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Modeling Seismoacoustic Propagation from the Nonlinear to Linear Regimes

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Introduction

Explosions at shallow depth-of-burial can cause nonlinear material response, such as fracturing and spalling, up to the ground surface above the shot. These motions at the surface affect the generation of acoustic waves into the atmosphere, as well as the surface-reflected compressional and shear waves. Standard source scaling models do not account for such nonlinear interactions above the shot, while some recent studies add a non-isotropic term to the moment tensor to represent them (e.g., Patton and Taylor, 2011). We use Sandia's CTH shock physics code to model the material response in the vicinity of underground explosions, up to the overlying ground surface. We then couple the signals from CTH into a finite-difference (FD) seismoacoustic code to efficiently propagate the wavefields to greater distances. The FD algorithm we have implemented applies the wave equations for velocity in an elastic medium and pressure in an acoustic one, and matches the normal traction and displacement across the interface. The Source Physics Experiment (SPE) in Nevada has collected seismic and acoustic data on numerous explosions at different scaled depths, providing an excellent testbed for investigating seismoacoustic interactions.

The CTH shock physics code

CTH models material response to extreme pressures and stresses. Since its original release in the 1980s, it has been applied to a wide range of physical phenomena, including large explosions, projectile impacts, and planetary-scale collisions. Kring and Boslough (2014) used CTH to model the bolide event over Russia in February 2013:

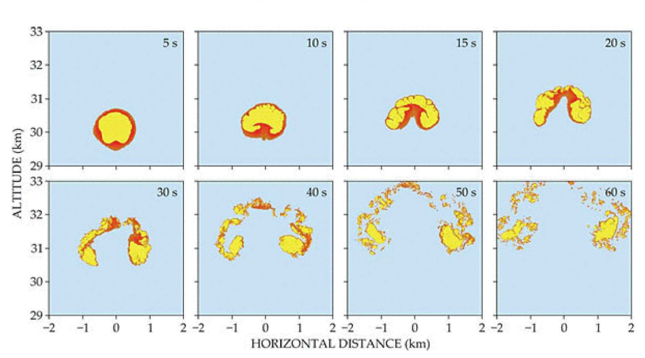

Figure 1. CTH simulation of the Chelyabinsk bolide contrail.

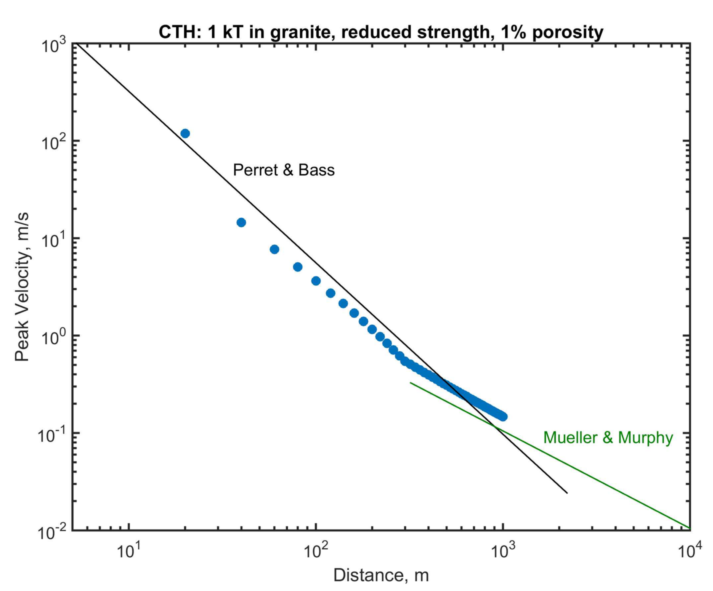

Figure 2. Tuning rock properties for CTH. Using free-field simulations of 1-kT nuclear explosions in granite, we adjusted the material parameters to match data collected for underground tests. The Perret and Bass (1974) line shows their regression result for data from the hydrodynamic and nonlinear regions for tests in hard rock. The Mueller and Murphy (1971) line shows their linear source model for standard depth of burial in granite.

Axisymmetric FD code

Building on work by Stacey (2003), we have developed a finite-difference code for modeling seismoacoustic propagation through domains with both solid and fluid media. The code currently implements 2D cylindrical geometry, so it can model 3D spherical spreading for axisymmetric problems. This facilitates propagating the waves to greater ranges than full 3D modeling with comparable resources. We validated the FD routine, as well as linear wave propagation in the CTH program, using analytical and generalized-ray solutions for classic point-source and pressurized-cavity problems in both a uniform wholespace and an elastic halfspace with an overlying atmosphere.

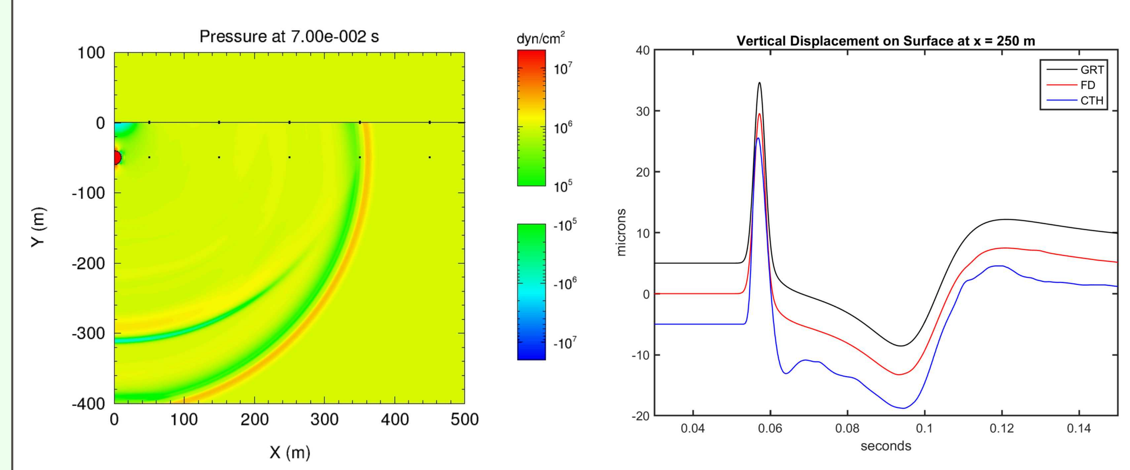

Figure 3. Validating the FD and CTH codes for a source in a halfspace. Comparison of surface vertical displacements at x=250m. CTH used a pressurized cavity (r=10m) at 50m depth, FD and GRT used a point source with the same depth and moment, and a time function consistent with the cavity's corner frequency. Amplitudes and timing of the P and Rayleigh arrivals agree well. Scattering of pP and pS by the cavity is the likely cause of the extra oscillations in the CTH signal.

Nonlinear to linear coupling

We couple the motions exiting the nonlinear regime of the CTH grid into the linear FD code by applying the Representation Theorem. If we assume that energy only propagates outward from the source region, then we can simply match the vertical and radial particle velocities on the coupling interface; we can ignore the tractions. In the FD grid, waves will be radiated both outward and inward from the boundary, but the latter do not affect the outward-travelling waves.

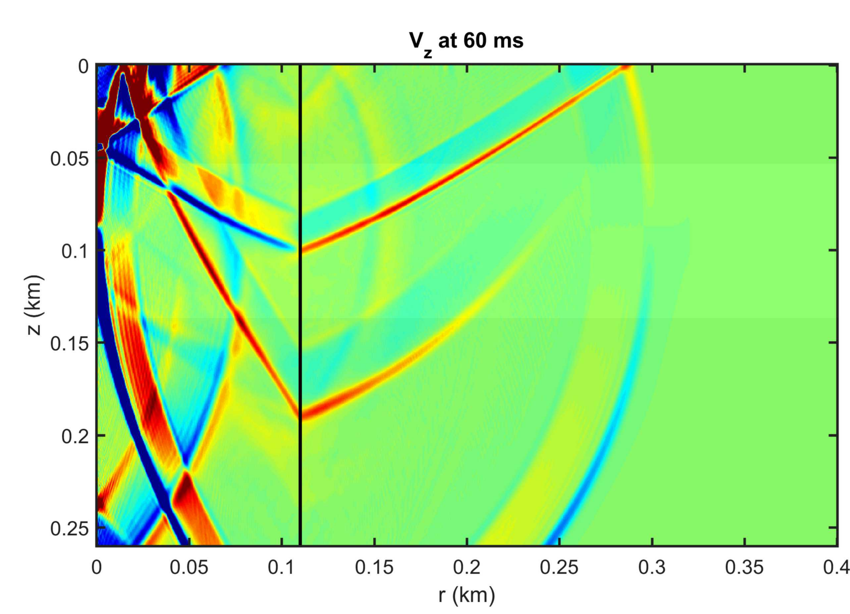

Figure 4. FD grid driven by CTH motions. The FD grid along r = 0.11 km is forced to match the vertical and radial velocities from CTH. Waves propagating to greater r are accurately modeled; motions between r = 0 and r = 0.11 km have no effect and can be ignored.

Simulations for SPE-4' & SPE-5

The SPE program (Snelson et al., 2013) conducts explosive tests at the Nevada National Security Site (NNSS) to better understand source scaling and S-wave generation for underground shots. In the initial phase of this effort, shots are being fired in the Climax Stock, a fairly homogeneous granitic intrusion which was the site of the underground nuclear tests Hardhat and Piledriver in the 1960s.

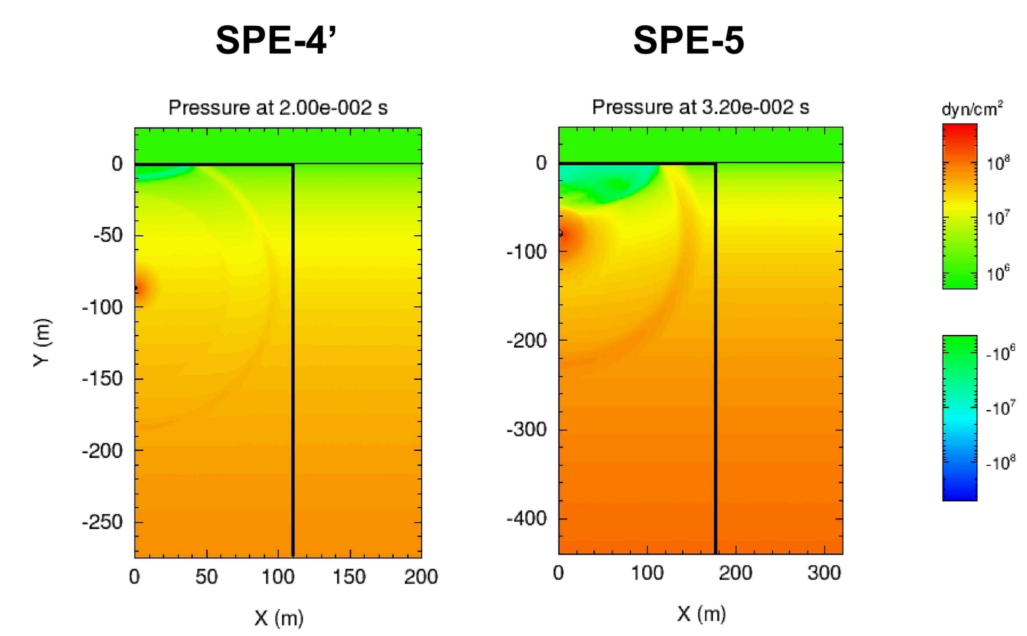

Figure 5. CTH simulations of SPE-4' & SPE-5. The SPE-4' shot was fired at NNSS on 21 May 2015. The charge consisted of 89 kg of C-4, fired at a depth of 87 m; it was intended to produce little or no nonlinear deformation in the rock at the ground surface. The left plot shows CTH's prediction of the pressure field 20 ms after detonation. The color gradient from green to orange shows lithostatic pressure from 1 bar at the ground surface to about 71 bars at the bottom. The right plot is a corresponding image for the planned 5000-kg SPE-5 shot at 32 ms. Tensile failure or spall has occurred in the turquoise region above the shot. The black boxes represent the surfaces used for coupling the CTH motions into the FD code.

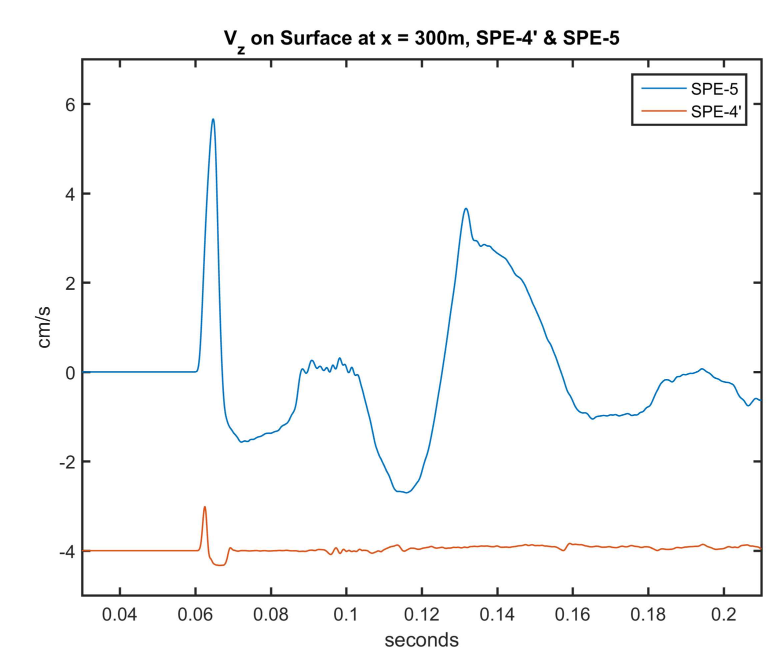

Figure 6. Ground motion at r = 300 m. The plot shows the vertical velocity predicted at r = 300 m from the SPE-4' (red) and SPE-5 (blue) shots. The much larger SPE-5 blast results in a larger amplitude and longer duration P arrival, as expected. Extensive spalling above this event generates a prominent Rayleigh wave, not readily apparent in the velocity trace for SPE-4'. This dramatic difference in the surface wave excitation is not predicted by conventional explosion scaling models.

Air waves

Our ultimate goal is to accurately model the coupling from the ground motions into acoustic waves in the atmosphere. The FD code satisfies the stress and displacement boundary conditions along the air-ground interface, radiating acoustic waves outward from the source region. The character of these signals is dependent on the nature of the rock response near the ground surface. The small SPE-4' shot caused little if any nonlinear deformation at the surface; in contrast, the much larger SPE-5 shot should cause significant spalling.

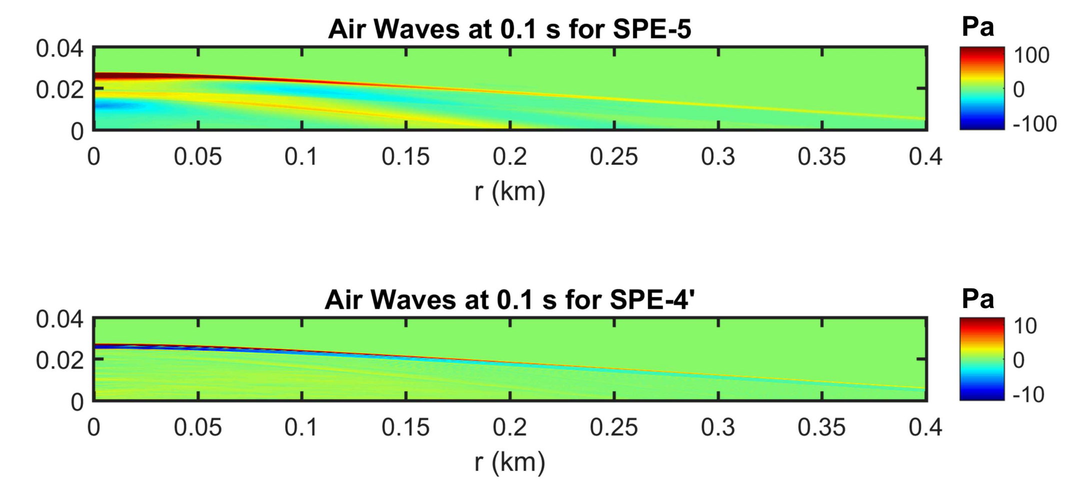

Figure 7. Acoustic waves for SPE-5 and SPE-4'. Predicted overpressure profiles in the air 0.1 s after detonation. As in Figure 6, the near-surface nonlinear response above SPE-5 enhances the acoustic signal due to the Rayleigh wave. Note the color scales for the two plots differ by a factor of 10.

Discussion

Our initial modeling of SPE explosions illustrates the importance of nonlinear material response between the shot point and the ground surface on both the surface seismic motions and the acoustic waves in the air. Future work will focus on refining the strength and fracture models for the source rock. Also, we have so far assumed homogeneous granitic rock in the region; other SPE research has shown that the weathered granite at shallow depth has much different properties, and there are strong lateral variations in structure around the Climax Stock. Seismic and acoustic data collected on the SPE-4' and future SPE-5 tests will be used to help improve the material parameters for both the nonlinear and linear codes.

References

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