T_{12} = i\frac{v}{S_1}\frac{z_2}{z_2}\sin(kl)$$

$$T_{21} = i\frac{S_1}{v}\sin(kl)\left(\frac{z_2}{z_1} + \frac{1}{(kz_1)^2}\right) - i\frac{S_1}{vkz_1^2}\cos(kl)$$

$$T_{22} = \frac{z_1}{z_2}\cos(kl) + \frac{1}{kz_2}\sin kl$$

Easwaran and Munjal, J. Sound and Vibration 152 (1992), 73-93.

Trends
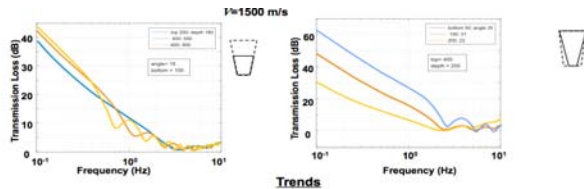
1. Increasing the depth at constant angle increases attenuation at the lower frequencies, but reduces attenuation at the higher frequency due to multiple nodes
2. Increasing the depth at constant top & bottom, i. e., while reducing the angle, reduces attenuation across the entire frequency range
3. Increasing the bottom opening reduces attenuation across the entire frequency range

IV. Computer Modeling and Bench Scale Measurements

We initially studied the phenomenology and feasibility of using subsurface man-made structures to attenuate and divert hazardous seismic waves using 2D and 3D computer numerical models. Our effort involved 1) identifying hazardous seismic waves from earthquakes, 2) developing computational model of seismic wave propagation in complex geological media, and 3) developing metamaterial models applicable to seismic cloaking to induce seismic wave diversion and attenuation. Modeling results show subsurface borehole arrays may reduce the seismic energy from hazardous earthquakes in the vicinity of high value structural assets. Such seismic barrier structures may span 100s of meters to a kilometer in aerial range, with well depths of 100 meters or less, and costs that would justify construction. We conclude that such barrier arrays may reduce seismic wave amplitudes by 30 – 50 dB that would otherwise reach a high value asset facility. A model is shown below using a recent California earthquake's parameters for input in figure 2.
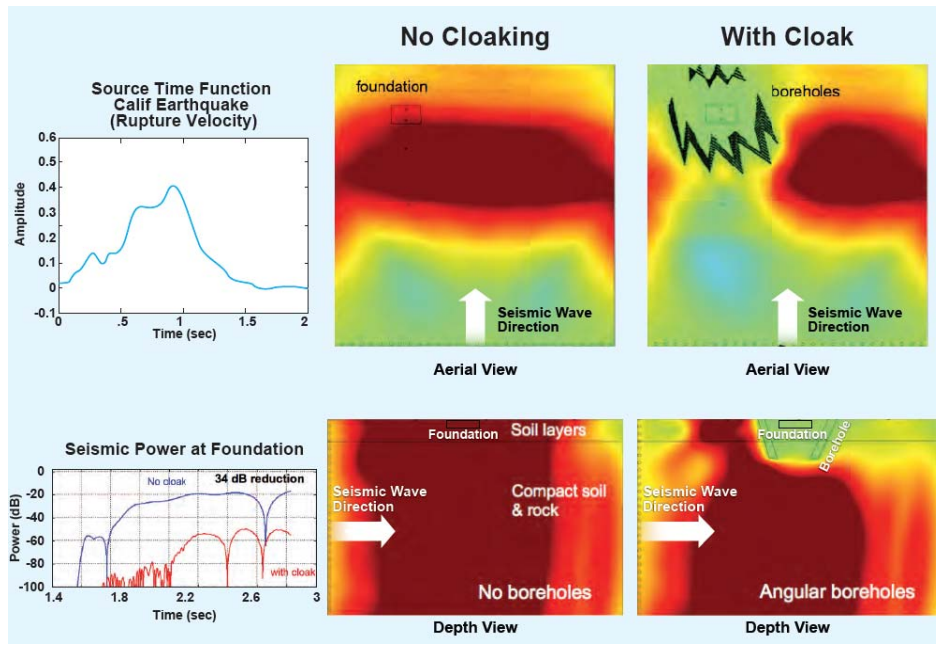
Figure 2. Finite Difference Model of the effects on seismic wave propagation from seismic cloaking – barrier structure. The seismic event is modeled for the response of the source function estimated for the Hector Mine earthquake in 1991 (Mag. 7.1 - USGS). Typical seismic frequencies are less than 1 Hz with minimal power above 1 Hz. *Top:* Areal view of seismic wave snapshots, with and without cloaking structures. *Bottom:* Vertical – depth view snapshot of the effects of the cloaking – barrier device. Using a single vertical borehole array or trench may significantly reduce the surface wave energy reaching a protected region. However, energy is able to diffract around the barrier. Using a V-shaped muffler is more effective in blocking surface waves in the 3D extent.

We next studied borehole arrays and trenches embedded in elastic media analogous to rock and compact soil using a machined table-top scaled physical model and compared with 3D computer modeling results. The effort focused on examining the effects of barrier structures on seismic wave propagation, diversion, scattering, and attenuation through spatial measurements from controlled seismic sources. The solid model was composed of Delrin plastic with a P-wave speed of 1700m/s, S-wave speed of 855m/s, and a density of 1.41g/cm^3 representing reasonable earth material analogs and is shown in figure 3. We observe that both 3D modeling of the Delrin block and measurements compare well within a factor of 2 demonstrating that our modeling approach is valid and supports merit to the seismic barrier concept.

We next compare the effects of the barrier structures on seismic wave reduction in terms of earthquake magnitudes. In this analysis, we reference the seismic power drop in dB to magnitude drop using the seismic moment magnitude scale, M_w. In figures 5 and 6, the V-trench structure as modeled and measured in the Delrin block is capable of reducing the seismic energy reaching a protection zone from seriously destructive

and dangerous levels down to minor damage with minimal risk of incurring fatalities.
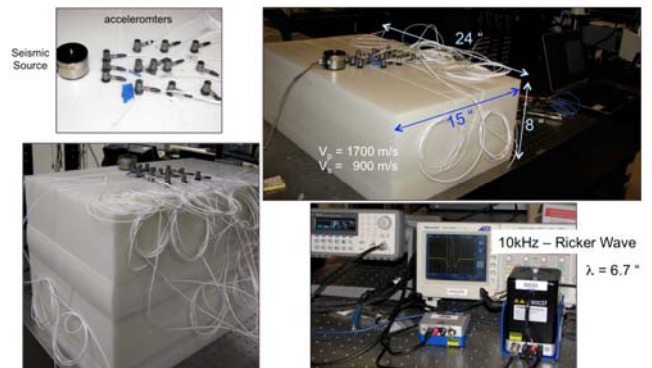

Figure 3. Table-top experimental configuration. Delrin blocks were machined to contain boreholes in prescribed patterns or trenches defining a V-shaped muffler and compared with homogeneous solid blocks.
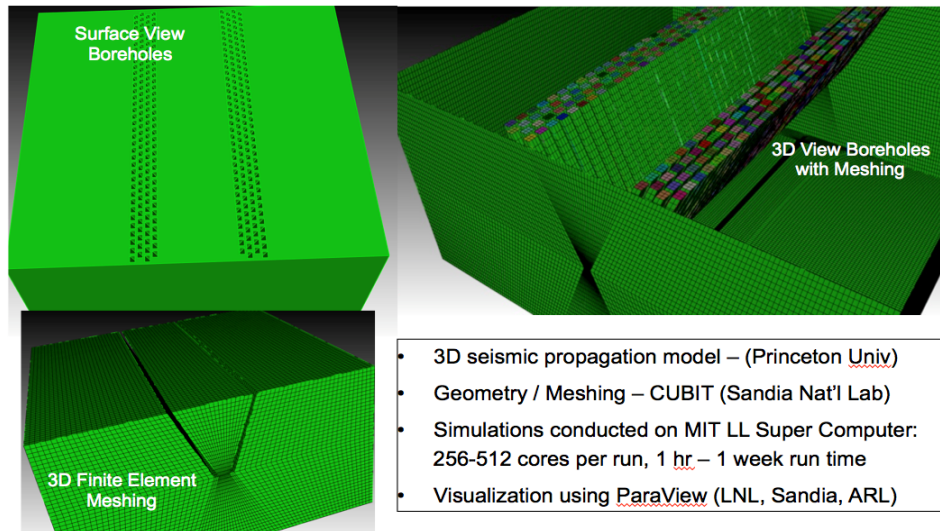
Figure 4. 3D Finite Element Model of the effects on seismic wave propagation from V-shaped muffler seismic cloaking – barrier structure.   The seismic event is modeled for the response of a Ricker Waveform source function.
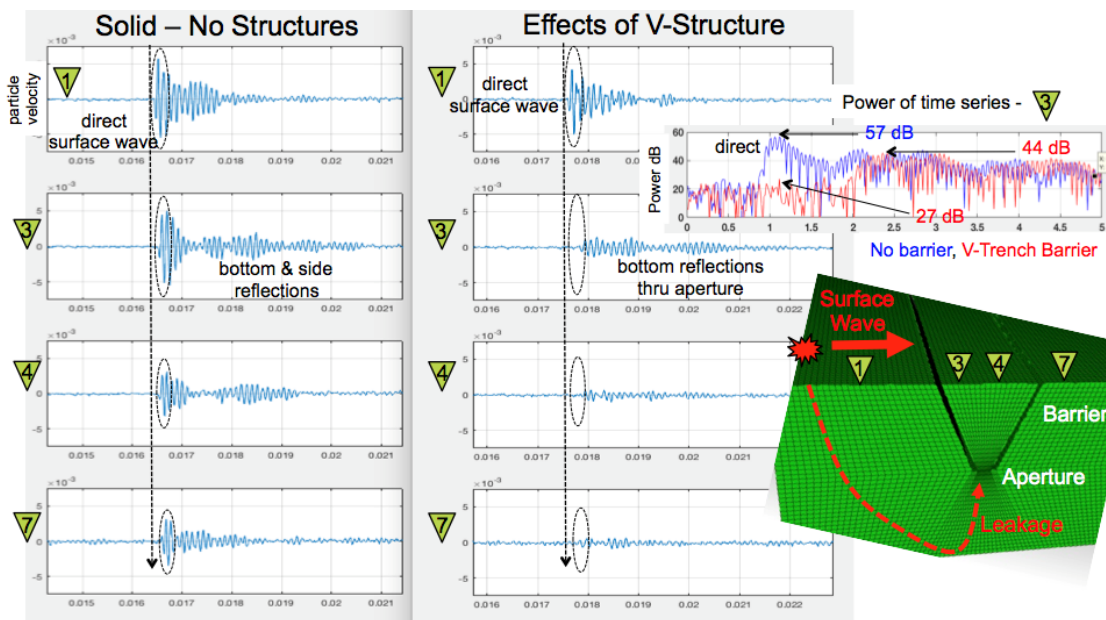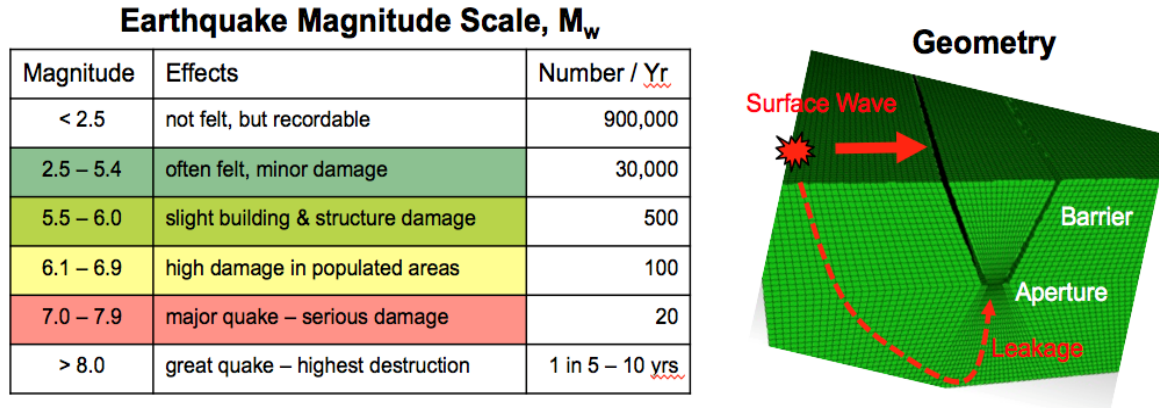

Figure 5. Measurement results showing effects of V-trench machined in delrin block Table-top experimental configuration.

Left: 4 accelerometer time series traces measured in the center line across a homogeneous solid delrin block relative to the transducer source location. Receiver 1, 3, 4, and 7 are 1, 3, 4, and 7 inches from the source. Particle velocities are computed by integrating the measured accelerations and then applying a high-pass filter to remove low frequency drift. A single 10kHz Ricker vertical load burst is recorded as it travels from its source. Each trace records a similar time series, showing a direct surface wave arrival (circled outline) followed by later reflection arrival interference from the delrin block side and bottom boundaries. The first break of the direct arrivals show a wave speed of 1693m/s. Spherical spreading and delrin attenuation losses are not compensated in the measurement plots. At the observed wave speed, the P-wave length is estimated at 17mm.

Right: 4 accelerometer time series traces measured in the center line across the delrin block that contains a V-trench barrier structure perpendicularly oriented to the direction of elastic wave propagation relative to the

transducer source location. Receiver 1, 3, 4, and 7 are 1, 3, 4, and 7 inches from the source, where receivers 3 and 4 are between the near and far trench walls. The trench barrier structure is shown in the green schematic to the right. The times series traces show that the direct surface wave is reflected off the near trench wall where, no to very little direct wave is observed inside the keep out zone between the near and far trench walls. The reflected arrival interference from the bottom surface is observed at the surface between the trench walls. In this geometry, elastic waves are able to leak through the aperture at the trench bottom and travel to the surface. These amplitudes, however, are lower than those of the peak surface wave that would be observed in the same locations if the barrier cloaking structure is not present.

We also model above the Delrin block and vibrational source using the 3D model described and observe that the computer models and measurements compare very closely as depicted in figure 6.

Earthquake Magnitude Scale, M_w

Magnitude	Effects	Number / Yr
< 2.5	not felt, but recordable	900,000
2.5 – 5.4	often felt, minor damage	30,000
5.5 – 6.0	slight building & structure damage	500
6.1 – 6.9	high damage in populated areas	100
7.0 – 7.9	major quake – serious damage	20
> 8.0	great quake – highest destruction	1 in 5 – 10 yrs

Extrapolation from measured and modeled results (ref to Mag 7 Quake)

Barrier Structure	Peak Surface Wave Reduction				Peak Surf to Leakage Reduction			
	measured		modeled		measured		modeled	
	dB	ΔMag	dB	ΔMag	dB	ΔMag	dB	ΔMag
Trench – V - block	24 - 30	5.4 – 5.0	26 - 30	5.3 – 5.0	13 - 14	6.1 – 6.2	11-13	6.2 – 6.3
Trench – V - earth			34 - 43	4.1 – 4.7			21-22	5.5 – 5.6

Figure 6. 3D Finite Element Model of the effects on seismic wave propagation from V-shaped muffler seismic cloaking – barrier structure. *Top:* Model geometry and mesh representing geological media and V-shaped muffler borehole / trench component structures. *Bottom:* In this simple analysis, the power drop observed in the measurement and model studies are presented in terms of M_w reduction. The V-trench structure shows that a magnitude 7.0 earthquake energy intensity can be reduced to 5.4 – 5.0 for the peak power of the direct destructive surface wave. The leakage through the aperture is measured to show a modest reduction. However, when modeling the earth, where the boundaries are infinite, diffraction leakage through the aperture is small and would provide a significant reduction.

Discussion - Conclusions

Constructing subsurface borehole arrays have the potential to divert, attenuate, and cause self-interference of seismic waves from earthquakes and significantly reduce the impact of hazardous waves reaching a designated building structure. Modeling and bench scale measurement results support this concept. Our next milestone is to conduct measurement and modeling of a controlled outdoor experiment where we use a water well drilling truck to drill the borehole array. A commercial seismic source will then be used to simulate the close to those of an earthquake. We will then measure before and after the emplacement of the borehole array to estimate it effectiveness: the amount of seismic wave power drop in a 'protection zone'.