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Limitations of the acoustic approximation for seismic crosshole tomography

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Modelling and inversion of seismic crosshole data is a challenging task in terms of computational resources. Even with the significant increase in power of modern supercomputers, full three-dimensional elastic modelling of high-frequency waveforms generated from hundreds of source positions in several boreholes is still an intractable task. However, it has been recognised that full waveform inversion offers substantially more information compared with traditional travel time tomography. A common strategy to reduce the computational burden for tomographic inversion is to approximate the true elastic wave propagation by acoustic modelling. This approximation assumes that the solid rock units can be treated like fluids (with no shear wave propagation) and is generally considered to be satisfactory so long as only the earliest portions of the recorded seismograms are considered. The main assumption is that most of the energy in the early parts of the recorded seismograms is carried by the faster compressional (P-) waves.

Although a limited number of studies exist on the effects of this approximation for surface/marine synthetic reflection seismic data, and show it to be generally acceptable for models with low to moderate impedance contrasts, to our knowledge no comparable studies have been published on the effects for cross-borehole transmission data. An obvious question is whether transmission tomography should be less affected by elastic effects than surface reflection data when only short time windows are applied to primarily capture the first arriving wavetrains. To answer this question we have performed 2D and 3D investigations on the validity of the acoustic approximation for an elastic medium and using crosshole source-receiver configurations. In order to generate consistent acoustic and elastic data sets, we ran the synthetic tests using the same finite-differences time-domain elastic modelling code for both types of simulations. The acoustic approximation was implemented by setting the shear wave velocity to almost zero (Vs $\sim$ 0). This approach was checked against a purely acoustic 2D pseudo-spectral time-domain modelling code and found to yield very similar results.

In a variety of numerical 2D and 3D experiments, we propagated both acoustic only and full elastic waves through models of increasing complexity. We first investigated three basic simple-shaped anomalies embedded in a homogeneous background, including i) a vertical layer ii) a horizontal layer and iii) two-rectangular blocks. Maximum velocity contrast in these models is about 50%
We then tested a more complex model representing a realistic-scale, engineered-nuclear waste repository-like structure, embedded in a granite host rock. Velocity contrasts were chosen to be much higher in this model.
Our results indicate that for the simplest models (horizontal and vertical layers) the acoustic approximation is reasonable for the early portions of the seismograms, but for even only moderately complex subsurface models involving several interfaces (e.g. the two block anomalies), the acoustic approximation breaks down and fails to account for the synthesised wavefields. We attribute this failure to the presence of significant P-to-S mode conversions at each interface. Comparable observations were found for both the 2D and the 3D simulations.

The main advantage of seismic waveform inversion is that subtle changes in amplitude and phase of the waveforms can be exploited for constructing subsurface models at sub-wavelength resolution. The significant deficiencies of the acoustic approximation for crosshole problems, even in the presence of relatively minor anomalies, therefore strongly question the usefulness of acoustic waveform transmission tomography. Consequently, efforts have to be made to implement the computationally much more challenging elastic waveform inversion scheme.