CHARACTERIZATION OF AN EXPLOSION SOURCE IN A COMPLEX MEDIUM BY MODELING AND WAVELET DOMAIN INVERSION

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ABSTRACT

Explosions often are conducted in complexes with chambers, tunnels, and shafts used for access and instrumentation. These structures can act as strong scatterers of seismic waves and complicate the radiation patterns from explosions. The objectives of this project are (1) to study the effects of these near-source scatterers on seismic waves radiated from explosions, and (2) to use a wavelet domain based moment-tensor inversion scheme to determine "explosive" and "multi-couple" components of the source.

The modeling of seismic waves from an explosive source near a strong scatterer, such as a tunnel, is done using a finite-difference code. The code is developed for realistic earth models including (1) free surface, (2) heterogeneous structure, (3) surface topography, and (3) seismic attenuation. In addition, a perfectly matched layer (PML) was incorporated into the code to improve the absorption at the boundaries. Forward modeling using the 3-D finite-difference code was conducted with an explosive source and a tunnel in a layered half-space. Calculations were carried out for (1) a reference model without a tunnel, and (2) a model with a finite length horizontal tunnel. The calculations show P to P and P to S scattering and a complicated radiation pattern. P to S scattering is amazingly strong and the tunnel acts as a virtual shear wave source. Because of shallow depth, surface waves dominate the seismograms and significant SH waves are generated by the presence of the tunnel.

The effects of wave scattering due to various topographical features are investigated. Realistic and smooth topographic features do not contribute much to scattering. However, features with sharp gradients or corners, such as a mesa or canyon, act as strong scatterers of seismic waves, especially of surface waves.

To determine the properties of a complex source, such as an explosion and a tunnel, we evaluated the effectiveness of two approaches. The first is a wavelet domain moment tensor inversion. Synthetic seismograms are used to test the performance of moment tensor inversion and its ability to separate the volumetric and shear components of the source. The method is well suited for sparse networks. With good azimuthal coverage, the moment tensor shows significant shear components in the presence of a scatterer. Second, we tested the applicability of the time reversed acoustics (TRA) approach for detecting the presence of a tunnel near the source. In this approach, the recorded seismograms are time-reversed and sent back into the earth at each station. The back-propagating wavefields focus at the source. The P wave focuses strongly at the explosion and the S wave at the tunnel. TRA has great potential for determining the seismic source properties.

OBJECTIVES

An explosive source in a laterally homogeneous layered half-space generates P, SV, and Rayleigh waves, but not SH or Love waves. However, seismograms from a large number of explosions show nonisotropic radiation patterns for P- and Rayleigh waves, and prominent SH and Love waves. The near-source contribution to nonisotropic radiation of P-, Rayleigh waves, and SH wave generation by an explosion can be attributed to one or more of several mechanisms: tectonic strain energy released by the explosions; the shape of the explosion cavity; scattering from surface topography; and near source scattering. The objective of this research is to study the role of scattering from near source structures such as tunnels, shafts, adits, and surface topography for contributing to the generation of complicated radiation patterns and SH waves from explosions. In addition, the study will test the performance of moment tensor inversion to separate the isotropic (i.e., explosion) and multi-couple components of the source as an aid to seismic discrimination.

RESEARCH ACCOMPLISHED

A three-dimensional (3-D) finite difference program was developed to model wave propagating and scattering in heterogeneous media. The program utilizes a variable grid implemented through a grid-stretching technique. A rotated staggered grid scheme is also implemented to handle arbitrary topography and high contrast interfaces in the media. The code is parallelized to run on a computer cluster. Calculations are conducted for 3-D modeling with an explosive source and a finite length tunnel in the earth with free surface and topography. The calculations show P to P and strong P to S scattering as well as a complicated radiation pattern when an explosive source is placed near a tunnel. A new wavelet-domain moment tensor inversion with the calculated seismograms shows that the equivalent source has a double couple component, but the isotropic component still dominates. The time reversed acoustics (TRA) approach is capable of detecting the presence of a tunnel near the source and shows great potential for determining the seismic source properties.

Modeling by the Finite Difference Approach

Various calculations were carried out for an explosive source. Figure 1 shows the 3-D geometry of the model with an explosive source and a finite length, horizontal, cylindrical tunnel, in a two-layer earth model. Simulation is also conducted without the tunnel. The dimensions of the model in the x, y, and z directions are 6,000 m, 6,000 m, and 400 m, respectively. The thicknesses of the first and second layers are 300 and 100 meters, respectively. PML absorbing boundaries are placed at five sides of the model to eliminate spurious reflected waves from the boundaries. The top of the model is the free surface. An explosion source with a center frequency of 10 Hz is placed at 100 m depth. The length and radius of the cylindrical tunnel are 50 m and 15 m, respectively. The axis of the tunnel is parallel to the y axis, as shown in Figure 1.

The elastic properties of the formations and tunnel are as follows. In the first layer, the formation compressional and shear wave velocities and density are 3000 m/s, 1700 m/s, and 2300 kg/m^3, respectively. In the second layer, the formation compressional and shear wave velocities and density are 4000 m/s, 2300 m/s, and 2800 kg/m^3, respectively. Inside the tunnel, we assume an acoustic velocity of 340 m/s and a compressed air density of 200 kg/m^3.

The receiver array with 100 m spacing forms a grid on the free surface. The first row of Figure 2 shows the x and z components of the seismograms along the x axis (velocity fields) when the tunnel is absent. Due to multiple reflections between the free surface and the layer boundary, P-, S-, and surface waves are generated and the wavefield becomes complicated. When the tunnel is present near the explosion source, strong scattering occurs. The seismograms in the second row of Figure 2 show that the strong shear waves are scattered from the tunnel. To demonstrate the effect of scattering, we subtract the seismograms with an explosion only from those with the explosion plus the tunnel. The third row of Figure 2 shows the scattered waves. These show that the scattered S waves are much larger than the scattered P waves.

The azimuthal variation of seismograms and scattering to SH waves due to the tunnel are demonstrated by showing the recordings at a circular array of points at the surface. Figure 3a shows the seismogram traces when a tunnel is present near the explosion. Figure 3b shows the scattered wavefields only, obtained by subtracting the wavefields due to an explosion only. Note the strong lobate azimuthal distribution of the SH waves.

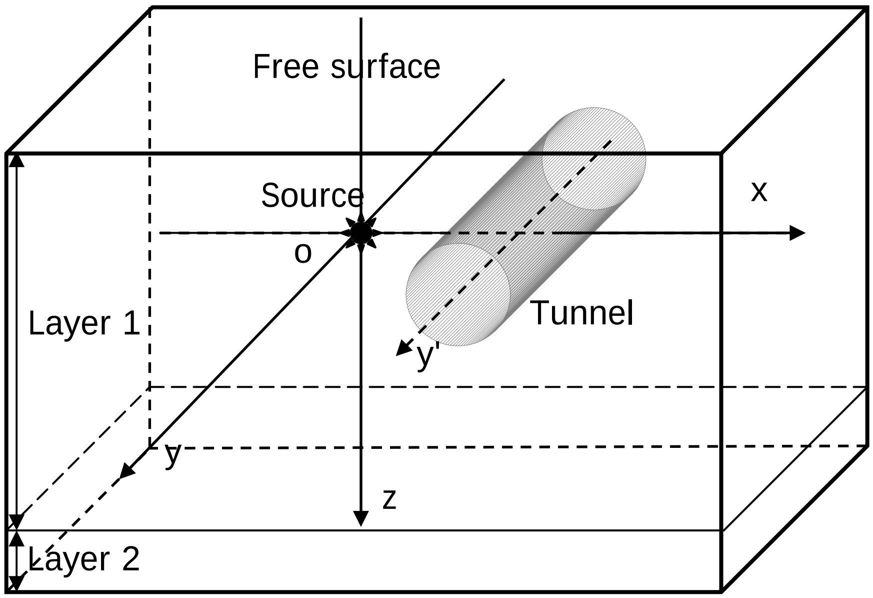


Figure 1. The geometry diagram of the tunnel model. The explosion source is located at 100 meter deep. A cylindrical tunnel is set 30 m away from the source, with radius of 15 m and length of 50 m. Its symmetric axis is parallel to the y axis. The receivers are set on the free surface. The distance between the adjacent receivers in x or y axis direction is 100 m.

Scattering due to topography

We study the effects of different topographic features on propagation and scattering of seismic waves from explosion sources at shallow depth. In the following calculations, we use a pressure Kelly wavelet with center frequency of 10 Hz as an explosion source. The formation compressional and shear wave velocities and density are 3000 m/s, 1700 m/s, and 2300 kg/m^3, respectively. A detailed study of topographic effects was carried out by Stevens (2004).

We first study the effect of a hill on wave propagation. The hill is 300 m high and 2000 m wide. A tunnel is placed 100 meters below the free surface, as shown in Figure 4a. An explosion source is also placed at the same depth. The configuration of the cylindrical tunnel is the same as shown in Figure 1. Figure 4b compares waveforms for a flat free surface model and a free surface with a hill. We see that the presence of the hill does not affect the direct body waves, but affects the surface waves.

To show the effects of topographic features with high slopes, we compare the snapshots of wavefields in the earth with a flat free surface (Figure 5a), in earth with a hill (Figure 5b) and in earth with a mesa (Figure 5c). In all cases, the explosive source is at a depth of 100 m. Both the hill and the mesa are small features: 50 m high and 100 m wide. Note that for the 10 Hz center frequency source, the dominant P wavelength is 300 m and the dominant S-wavelength is 170 m. The snapshots in Figure 5 are a 2-D model. The top row shows the divergence and the bottom the curl of the wavefield. P-and S-waves are clearly separated. Both the hill and the mesa act as strong scatterers for the S- and surface waves. Both forward and backward scattering are observed. Even though the general patterns are similar for the hill and the mesa, scattering due to the mesa, especially at the corners, is more prominent.

<u>Source Characterization: Detection of a Scatterer</u>

Forward modeling of the seismic radiation from an explosive source near a tunnel showed the effects of scattering from the tunnel, especially the strong P to SV and SH scattering. In this section, we investigate two methods of determining the properties of the composite explosion-scatterer source from the seismograms. The first method is wavelet domain moment tensor inversion. The second is based on time-reversed acoustics (TRA). Both methods assume some knowledge of the Green's function, either calculated from a model of the structure, or determined empirically.

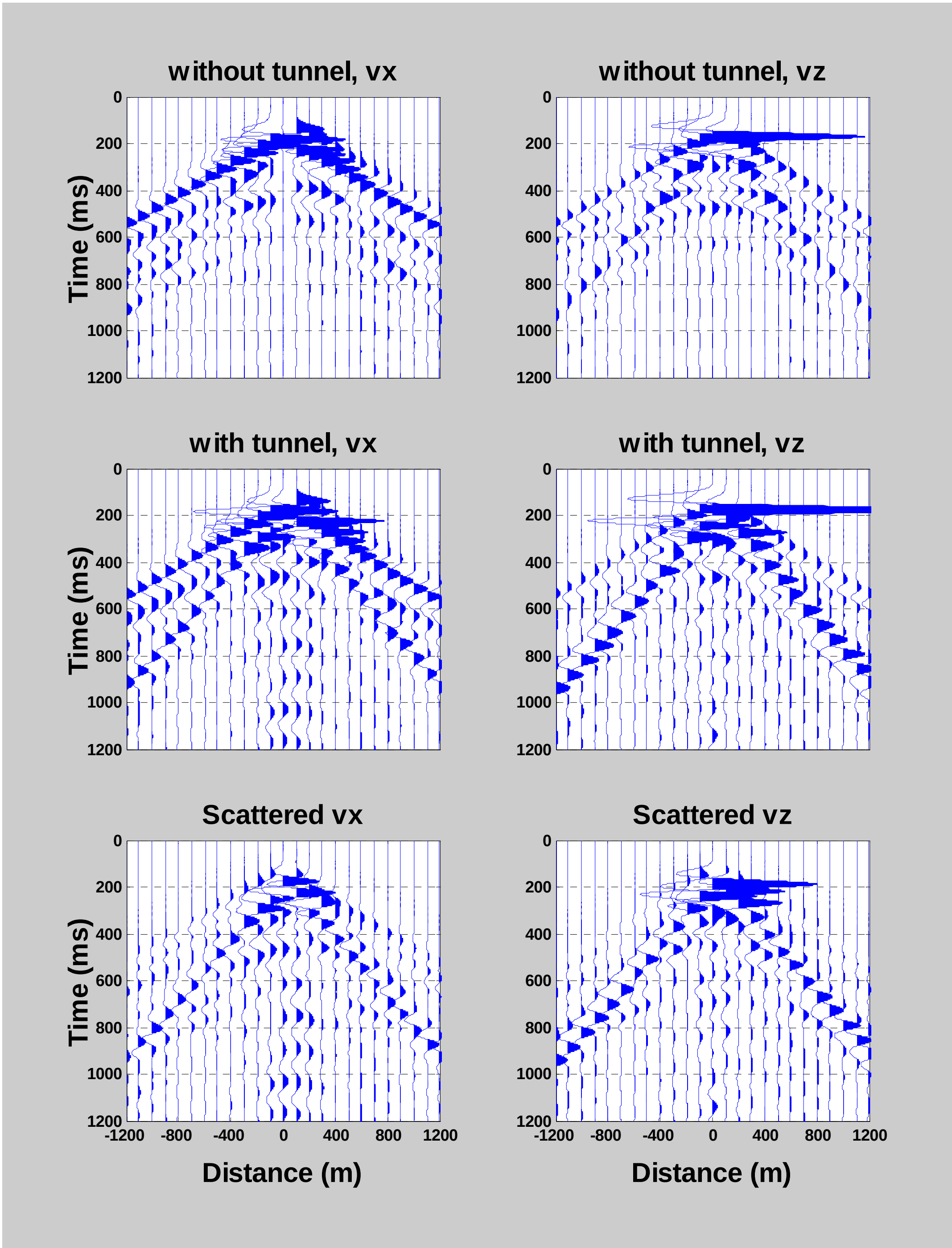


Figure 2. Comparison of the x and z components of the velocity fields at the free surface in the absence and the presence of the tunnel. Respective scattered velocity fields of the x and z components, obtained by subtracting row 1 from row 2, are also shown in the last row of this figure.

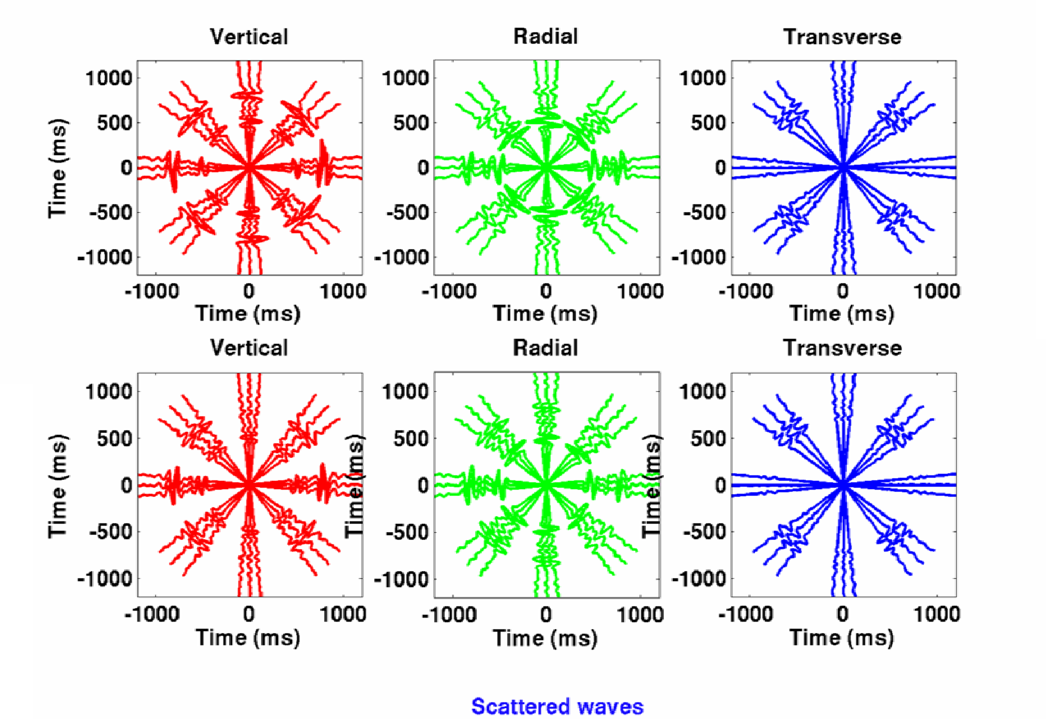


Figure 3. Three components of the recorded wavefields at 1 km offset of different azimuths. a) Free surface with tunnel near the explosion. b) Scattered wave only.

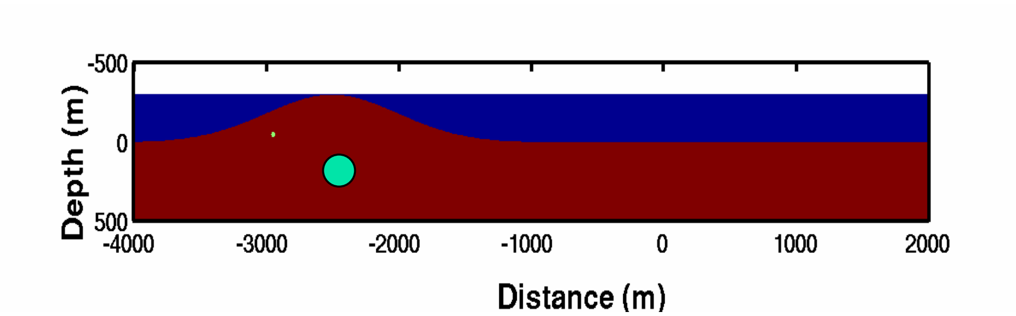


Figure 4a. Model for an explosion and a tunnel under a broad hill.

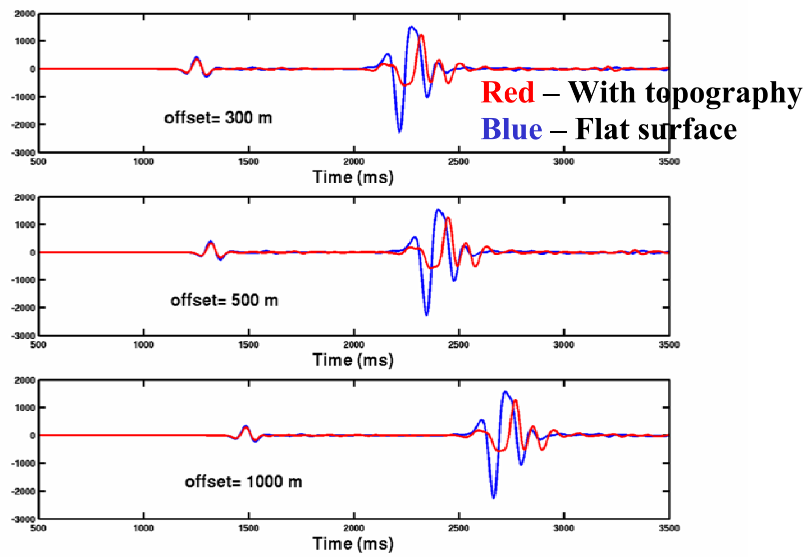


Figure 4b. Comparison of waveforms for an explosion/tunnel under a flat free surface and under a hill.

Moment Tensor Inversion

We used synthetic seismograms to test the performance of the wavelet-domain moment tensor inversion method to separate the explosion component from that of the scatterer. The method involves the representation of the source time function and the seismograms in terms of wavelets (Sze and Toksoz, 2005). The inversion is done in a wavelet domain.

To test the method we use a set of finite-difference, synthetic seismograms calculated for the explosion/tunnel source geometry shown in Figure 1. Figure 6a shows the results of the wavelet-domain moment tensor inversion. Figure 6b shows the fit to the waveform. The wavelet-domain inversion method was able to retrieve the explosive source, indicated by the large isotropic components and zero deviatoric components before 0.05 s. The effect of scattering from the tunnel is the late shear event at around 0.15 s (Figure 6a). The fit to the waveforms is excellent (Figure 6b). The moment of the explosion is about two times that of the multi-couple moment due to scattering from the tunnel.

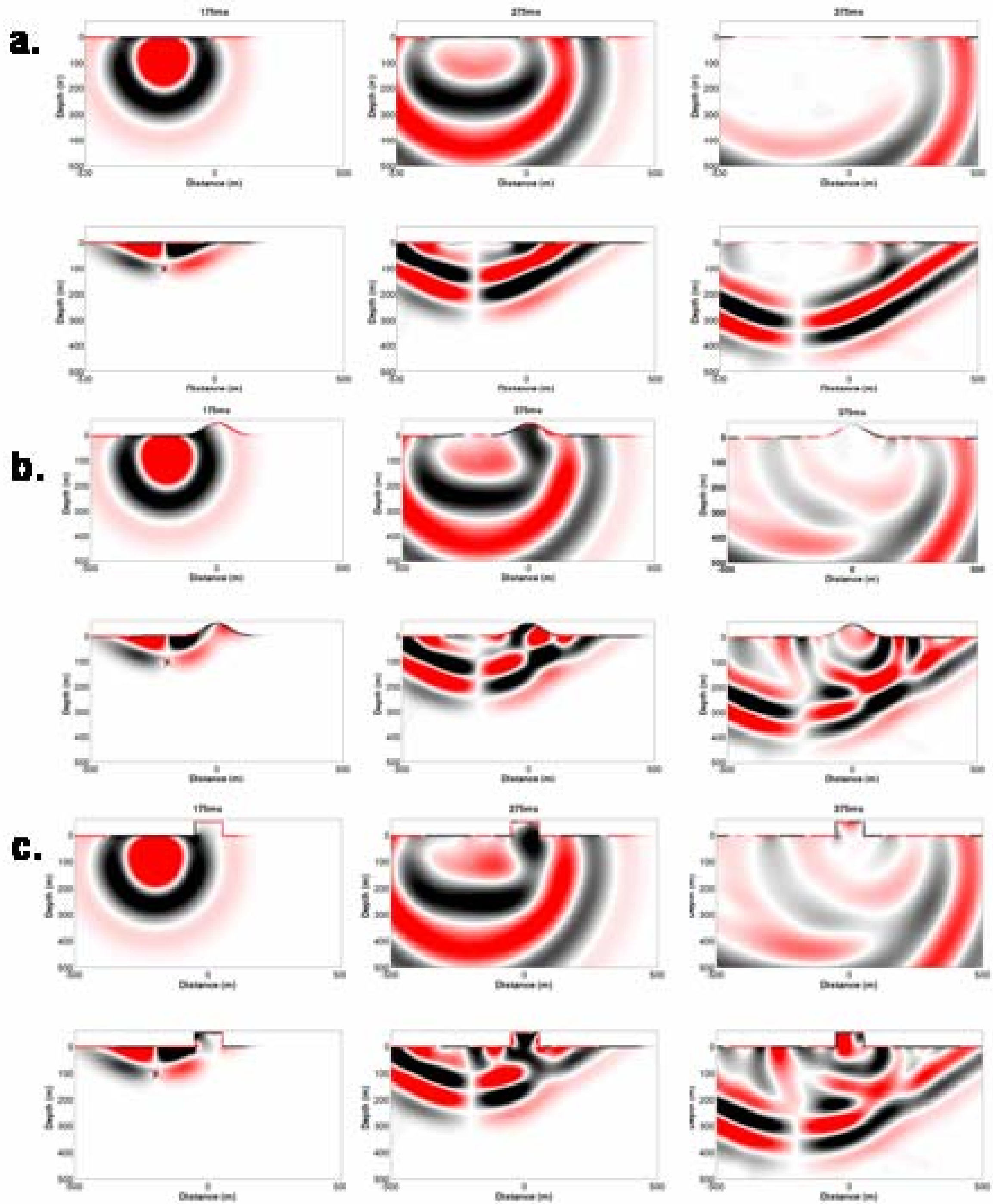
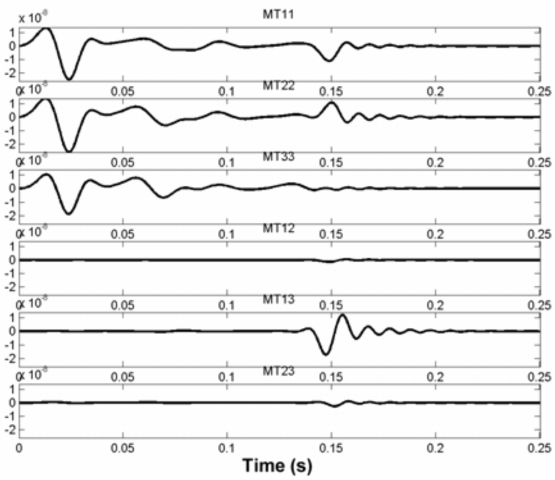
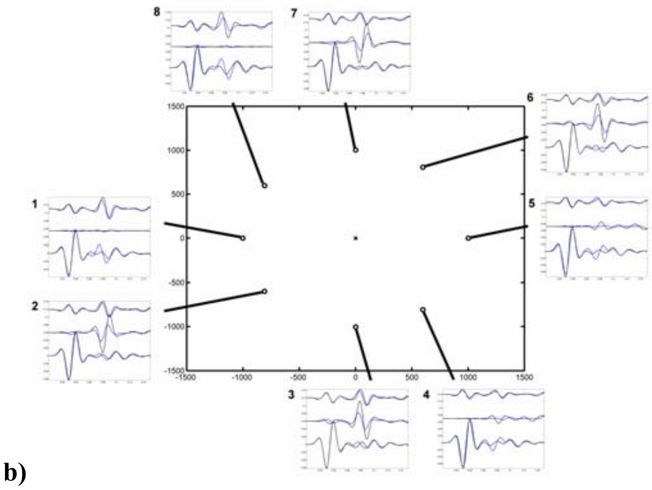


Figure 5. Snapshot of the divergence (upper panel) and curl (lower panel) of the wavefield from an explosion in the earth with (a) a flat surface, (b) a hill, (c) a mesa. Note the strong scattering due to the corners of the mesa.



a)



b)

Figure 6: a) The results of wavelet-domain moment tensor inversion for an explosion with tunnel. Some anomalous components of M11, M22 and M13 showed up at a later time (~0.15 s) but the inversion was still able to retrieve large isotropic components (M11, M22, M33) and zero deviatoric components (M12, M13, M23) in the beginning. b) Fitting of waveforms (blue) by the wavelet-domain inversion to the synthetic data (black) of an explosion with tunnel. Data from eight stations (circles) surrounding the explosion (cross) were used for the inversion. At each station traces are (top to bottom) vertical, tangential and radial components.

Source and Scatterer Imaging Using Time Reversed Acoustics

According to the TRA concept, acoustic waves recorded at several stations when time-reversed and put back into the medium, propagate and focus at the original source (Fink, 1993, 2001; Song and Kupperman, 1999; Derode et al., 2000; Lu and Toksöz, 2004). The concept is illustrated schematically in Figures 7a, and 7b. To demonstrate the applicability to seismic source characterization, we conducted two numerical experiments. In each experiment, seismic waves generated by a source in heterogeneous media were calculated using the finite difference code. Then these seismograms were time reversed and "pumped" back into the medium.

Figure 8 shows the geometry of the first experiment where an explosion source is placed in a layered medium and recorded by a circular array of receivers. Note that the source is off-centered. Figure 9 shows, through a series of snapshots, the convergence of the waves to the source.

The next example is for an explosion that is located near a tunnel. Synthetic seismograms calculated by the finite difference code are recorded at 18 surface stations. The TRA methodology is applied to these recorded seismograms by first reversing them in time and then applying them as sources at the top of the same 3D elastic model. Figure 10 shows snapshots of the back-propagated wavefield at four different times. The left column shows the horizontal component of motion, the middle column shows the divergence of the wavefield (the P-wave energy), and the right column shows the curl of the wave field (the shear wave energy). The star indicates the location of the source and the circle shows the outline of the tunnel. The recorded length of the data used for back propagation is 0.4595 s. The top row of snapshots is 0.2995 s and the subsequent frames shown are at 0.3775 s, 0.4405 s, and 0.494 s. The bottom row of snapshots, at 0.4595 s, is the zero source time. Clearly seen in the bottom row at the original model time is the convergence of the P-wave energy at the source position in the left and middle figures. The shear wave energy converges to the tunnel, the source of the P to shear wave conversion, at a back propagation time of 0.4405 s. The difference, between 0.4595 and 0.4405 s, is due to travel of the P waves to the tunnel and scattering at the tunnel.

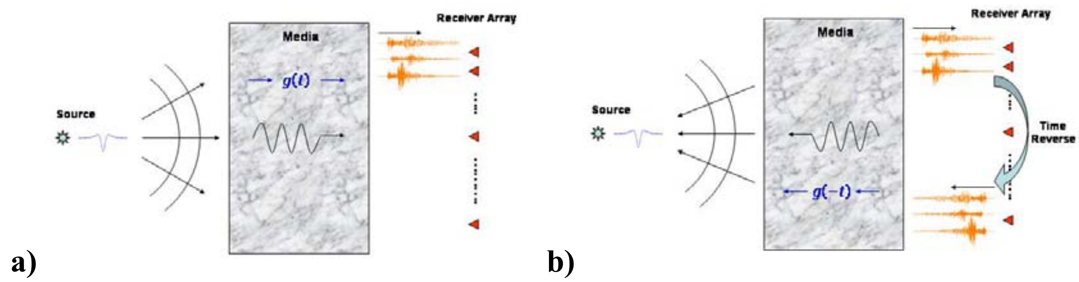


Figure 7. a) Schematic showing energy from a seismic source propagating through a medium with many scatterers, and being recorded at the stations denoted by red triangles. The yellow traces represent the recorded seismograms. The recorded traces are created by a convolution of the source function, s(t), with the appropriate transfer function, $g_j(t)$. b) Schematic showing the TRA process on the data recorded as Figure 7a. First the recorded seismograms (top yellow traces) are reversed in time (bottom yellow traces) and pumped back into the medium at the station locations. The energy reverses its path through the medium and converges upon the original source position.

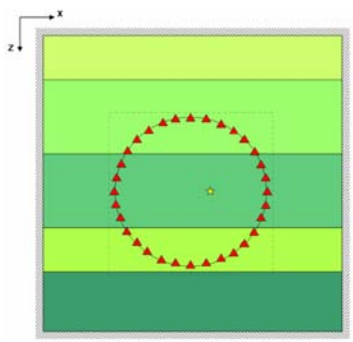


Figure 8. Simple 2D layered earth model with seismic source located at the yellow star, and a ring of receivers, each indicated by a red triangle.

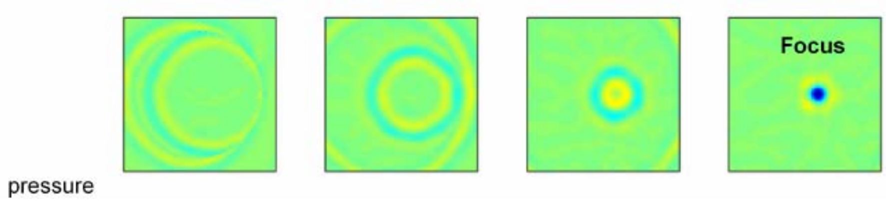


Figure 9. Progressive snapshots of the wavefield (recorded by the receivers in Figure 8) propagated backward in time. The fourth frame corresponds to zero time.

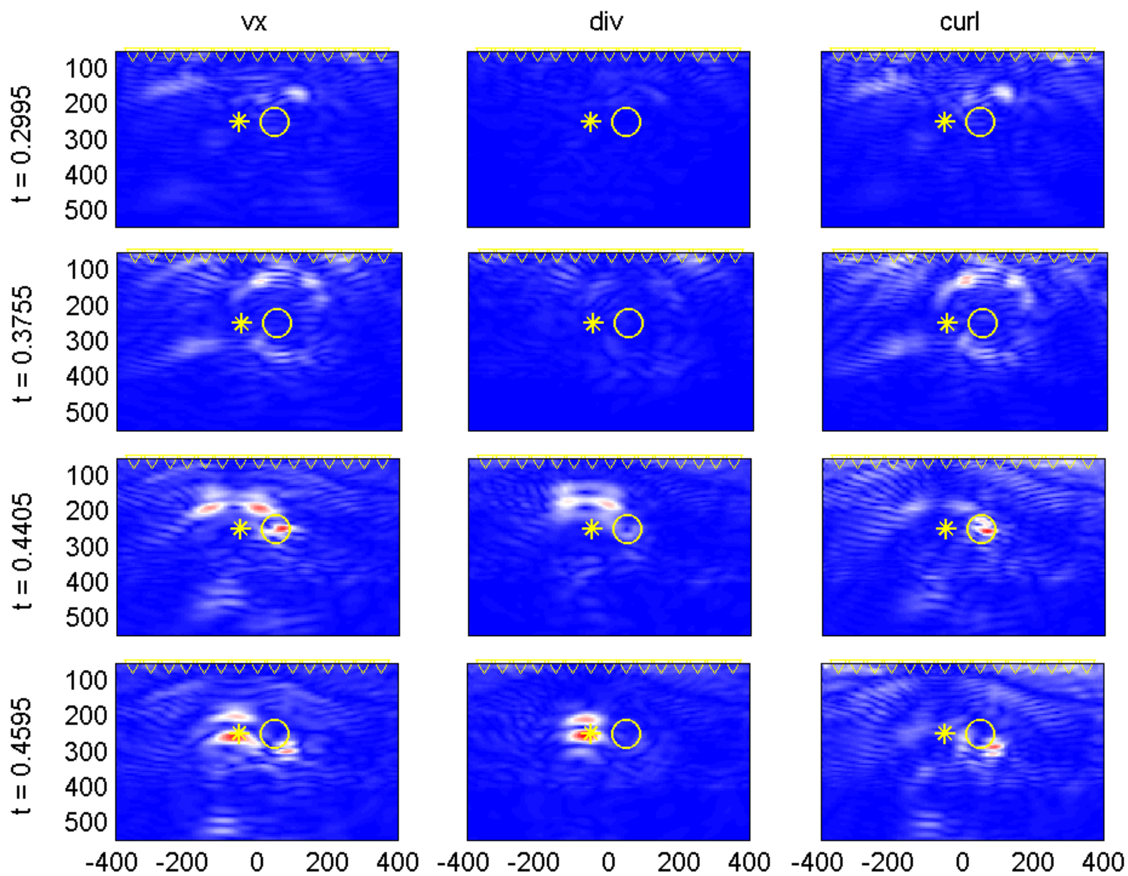


Figure 10. Snapshots of back propagated records for an explosion (star) located next to an air filled tunnel (circle). The left column shows the vertical component of motion, the middle column shows the divergence of the field (P wave energy only), and the right column shows the curl of the field (shear energy only). The bottom row represents zero time in the original forward model.

CONCLUSIONS

1. A tunnel near an explosion acts as a strong scatterer. P to S scattering is much stronger than P to P scattering. Some energy is scattered into SH waves. **2.** Surface topographic features act as scatterers. Overall, scattering from topography is small compared to that of tunnels. The smooth topography effect on scattering is relatively small. Sharp topographic features (e.g., mesas) cause strong scattering of the surface waves. **3.** For explosion identification, wavelet-based moment tensor inversion recovers the relative strengths of the explosion and the scatterer source. **4.** TRA methodology has the potential of determining seismic source properties with good resolution.

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