Elastodynamic Simulation of Tunnel Detection Experiments in Heterogeneous Geological Media

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ABSTRACT: The detection of unknown tunnels and underground voids, such as old mine workings or solution cavities in karst terrain, is a challenging problem and an important concern for geomechanical design, public safety, and domestic security. Over the years many near-surface seismic methods have been developed and used to find such openings, but with oftentimes poor results. The most promising of these techniques include surface wave backscattering, surface wave transmission, and body wave diffraction imaging. One confounding element is accounting for the natural heterogeneity of the subsurface velocity model. In our proposed method, we simultaneously solve the problems of wave propagation around a void and through a heterogeneous embedding medium. We generate a range of three-dimensional, synthetic, heterogeneous velocity models using fractal statistics, embed them with fluid-filled tunnels, and then simulate commonly used void detection experiments using the elastodynamic wave propagation code E3D. Our results show that, even for small levels of heterogeneity, the primary scattered wavefield and undesirable resonant coupling between the void and heterogeneities may obscure the useful signal. In addition, our results show that as the magnitude of heterogeneity in the velocity model increases and the fractal dimension increases, the confidence level in geophysical anomalies decreases and the void detection threshold size increases due to scattering and reflections in the medium.

1. INTRODUCTION

Tunnel and void detection is an important, yet challenging problem in geophysics, which has applications in mining transportation public safety, and even domestic security. Over the years, researchers have developed a number of geophysical techniques to locate these objects, including gravity measurements [1, 2, 3], electrical methods [1, 3, 4, 5, 6], GPR [1, 3, 7, 8], and seismic methods such as surface wave backscatter and body wave diffraction [1, 3, 9, 10, 11, 12, 13, 14]. Some case studies have shown success in void detection; however, problems with uniqueness and resolution are common. In this paper we will be focusing on three seismic methods: body wave diffraction, surface wave backscattering, and resonant emission.

The geophysical community has extensively studied body wave diffraction imaging, since its first reported use in 1952 by Krey [14]. This technique relies upon the interaction of high-frequency seismic waves with low-velocity inclusions embedded within an elastic medium. The interaction generates a secondary wavefield, which radiates outwards in a predictable manner, and may be detected by geophones in the far field [15]. A number of researchers have reported success in determining the lateral location and depth of tunnels using this method [3, 15].

In contrast to diffraction imaging techniques, surface wave backscatter imaging uses much lower frequency seismic waves, and has recently become popular in the literature [3]. The imaging relies upon the interaction of Rayleigh waves with objects in the subsurface, which causes the wavefield to scatter, attenuate, or experience phase dispersion. Researchers have also reported success in determining the lateral location of tunnels using this method [3, 9, 10, 11, 12].

Resonant seismic imaging is a novel technique for estimating the size and location of voids in the subsurface. When the primary wavefield interacts with an inclusion, it generates a number of secondary waves that propagate within and around the object. If the inclusion is a fluid, then a slowly decaying Stoneley wave may be excited within it [16]. Then, when the Stoneley wave interacts with the surrounding rock mass, it may radiate energy outwards. The end-result is a persistent, harmonic tertiary wavefield that may be recorded by far-field geophones. Korneeve reported success in determining the location of a small fluid-filled barrel using a phase inversion technique on the resonant wavefield [17].

There is a significant omission within most studies involving seismic void detection methods: a comprehensive analysis of efficacy of these methods in
realistic, heterogeneous geologic media. Historical measurements, including borehole measurements and surface observations, show that over wide range of scales geologic media are heterogeneous. The statistical behavior of this heterogeneity is well understood and is commonly modeled using fractal techniques [18, 19]. In spite of these observations, it is common to assume that the tunnel-embedding medium is a homogeneous, isotropic material.

There are two primary strategies for solving the wave equation in heterogeneous media. The first is to solve the stochastic wave equation using a low material contrast approximation, such as Born or Rytov [20, 21]. This strategy is useful because it generate statistically meaningful information about the wavefield; however, the useful frequency range is limited and the method is only accurate for a single mode of scattering (e.g.: forward or backward scattering) [21]. The second strategy is to use a numerical simulation technique, such as finite difference or finite elements, which solve the problem directly using the momentum equation. This strategy tends to be mathematically simpler, but requires a much larger computational effort [22].

While the problem of wave propagation through an object containing a void, or an object containing heterogeneity is well understood, wave propagation in an object containing both of these is not understood. The signals used for void imaging techniques are often small, and may be obscured by scattered wave film phenomena including code waves dispersion and scattering attenuation [23, 24]. In our method, we simultaneously solve these two problems to evaluate the effects of scattering and resonant coupling on the signals used for tunnel detection methods. We begin by generating a matrix of synthetic, heterogeneous velocity models using fractal statistics, and then we embed the models with a cylindrical fluid filled void. Finally, we simulate the tunnel detection experiments using the 3D elastodynamic wave propagation code E3D [25].

### 2. MODEL GENERATION

#### 2.1. Black Diamond Mine

The reference case study used in this research is a tunnel located in the old Black Diamond Mine, near Antioch California [26]. The tunnel is roughly 1.7 m in diameter, and is buried 4.3 m below the surface. The surrounding rock mass consists of a low-quality shale, coal seams and a section of debris. The average compressional wave velocity in this area is 1.5 km/s, the shear velocity is 1.0 km/s, and density is 2300 kg/m$^3$.

During 2012, a group of students from UC Berkeley collected surface seismic data around this tunnel. They observed significant surface wave backscattering from the tunnel and Rayleigh wave attenuation across the tunnel axis (publication forthcoming). Our goal is to develop a numerical model with this same geometry that displays the features observed during this investigation.

#### 2.2. Geologic Heterogeneity

The distribution of material properties in heterogeneous geologic media, including density, velocity, and attenuation, is commonly modeled using fractal statistics [18, 19, 21]. To generate a synthetic fractal distribution, we begin by generating a matrix of normally distributed random values. We transform these values into the frequency domain and then scale the results using the fractal filter given in Equation 1, where $k$ is the wave number, $\beta$ is the fractal exponent, and $S$ is the fractal filter. Finally, we bring the values back into the space domain and scale them to have the desired fractal amplitude ($\epsilon$) and mean ($\mu$).

$$S(k) = |k|^{-\beta/2}$$

For an isotropic medium, we assume that the fractal exponent is equal in all directions, and for a layered medium, we assume that the exponent in the horizontal directions is significantly greater than the exponent in the vertical direction.

The characteristics of the geologic medium in question govern the choice of fractal exponent. For $\beta$=zero, the resulting distribution is uncorrelated Gaussian noise. Low values of fractal exponent ($\beta<1$) correspond to rapidly changing chaotic media, whereas higher values of fractal exponent ($\beta>1$) correspond to cyclic deposition. For $\beta=2$, the resulting model is equivalent to Brownian walk [18].

We consider a range of fractal exponents and amplitudes in our study, but in this paper, we present the representative results for an isotropic fractal medium with $\beta=1.7$ and $\epsilon=5\%$. A realization of a velocity material that displays these fractal characteristics is included in Figure 1. In addition, we only permit a single degree of freedom for the heterogeneity by varying only the shear modulus. We chose these values because the resulting models display acceptable wavefield scattering behavior.

#### 2.3. Void Generation

We choose to analyze tunnels filled with a low-velocity fluid because it is a more stable problem, we want to generate Stoneley waves, and it is a realistic scenario. One major consequence of this choice is that the amplitude of the secondary wavefield will be lower in amplitude than for an air filled tunnel.

A common issue with elastodynamic wave propagation codes arises where two adjacent grid points have an impedance contrast that is too high. When we are generating the heterogeneity in the embedding medium, the fractal amplitude is low enough not to cause problems; however, the desired impedance between the
3. NUMERICAL ANALYSIS

We use the 3D, elastic, finite difference wave propagation code E3D to model the wavefield as it passes through the heterogeneous medium and interacts with the tunnel. E3D, which is developed by Shawn Larsen at Lawrence Livermore National Laboratory, is explicit, 4th order accurate in space, and 2nd order accurate in time [25]. The following sections describe the velocity model, boundary conditions, and the computational resources for modeling.

3.1. Velocity Model

Our numerical models are 60 m long, 30 m wide, 30 m deep, and have a grid size of 0.08m (see Figure 2). The models were designed to match the geometry and material properties at the Black Diamond mine. The embedding medium has an average P-wave velocity of 1.5 km/s, S-wave velocity of 1.0 km/s, a density of 2300 kg/m³, and fractal parameters $\beta=1.7$ and $\varepsilon=5\%$. A cylindrical fluid filled tunnel, with a radius of 1.7 m, is embedded 30 m from the source at a depth of 3.4 m. The tunnel is characterized by a P-wave velocity of 0.35 km/s, S-wave velocity of 0 km/s, attenuation coefficient of 30, density of 1000 kg/m³, and fractal parameter $\varepsilon=0\%$.

3.2. Boundary Conditions

A free-surface boundary condition is applied to the top of the model, and a quiet (Clayton and Engquist) boundary condition is applied to the sides and bottom of the model [27]. To mitigate the reflection of waves from the model boundaries, we apply a 25-gridpoint layer of highly attenuating material on the sides and bottoms of the model. In addition, we suppress the material-

tunnel and the embedding medium may differ by orders of magnitude. To address this, we grade the material velocity and density over 8 to 10 points in the model.

3.3. Computational Resources

Each model was run for a total of 150 ms, with the time step size less than 0.1 times that required by the Courant condition. This is twice the time required for the direct wave to travel the distance of the model, and is sufficiently long to model the late-arriving phases from the tunnel. These simulations were completed on a workstation with two-hex core Intel Xeon processors using the OpenMPI protocol. With some optimization, the total code runtime and post-processing completed in about one day per model. Data Processing

We scale the results of the model by applying a surface wave spreading correction to the data given in Equation 2, where $v_r$ is the Rayleigh wave velocity, $t$ is the model time, $V_z$ is the measured velocity, and $V_z^*$ is the corrected velocity. Instead of using the usual geometric source distance, we take distance as the product of time and velocity. This formulation of the spreading correction tends to accentuate the later arriving phases in the numerical model.

$$V_z^*(t) = V_z(t) \cdot (v_R t)^{1/2} \quad (2)$$

After applying spreading correction, we apply a 3rd order, Butterworth lowpass filter to the data, with a corner frequency of 4 kHz. This filter helps to diminish any high-frequency numerical noise, or any incoherent
high-frequency scattered waves that may be present in the results.

We are also interested in the amplitude spectrum of the late arriving wavefield, since it is theoretically related to the dimensions of the void. To calculate this, we select the data after the direct waves have passed the station, and apply a Gaussian window, and use Welch’s method with eight sampling windows. This yields a stable estimate of the late arriving power spectrum.

4. Results

To illustrate the effect of heterogeneity in the embedding medium on seismic tunnel detection techniques, we begin by presenting the results for a homogeneous reference model. Afterwards, we present the results for a model that includes fractal heterogeneity and compare the resulting wavefields.

4.1. Homogeneous Model

Figure 3 contains a common shot point gather along the surface of the homogeneous tunnel model, with the source located at X=0 m and the apex of the tunnel located at X=30 m. A number of important seismic phases are highlighted on this record. The direct compressional wave (P) and the direct Rayleigh wave (R) are the first two recognizable phases to arrive at the each station. We observe that the amplitude of the direct surface wave, after being corrected for spreading and attenuation, decreases as it encounters the tunnel (see Figure 3). This apparent increase in attenuation is expected, since the dominant wavelength is greater than the tunnel depth. In a Rayleigh wave attenuation analysis this anomaly would be interpreted as a void.

The next major phase to arrive at many stations is the boundary reflection (PP), which is the result of imperfect boundary conditions and is the greatest contributor of
broadband numerical noise in this model. Because this phase arrives at a predictable time, it does not adversely affect the results of this analysis.

The last two major seismic phases include the primary backscattered Rayleigh wave (RR) and the resonant emission from the tunnel (RTR). A detailed view of these phases as measured at X=0 m is included in Figure 4. In our models the backscattered wave tends to be larger of these two phases. Surface wave backscattering tunnel detection methods search for the point where the projected arrivals of the R and RR phases intersect. Figure 3 clearly shows that this intersection occurs at the apex of the buried tunnel.

The resonant emission wave arrives following the primary backscattered wave and tends to be lower in amplitude; however, this wave decay very slowly in time and it is distinguishable in the forward and backwards directions. The void detection technique described by Korneev uses a phase inversion to search for the origin of these resonant emissions using a long time window [17]. The usefulness of this technique may be illustrated visually by tracing lines of constant phase for this wave. From Figure 3, we see that the intersection of these lines occurs at the apex of the tunnel. There is also useful information contained within the power spectra for this wave (see Figure 4). Theory predicts that there will be a peak in the energy at the resonant frequency of the tunnel, and in our case, we see a clear peak at 250 Hz.

4.2. Heterogeneous Model

Figure 6 shows the common shot point gather along the surface of a heterogeneous tunnel model, with the source located at X=0 m and the tunnel apex at 30 m. In this model, the fractal exponent is $\beta=1.7$ and the fractal amplitude is $\varepsilon=5\%$. We highlight the same important seismic phases as in the homogeneous model (see Figure 5). Again, we see that the direct compressional wave and the direct Rayleigh waves are the first distinguishable phases to arrive. We also see a decrease in the surface wave amplitude around the tunnel (see Figure 5).

In the heterogeneous model, there are two significant changes to these waves: First, a significant amount of high-frequency noise is added to this signal, and is the result of interaction with the heterogeneity. Second, we observe that a coda wave follows each of these waves. This is most clear in Figure 5 for stations less than 30 m from the source. We also see the boundary reflection phase in this model, which arrives during the Rayleigh wave coda.

In the heterogeneous model, the later arriving modes are not as easy to distinguish, due to scattering and dispersion of the direct waves. A detailed view of these waves is included in Figure 6. Because of the high-frequency noise at the beginning of this trace, the arrival time of this phase is not as clear. Regardless, for this level of heterogeneity a backscatter imaging method would still successfully locate the position of the tunnel.

It is important to note that because we are using a spreading correction based upon travel-time, the signal to noise ratio of the signal is not altered. If the time window is too long or the signal to noise ratio is too low, then the processed signal will appear to grow with time and may provide erroneous results.

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Figure 5: (Left) Vertical velocity for a trace perpendicular to the tunnel axis using a heterogeneous velocity model with $\beta=1.7$ and $\varepsilon=5\%$. The P, direct Rayleigh, boundary reflection, backscattered Rayleigh, and resonant emission waves are highlighted. (Right) The observed amplitude of the direct Rayleigh wave. A distinct increase in attenuation is observed near the tunnel.
The coda wave from the primary backscattered surface wave partially extends into the resonant emission wave. In addition, we see minor phase distortions throughout the wave, which are akin to a coda wave, except that they are generated from a continuous harmonic source. Because these distortions are small, we are still able to trace lines of constant phase and locate the tunnel. For larger distortions, a Radon transform may be necessary to distinguish these linear features. Again, we include the power spectrum of this signal in Figure 6. Compared to the previous model, the spectrum has broadened, but we still see a peak around 250 Hz.

5. DISCUSSION

The initial results of our models suggest that tunnel detection in heterogeneous geologic media is possible, but faces certain challenges: First, the resultant signals associated with tunnel detection are often very small. The models presented in this paper had a small degree of heterogeneity contrast in the embedding medium ($\varepsilon=5\%$) compared to the impedance contrast between the tunnel and the medium (~90%). This resulted in coda waves on the direct and backscattered waves, and some minor phase distortions of the later arriving signals. As the amplitude of the heterogeneities increases, then these features will become more severe, and void detection methods may cease to be accurate.

The second challenge to tunnel detection in heterogeneous media is related to the fractal exponent of the embedding medium. As long as the dominant wavelength of the signal is much larger than or much smaller than the average size of the heterogeneities, the scattering will be in the backward scattering regime or forward scattering regime, respectively. These types of scattered wavefields are easily characterized by the Born or Rytov approximations, and do not pose any particular challenges to tunnel detection. However, when the average size of the heterogeneities is on the order of the dominant wavelength, then resonant scattering will dominate. By itself, this could lead to the trapping of energy within the geologic structure. The challenge to tunnel detection methods is the possibility of resonant coupling between the void and the geologic structure, which may lead to chaotic behavior. We believe that there is some critical ratio between the heterogeneity amplitude and the tunnel amplitude contrast, such that the problem of tunnel detection becomes untenable due to one of the issues described above.

6. CONCLUSION

The problem of tunnel and void detection using seismic waves is challenging, and in the presence of naturally occurring heterogeneity the problem becomes increasingly difficult. Using a combination of fractal statistical methods and numerical simulations, we evaluate the effectiveness of surface wave backscattering and diffraction imaging for a heterogeneous medium. Moving forward, the goal of our research is to explore this problem for a wide variety of fractal characteristics and tunnel dimensions to determine the conditions where we expect these methods to yield positive results.

REFERENCES


