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Seismic Barrier Protection of Critical Infrastructure from Earthquakes

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Abstract **–** Each year, on average, a magnitude-8 earthquake strikes somewhere in the world. In addition, 10,000 earthquake related deaths occur annually, where collapsing buildings claim most lives. Moreover, in recent events, industry activity of wastewater reinjection is suspected to cause earthquake swarms that threaten high-value infrastructure and properties. Earthquake engineering technology has evolved over many years to minimize the destructive effects of seismic waves. However, even under the best practices, significant damage and fatalities can still occur.

Here we present a novel concept that redirects and attenuates hazardous seismic waves using an engineered subsurface seismic barrier. The barrier consists of borehole array and trench complexes that inhibit destructive seismic waves from entering a designated ‘protection zone’. The barrier is designed to counter not only surface waves in the aerial-horizontal plane, but employs a vertical ‘V’ shaped muffler structure composed of opposing boreholes or trenches to mitigate seismic waves from diffracting and traveling in the vertical plane.

Computational seismic wave propagation models suggest that air or fluid filled subsurface V-shaped muffler structures are critical to the redirection and self-interference 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-sized models containing borehole arrays and trenches. The computer models and bench scale measurements indicate that effects of a devastating 7.0 M_w -magnitude earthquake can be attenuated to those of a minor magnitude-4.5 or -5.5 M_w earthquake within a specified protection zone.

Keywords **–** *seismic cloaking, acoustic muffler, metamaterials, borehole structures, earthquake mitigation*

Introduction

Damage caused by naturally occurring earthquakes to critical infrastructure such as power plants, regional hospitals, airport runways, gas lines, dams, etc., pose significant risk to civilians while adding tremendous cost and recovery time to regain their functionality. Lower energy earthquakes caused by industry activity are also a concern and were first recognized as a problem in the early 1950’s when nuclear waste was injected into wells at the Rocky Flats arsenal in Colorado [1]. Such earthquakes have been rapidly increasing worldwide and are attributed to wastewater reinjection practices used by the oil industry [2, 3]. For example, the state of Oklahoma experienced over 900 minor earthquakes in 2014-2015, with a recent 2016 quake of magnitude 5.8 [2,3]. These continual, albeit low-magnitude, earthquake swarms threaten extremely high value above- and below-ground pipelines that control oil supply, storage tanks, and transport in the U.S. by continuous shaking and are major economic and environmental risks.

Consequently, the need for a means to reduce the effects of earthquakes on critical infrastructure is of high importance and can have large economic and societal impact. Although effective building practices are being routinely applied to new construction, older existing high value structures are unlikely to be retrofitted, thus posing significant risk to civil function, the economy, the environment, and cause human casualties.

Figure 1 (left) describes the different kinds of seismic waves, including body and surface waves [4]. From the civil engineering perspective, the most destructive are surface waves (Rayleigh, Love, shear) which can travel great distances in the far field from the earthquake hypocenter and strike cities and critical infrastructure without warning. Here, we propose a novel concept to redirect and reduce the ground motion of earthquake surface waves by implementing an engineered below-ground seismic barrier optimally placed in the vicinity of high value structures. As shown schematically in Figure 1 (right), the structures employ borehole arrays to act as broadband seismic wave barriers that conceptually create a *cloaking* [5] metamaterial media that significantly reduces the energy that would otherwise reach an area we desire to protect. In this context, a metamaterial is defined a synthetic composite material composed of many subwavelength elements that significantly modify constitutive properties of a media, such as effective elastic moduli and mass density [6]. In this paper, we present computational and scaled experimental results of this concept that demonstrate the potential of seismic ground motion reduction at a critical structure's location by implementing an engineered below-ground seismic barrier in the asset vicinity.

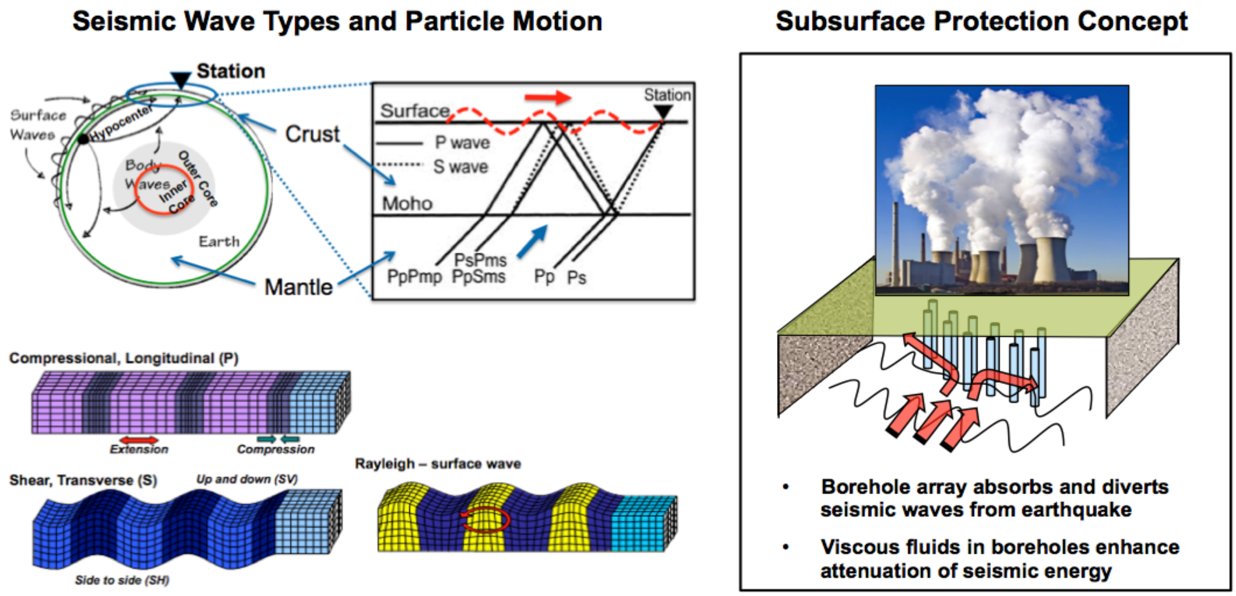


Figure 1. *Left:* Typical seismic wave types caused by earthquakes. Statistically, surface seismic waves (Rayleigh – ground roll, Love, Shear) can cause significant damage and destruction to man-nade structures in critical infrastructure [3]. *Right:* Notional borehole array

concept that diverts and absorbs hazardous seismic waves prior to reaching critical infrastructure.

Prior Investigations

The concept of seismic cloaking has been recently proposed as a means to redirect hazardous waves in the earth's subsurface by a few investigators [7-10]. The main limitation of most published results is the resonant nature of the proposed cloaking structures which does not address the broad bandwidth of naturally occurring and industry-induced earthquakes. Furthermore, there are limitations of scalability to low frequencies (large structures) as well as applicability to all seismic wave types. In addition, redirection can cause seismic waves to focus and concentrate as they propagate around the barrier actually increasing the ground motion experienced by neighboring sites to the side flanks of the barrier.

May and Bolt [7] performed some of the first numerical modeling simulations of the interference effects caused by air filled vertical trenches on seismic wave propagation. Their results showed that trenches greater than 100 meters could impede and attenuate seismic ground motion, however, seismic waves could still diffract underneath the trench and impact a 'protection zone' behind the trench. They found that using two trenches strategically placed on both sides of the protection zone would significantly reduce the seismic motion between the trenches. However, the trenches needed to be quite deep, on the order of several hundred meters. Moreover, constructive resonant behavior was observed between the trenches that depended on the seismic wave frequency, trench spacing, and trench depth. The excessive trench depth and risk of resonant behavior indicate that vertical trenches are ineffective and impractical for seismic motion reduction in a protection zone at the surface.

Brule et al. [8], performed the only controlled outdoor field experiments to date by a team from Institute Fresnel and Menard Construction company. An array of several dozen air filled vertical holes was constructed in an alluvial fill sedimentary basin outside of Grenoble, France to examine their effects on seismic motion reduction and attenuation. The holes were 1 meter square and 5 meters deep. The alluvial fill exhibits very slow seismic velocities with smaller wavelengths in comparison to those of most sedimentary and crystalline rock formations. A seismic 50 Hz CW source was generated by a vibrocompactor employed at the ground surface and was in close proximity to the hole array in the seismic near field. A modest attenuation of 3-5 dB was achieved by the borehole array, but shows that boreholes can have an effect on seismic energy reduction.

In other approaches, Kim and Das [9], suggested that burying large resonator tanks would convert incident seismic energy into acoustic energy and, thereafter, into heat. Our analysis of this approach using 3D finite element modeling, found that only energy at discrete resonance frequencies could be dissipated. Furthermore, shear waves cannot couple into and drive air or fluid filled resonator structures thus reducing the utility of this approach precisely for the more damaging types of waves. Krodel et al. [10], proposed burying seismic dampers for energy dissipation. In a scaled experiment in a sand tank, they found that many dozen different-size resonators would be required to cover the relevant frequency spectrum. However, scaling such approaches to full seismic wavelengths leads to structures hundreds of meters to a kilometer of extent in depth and would be impractical. In an alternative above-ground concept, Colombi et al. [11] suggested that tall trees or steel towers could be placed strategically to absorb some of the ground vibrations and dissipate seismic energy. However, in order to affect seismic frequencies below 10 Hz, the height of the above ground structures would have to be several hundred meters with a high density of objects over distances on the order of a kilometer. In addition, from the previous measurements and calculations, only energy at discrete resonant frequencies can be dissipated with this approach and requires towers of many heights and configurations.

‘V’ Shaped Opposing Borehole-Trench Muffler Structure

By contrast to the previously explored approaches that exploit metamaterial phenomena and narrow frequency band behavior, we propose a modification to the two-vertical trench design introduced by May and Bolt [7]. This approach may be significantly more effective in seismic motion reduction over a broadband frequency range while being more practical to build due to the shallower depth requirements. Our design involves a ‘V’ shaped borehole array or trench structure that is air or fluid filled, combining reflection from scattering theory, as well as attenuating acoustic muffler designs that enable not only aerial plane seismic wave diversion, but also vertical-depth plane protection against diffracted and upgoing waves. Such a design lends itself more realistically than the previous section strategies to the vertical extent of surface waves which can approach a kilometer in depth [4].

We first use the equations describing those of an acoustic muffler, plane wave propagation in conical and exponential pipes, derived by Easwaran and Munjal [12] to get an intuitive feel for the seismic wave attenuation performance of a conical muffler (Figure 2) and how this can apply to a subsurface system.

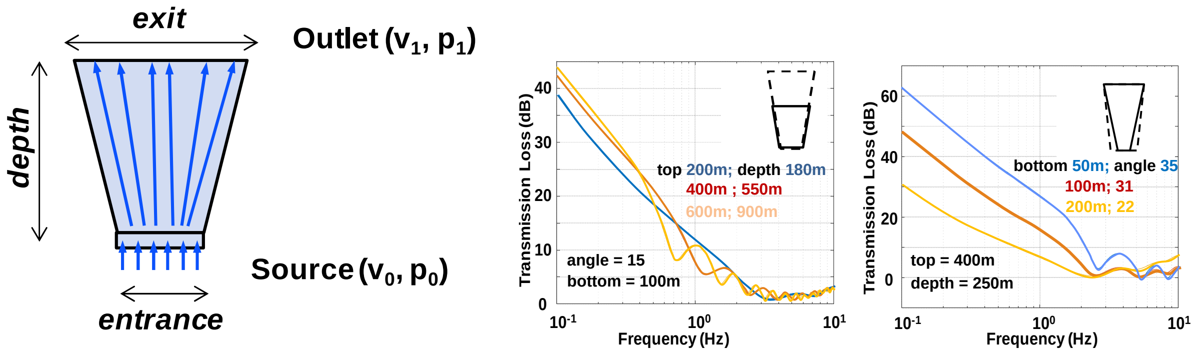


Figure 2. Left: Typical geometry for a conical muffler. Right: Acoustic wave transmission loss calculations for a conical muffler geometries of various dimensions. *Left:* Effects of increasing surface spacing and muffler length-bottom aperture depth. Taper angle and bottom opening are fixed. *Right:* Effects of increasing bottom aperture and muffler wall angle. Top opening and depth are fixed.

The model calculations show that: 1) increasing the muffler depth extent at constant angles increases attenuation at the lower frequencies, but reduces attenuation at higher frequencies due to multiple node resonance behavior, 2) increasing the muffler depth extent while holding a constant surface spacing and bottom entrance spacing, i.e., while reducing the angle, reduces attenuation across the entire frequency range, and 3) increasing the bottom muffler entrance reduces attenuation across the entire frequency range. To achieve the maximum attenuation of seismic motion for a broadband frequency response, the muffler parameters include a small bottom (entrance) aperture, shallow depth, and steep muffler wall angle. In our calculations, a 25-30 dB transmission loss from the muffler is possible for a shallow, steep angle structure at 1 Hz seismic frequency with greater reductions at frequencies less than 1 Hz. Broadband frequencies from hundreds of millihertz to 1 or 2 Hz are common for most large magnitude earthquakes where this frequency band appears to be well suited for the muffler structure. The achieved seismic motion loss at these frequencies implies that a destructive earthquake's effects can be significantly reduced to a magnitude that is much less destructive and hazardous. These results will be explored and described in sections below.

Achieving a steep wall muffler with a small bottom aperture may be challenging to build. We assume a bottom aperture is necessary to provide structural support to the 'protection area' without the muffler collapsing and closing on itself. We also assume that the boreholes or trench sides constructing the muffler can be built with modern engineering techniques.

Computer Modeling and Bench Scale Measurements

Following the analytical models describing muffler behavior, we performed full-scale analyses using 2D and 3D computer models. Our effort involved developing computational models of seismic wave propagation in complex geological media that contain high densities of boreholes and trenches. We then carried out scaled experiments at higher, non-seismic frequencies in large Delrin (plastic) blocks to examine the effects of machined trenches and borehole arrays. Computer model simulations and Delrin block measurements were compared for verification. Given the strong agreement between the computational model and the experimental measurements, the computer model was then extrapolated to study the effects of barrier structures on seismic wave propagation in an earth scale system.

2D Numerical Model Simulations

We first developed a fully explicit, 2D finite difference seismic wave propagation model for this study using the mathematical expressions described by Kelly [13]. The computer model was tested and compared against the published results of May and Bolt [7] for accuracy that provide the dimensions and properties of trench designs as a means to reduce seismic motions. First, we show 2D finite difference models to demonstrate the effectiveness of a complex 'V' shaped borehole array to mitigate seismic wave energy in a 'protection zone'. The model earthquake forcing function and geological cross-section was approximated from the parameters of the California Hector Mine earthquake in 1991 (Mag. 7.1 – USGS database) for input that is depicted in Figure 3. In the Figure, the seismic scattering due to the barrier array is shown in the horizontal and vertical planes separately for a far field seismic line source representing a plane wave. Since the model is 2D, the horizontal plane model assumes the borehole array is infinite in depth. Similarly, the vertical plane model assumes the borehole array is infinite in the cross-line direction, but finite in the in-line direction and depth.

Our modeling results show subsurface borehole arrays may reduce the seismic motion from a far field seismic plane wave as it encounters high value structural assets. In the Figure, the forcing function is injected into the model at the problem space edge as a particle velocity line source. Time planar snapshots of the particle velocity show that the seismic wave is reflected upon itself and redirected around the flanks of a jaggedly arranged borehole array that protects a foundation.

In the case without the borehole array, the foundation encounters the seismic wave at its full amplitude. We also show in the Figure, that the 2D vertical model displays the effects of a vertical single trench (in this case the borehole becomes a trench since the cross-line direction is infinite) and two opposing angular trenches comprising the V-shaped muffler. We observe that such barrier structures reduce seismic wave powers by 10 – 40 dB that would otherwise reach the foundation location. Moreover, the effectiveness of the muffler design is significant over a single vertical frontal trench by at least 10 dB and does not exhibit defined resonances that propagate up the muffler.

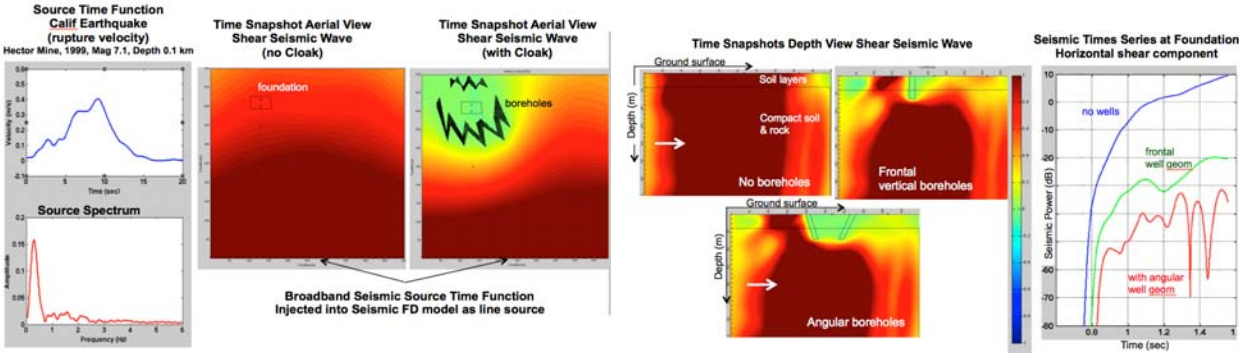


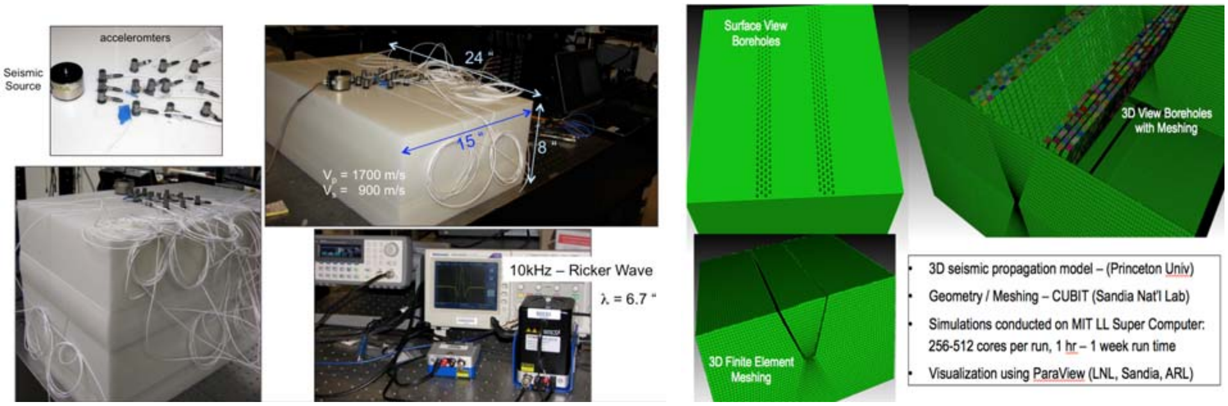
Figure 3. 2D Finite Difference Model of the effects on seismic wave propagation from jaggedly arranged borehole array – barrier structure. The seismic event is modeled for the response of the source function estimated for the Hector Mine earthquake in 1991 (Mag. 7.1 - USGS). Typical seismic frequencies are less than 1 Hz with minimal power above 1 Hz. *Left:* Areal view of seismic wave field time snapshots, with and without the borehole array. *Right:* Vertical – depth view snapshot of the effects of the V-shaped borehole line – barrier device. Far right: Seismic power reduction observed at the building foundation location for vertical well and V-shaped angular geometries.

3D Numerical Model Simulations and Comparisons to Bench Scale Measurements

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 them with 3D computer modeling results. For the 3D simulations, we used the SPECFEM3D geophysical package [14] that is designed for simulating full seismic wave propagation in complex geological media. In the model, geological elements are defined by the elastic properties of rock and compact soils that can be arranged in complex geometries representing naturally occurring geological features. In addition, we were able to include large numbers of small air-filled boreholes or trenches utilizing Python scripting capabilities of the modeling package. Mesh element sizes of about 1/1000ths of the wavelength were required in order to adequately resolve the borehole diameter dimensions. The SPECFME3D code was implemented on the MIT Lincoln Laboratory super parallel computer.

The effort focused on examining the effects of barrier structures in a large solid model on seismic wave propagation through spatial measurements from controlled seismic sources. The solid model was composed of Delrin plastic 24 inches across, 15 inches wide and 8 inches deep 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 5. We stacked several solid blocks to make the vertical extent 24 inches and reduce bottom reflection interference in signals of interest. The Delrin blocks contain air-filled boreholes in prescribed patterns or trenches defining a V-shaped muffler. Each borehole has a diameter of 3mm and is separated 3mm apart from neighboring boreholes forming a single line, where the line extends the entire length of the block. A near and far angular opposing borehole line forms the V shaped pattern where the near and far borehole line spacing is 3 inches apart on the Delrin surface, the boreholes are sloped with a 5-inch length (4 inch vertical depth), and provide an aperture opening at the V- borehole barrier structure base of 0.5 inches. Similarly, a V-trench barrier structure is machined in a separate Delrin block where the 3mm diameter boreholes are in contact forming continuous hollow walls on both sides of the barrier structure.

A Modal-Shop variable transducer is used to vertically load on the Delrin block surface to prescribed loading functions. We employ a 10 kHz Ricker waveform to act as the seismic input function to generate the elastic wave propagation in the Delrin blocks. PCB model 352C33 accelerometers are used to measure the vibration distributions observed on the Delrin surface. An IOTECH wavebook 516E records each time series trace using a synchronized 70 kHz sample rate per channel. We chose a 10 kHz source since the dimensional scaling of the Delrin block and seismic source by a factor of 10,000 translates to an earth scale computer model on the order of kilometers with a seismic frequency of 1 Hz.



- 3D seismic propagation model – (Princeton Univ)
- Geometry / Meshing – CUBIT (Sandia Nat'l Lab)
- Simulations conducted on MIT LL Super Computer: 256-512 cores per run, 1 hr – 1 week run time
- Visualization using ParaView (LNL, Sandia, ARL)

Figure 4. Left: 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. Right: 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 10 kHz Ricker Waveform source function.

In the measurement analysis of Figure 5, four accelerometer time series traces measured in the center line across the homogeneous solid Delrin block relative to the transducer source location. Receivers 1, 3, 4, and 7 are 1, 3, 4, and 7 inches from the source, respectively. Particle velocities are computed by integrating the measured accelerations. A single 10 kHz 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 shows a wave speed of 1693 m/s. Spherical spreading and Delrin attenuation losses are not compensated in the measurement plots.

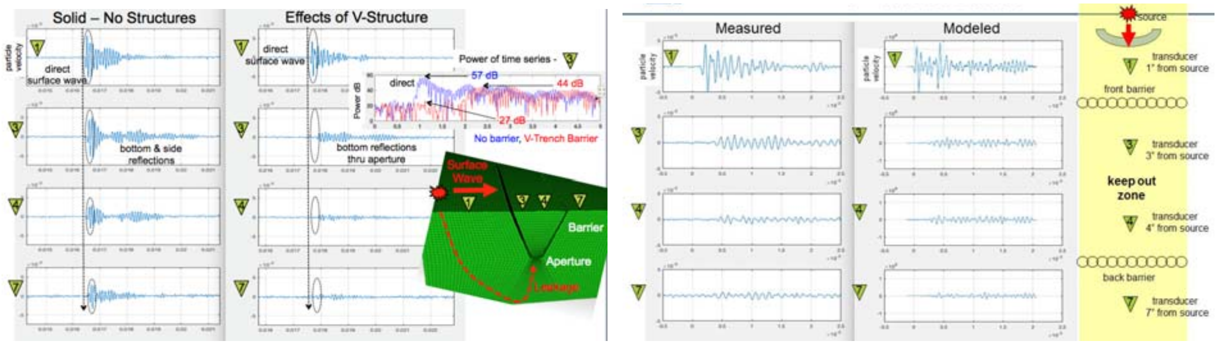


Figure 5. Left: Measurement time series results showing effects of V-trench machined in Delrin block Table-top experimental configuration on seismic wave propagation. Also shown are the time series for the identical location in a solid homogeneous Delrin block without any barrier structures. Right: Measurement and SPECFEM3D model results of the effects of the V-trench on seismic propagation showing good agreement.

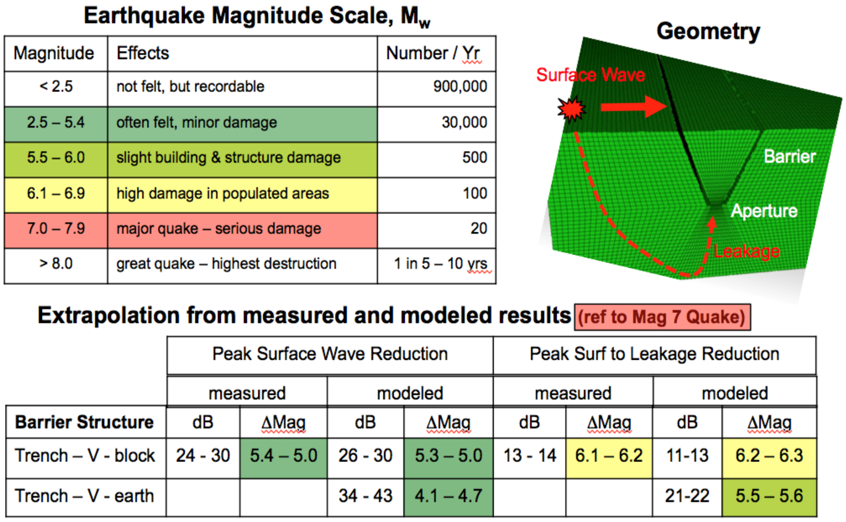
In Figure 5, the effects of the machined V-shaped structure are depicted by the four accelerometer time series traces measured in the center line across the Delrin block that contains a V-trench barrier structure perpendicularly oriented to the direction of elastic wave propagation relative to the transducer source location. Receivers 1, 3, 4, and 7 are 1, 3, 4, and 7 inches from the source, respectively, 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 time series traces show that the direct surface wave is reflected off the near trench wall where little to no 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.

A comparison between measurement and modeled time series results for the four stations is shown in the right side of Figure 5. The Delrin block and computer model contain a V-trench. The computer model contains the air-Delrin side and also the Delrin-table boundaries, so as to mimic as closely as possible the experimental geometry and composition. The plots show that the measured and modeled waveforms compare closely for each receiver location along the center line of the Delrin block. The 3D modeling of the Delrin block and experimental measurements compare well within a factor of 2 in magnitude. These results give us confidence that the 3D computer model can reasonably represent complex borehole and trench structures in elastic media and thus, we implicitly estimate that such structures can be reasonably modeled in the earth's subsurface. In addition, this comparison provides confidence that the computer model can be used to model more complex borehole arrays and trench designs at the earth dimensional scale of kilometers and seismic frequencies on the order of 1 Hz.

Estimated Effectiveness of V-Trench Barrier Structure in Scaled Earth Model

We next compare the effects of the barrier structures on seismic wave reduction in terms of earthquake magnitudes in an earth scale model. In this analysis, we reference the seismic power drop in dB to magnitude drop using the seismic moment magnitude scale, M_w. First, we examine the power drop in the Delrin block measurement and corresponding 3D model for a 10 kHz Ricker seismic source and then extrapolate to an earth-scale 3D computer model simulation using a 2 Hz Ricker source. Two cases are examined: a homogeneous volume and the same volume and properties with a V-trench extending across the volume.

In Figure 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 (when scaled to a 7.0 M_w earthquake for reference) and dangerous levels down to minor damage. In the top part of Figure 6, a table of earthquake magnitudes and relative destruction levels are summarized [15]. Next to the table shows the model geometry and mesh representing geological media and V-shaped muffler trench component structure dimensions as described in the previous section. In the bottom portion of Figure 7, simple analysis shows the power drop observed in the measurement and computer modeling studies that are presented in terms of M_w reduction. The V-trench structure shows that a 7.0 M_w earthquake energy intensity can be reduced to 5.4 – 5.0 M_w for the peak power of the direct destructive surface wave when encountering the V-trench muffler barrier. The leakage through the V-trench bottom aperture is measured and shows a modest reduction on the order of 11-14 dB. However, when modeling the earth scale, where the boundaries are infinite, diffraction leakage through the aperture is small and would provide a significant reduction, now 21-22 dB. The peak direct wave power change prevented by the barrier provides a 24-30 dB drop in the Delrin block and associated scaled computer model. For the case of the earth scale model, the trench barrier yields a 34-43 dB seismic power drop as observed at the surface station locations.



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)

	Peak Surface Wave Reduction				Peak Surf to Leakage Reduction			
	measured		modeled		measured		modeled	
Barrier Structure	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

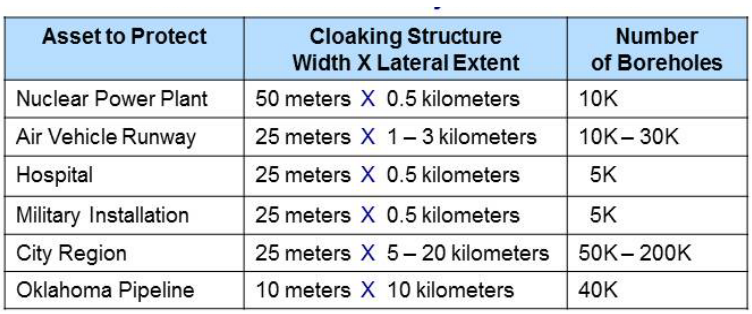
Figure 6. Top left: Table of earthquake magnitudes, destruction level, and numbers observed each year. Top right: 3D Finite Element Model geometry of the V-shaped muffler – barrier structure with seismic raypath. *Bottom:* Extroplation of measured and modeled results in terms of earthquake damage and the damage reduction predicted by the use of the V-trench structure. The model is also extrapolated to an earth scale model and corresponding seismic frequencies from an earthquake source.

Discussion

The modeling and measurement results presented in this paper suggest that borehole arrays and trench structures constructed in the earth's subsurface can potentially yield a net reduction from hazardous seismic waves from earthquakes at a desired surface location. We observed that a continuous trench wall muffler (1 meter thick) and 150 meter deep, is quite effective and can provide a 30 dB or greater seismic power drop for a direct surface wave, giving merit for infrastructure protection against hazardous surface and body waves.

We found in our measurement and modeling studies that implementing a single borehole line only is relatively ineffective where the seismic amplitude is reduced only by a factor of 2 since much of the seismic wave energy communicates in between wells. However, our modeling studies also show that the effects of closely spaced boreholes laterally and in width of the array can yield similar power reductions as a relatively thin walled continuous air-filled trench. Spacing boreholes 2.5 meters apart laterally and in width can cause enough interference approximating a trench. Moreover, neighboring borehole rows need to be staggered to minimize seismic wave communication in between rows.

Using some simple assumptions where a single borehole has a diameter of 1 meter and spacing boreholes 2.5 meters apart while staggering neighboring rows, 400 boreholes would fill an area of 100 x 10 square meters. These parameters can now be used to estimate the number of boreholes needed to protect critical structures with examples shown in Table I.



Asset to Protect	Cloaking Structure Width X Lateral Extent	Number of Boreholes
Nuclear Power Plant	50 meters X 0.5 kilometers	10K
Air Vehicle Runway	25 meters X 1 – 3 kilometers	10K – 30K
Hospital	25 meters X 0.5 kilometers	5K
Military Installation	25 meters X 0.5 kilometers	5K
City Region	25 meters X 5 – 20 kilometers	50K – 200K
Oklahoma Pipeline	10 meters X 10 kilometers	40K

Table I. Example Assets and Estimated Borehole Array Structure Size and number of boreholes required. The borehole density is assumed to be 2.5 m in spacing each with a 1 meter diameter.

We estimate a borehole array width to be effective in reducing the magnitude of a hazardous naturally occurring earthquake, on the order of a 6 M_w or greater may require 10 boreholes in thickness (25 meter width). For an earthquake swarm caused by industrial activity, the typical earthquake magnitude would be less than 6 M_w and could afford to use an array width of 10 meters when protecting a pipeline. In the case of a nuclear power plant, using an array thickness of 50 meters may be warranted for extra protection and redundancy.

Conclusions

Constructing subsurface borehole arrays and trench structures may 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. Our ‘V’ shaped muffler formed by an air-filled trench of densely packed borehole arrays may provide a solution path that is feasible to impliment. Modeling and bench scale measurement results support this concept. Results indicate that effects of a devastating 7.0 M_w -magnitude earthquake can be reduced to those of a minor magnitude-4.5 or -5.5 M_w earthquake within a suitable protection zone at the earth’s surface using the ‘V’ shaped muffler barrier. These results are very promising, and warrant validation in field scale tests.

In terms of cost, drilling tens to hundreds of thousand boreholes is not trivial. However, when compared to the damages, loss of life, and loss of national asset security, the cost may be warranted and requires further study. Trench structures do deserve consideration if there is an ability to build them to the dimensions needed for the scale of protection. They appear to be quite effective in the form of the V-shaped muffler. A combination of trenches and boreholes may be more economical to build and may have merit for further investigation. It is important to note, that achieving a steep wall muffler with a small bottom aperture may be challenging to build. We assume that the boreholes or trench sides constructing the muffler can be built with modern engineering and drilling techniques, but may have limitations due to technology capabilities which we have not explored in detail.

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