Bypassing the near surface in full-waveform inversion of VSP data at the containment and monitoring institute field site

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Summary

Time-lapse full-waveform inversion has the potential to be a valuable tool for monitoring stored CO2. To test this approach, it is necessary to obtain a baseline inversion of the study region before significant injection of CO2 occurs. Here, we apply full-waveform inversion to a 2D VSP data set taken at the Containment and Monitoring Institute Field Research Site. Because near-surface effects can have a negative impact on inversion results, we develop and use an inversion approach that bypasses characterization of the near-surface, and replaces this part of the model with a wavefield estimate. When applied to the field data, this approach achieves a good data fit, indicative of a reasonable subsurface representation.

Background

The challenges posed by climate change have led to growing research into a number of techniques for management of human carbon dioxide emissions. One such branch of research focusses on the geologic sequestration of captured carbon dioxide emissions from industrial processes. While geologic carbon sequestration offers a promising avenue for reducing CO2 emissions from hydrocarbon sources of energy, this technology is still in the early stages of its development, and practical questions about specific features remain. The Containment and Monitoring Institute Field Research Station (CaMI FRS) in southern Alberta is a research site focused on developing technologies for subsurface monitoring of potential leaks from CO2 sequestration sites (Lawton et al., 2017). A wide range of technologies for subsurface monitoring have been deployed at CAMI FRS, including walkaway vertical seismic profiling (VSP).

Seismic acquisition geometries in which surface seismic sources and well-based seismic sensors are deployed are generally referred to as VSP surveys. While seismic surveys could, in principle, be used individually to detect CO2 in the subsurface, a more robust and more thoroughly tested approach is to use multiple seismic surveys to do time lapse analysis of CO2 storage sites (e.g. Arts et al., 2010). At CAMI FRS, a number of pre-injection VSP surveys have been taken with the goal of providing a baseline for later time-lapse monitoring. Here, we focus on a 2018 survey.

The CaMI FRS 2018 VSP survey consisted of 12 lines of UniVib shot points firing into 296 downhole Inova VectorSeis three-component accelerometers. Our focus here is on one of these lines, oriented East-West with a shot spacing of 10 m and a maximum well offset of 480 m in each direction. The accelerometers were stationed at 1m intervals from the surface down to 266 m, with 2 m intervals down to 300? m. The target formation, where CO2 is to be injected, is the Basal Belly River sandstone, at a depth of about 300 m, and the point of injection is about 10 m offset from the VSP well.

Our goal here is to use the full waveform inversion (FWI) approach to establish a baseline model for later time-lapse monitoring at the CaMI FRS field site. The FWI approach has been established as a powerful tool for recovering elastic properties from seismic data, but it can be hampered by the presence of data features which are difficult to model or reproduce. Surface waves, topology, and near-surface effects in particular have been significant obstacles to the successful implementation of FWI on land datasets. Here, we outline and demonstrate a VSP FWI strategy that bypasses the effects of surface waves and the near surface in the FWI problem, and successfully recover a baseline model for the CaMI FRS field site.

Theory / Method

A conventional FWI is based on an optimization problem of the form

$$m_{\text{FWI}} = \underset{m}{\text{argmin}} \frac{1}{2} ||Ru - d||_2^2 \ \text{ subject to } \ S(m)u = f, \tag{1}$$

where m_{FWI} is the FWI estimate of the subsurface, R is a matrix applying the receiver sampling, d are the measured data, u is a synthetically modeled wavefield, S is a Helmholtz matrix, representing a finite-difference approximation of the frequency domain wave equation, m is a model vector, characterizing the properties of the subsurface, and f is a source term. The first part of the right-hand side of equation 1 is a minimization of the data misfit with respect to the subsurface model and the second part is the requirement that the modeled wavefield, source term, and the subsurface model together satisfy the wave equation assumed for the synthetic modelling.

While FWI formulations like equation 1 have been successfully applied in a variety of settings, they can be challenging to apply when there are regions of the model that both have a very large impact on the modeled wavefield u and are difficult to accurately estimate a priori. In particular, for land seismic data sets, the near surface often presents a major complication for the FWI approach, given its large impact on the source signature and the difficulty of characterizing this region with other methods. Because this region is often low (but unpredictable) velocity, highly variable, and lies between the sources and receivers, it has an extremely large impact on our seismic measurements, and the need for accurate recovery of this region can be a major obstacle to the success of FWI approaches.

Suppose we define a depth z^* that is below the very low-velocity, complex near-surface region, and at a depth where first arrivals in a VSP data set can provide a reasonable 1D starting model for FWI. Provided that the region of interest in our seismic survey is deeper than z^* (which it typically will be), the requirement that we accurately characterize the near-surface in our inversion arises from the need to know the wavefield u at depth z^*, and the need for the wavefield to satisfy our wave-equation condition $S(m)u = f$. The structure of finite difference operators like S is such that it defines local relationships between wavefields and elastic properties. So, if we want to model wave propagation from surface sources, it is necessary to have an estimate of the elastic properties of the subsurface near the seismic sources. It also means, however, that if we know the wavefield at some boundary of the model, as well as the elastic properties of the model within that boundary, we can determine the wavefield within the boundary. More specifically, if we know the wavefield at z^* and the elastic properties of the model below z^*, we need not know the elastic properties above z^* in order to simulate wave propagation deeper.

In practice, the redundancy of the elastic model above z^* with the wavefield at z^* suggests a reformulation of the FWI problem that bypasses characterization of the near-surface:

$$m_{\mathrm{FWI}}, u_{\mathrm{FWI}} = \underset{m^*, u_z}{\operatorname{argmin}} \frac{1}{2} ||R^* u^* - d^*||_2^2 \;\; \text{subject to} \;\; \begin{bmatrix} I \\ S^*(m^*) \end{bmatrix} u^* = \begin{bmatrix} u_z \\ 0 \end{bmatrix}, \tag{2}$$

where the * variables are equivalent to the corresponding terms in equation 1, but only for positions below z^*, u_z is the wavefield at depth z^*, and I is an identity matrix with a number of rows equal to the number of elements in u_z. The first term of the right-hand side of equation 2 remains a data-fit term, now involving only the receivers below z^*, but the second term is now a requirement that the wave equation assumed be satisfied below z^*, and that the wavefield at z^* is now a second inversion variable. This replaces the problem of recovering the near surface in equation 1 with the problem of recovering a wavefield below the near surface. This second problem is much better constrained by the data in problems where the near surface is complex.

Results

The inversion approach we consider here is an elastic, two-dimensional, frequency domain FWI. We consider frequencies between 10 Hz and 25 Hz, and shot points from 5m west of the well to 480 m east. Lower frequencies have a significant impact in FWI, so frequencies below 10 Hz would be very desirable, but 10 Hz was found to be the lowest frequency at which the ratio of seismic signal to noise was acceptable. At high frequencies, FWI is both very computationally expensive and offers limited improvement over migration-type techniques. In consequence, the 25Hz maximum frequency we consider is substantially below the peak frequency for the survey but represents a reasonable tradeoff between computational cost and spatial resolution. In the inversion, we consider accelerometer measurements from only the vertical and in-plane horizontal components, with out of plane measurements assumed to have limited value due to the limited anisotropy expected in the study area (Hall et al., 2018) and our assumption of limited three-dimensional structures. We consider a model of 510 m in the x-direction, and 322.5 m depth. This model is split into grid cells 2.5 m in each direction for finite-difference modeling and inversion.

For the inversion, we consider eight frequency bands, each consisting of seven frequencies, starting with the lowest frequencies and ending with a band spanning from low to high frequencies. We parameterize the model in terms of a single well-based model parameter characterizing the v_P-v_S-ρ relation observed at the well. Based on the complexity of the data at shallower depths, we choose a z^* depth of 40 m. The initial model we use here was based on a smoothed version of the well logs available at the field site. We simultaneously invert for m^* and u_z, with 10 iterations of L-BFGS optimization used at each frequency band.

The real part of the measured data and modeled data, after both the source-only updates and after the whole inversion process, are shown for the shot at 450 m offset in Figure 1. As this comparison demonstrates, the data-fit is relatively good after inversion: across all shots, the data-fit objective function term after the inversion is 8.9% of the initial data-fit term (where the effective sources had zero amplitude). This figure also illustrates that much of the data fit is provided by the effective source only: the data fit term for this shot is 15.2% of the initial after updating only the sources, so much of the data residual can be eliminated just by updating the effective sources (or, equivalently by changing the modeling of wave propagation through the near-surface).

The inversion result is shown for vP in Figure 2. This result has several positive features: the model updates are largely layer-like, with limited heterogeneity in the x-direction, and the average model profile is similar to the known well profile, represented by the initial model. The inversion also seems to recover a large contrast at about the expected depth of the reservoir of interest (approximately 300 m). Negative features of this result include some apparent artifacts near the well itself, where the impact of model updates on the data is large. This may suggest that a larger layer-promoting regularization term is needed for this problem.

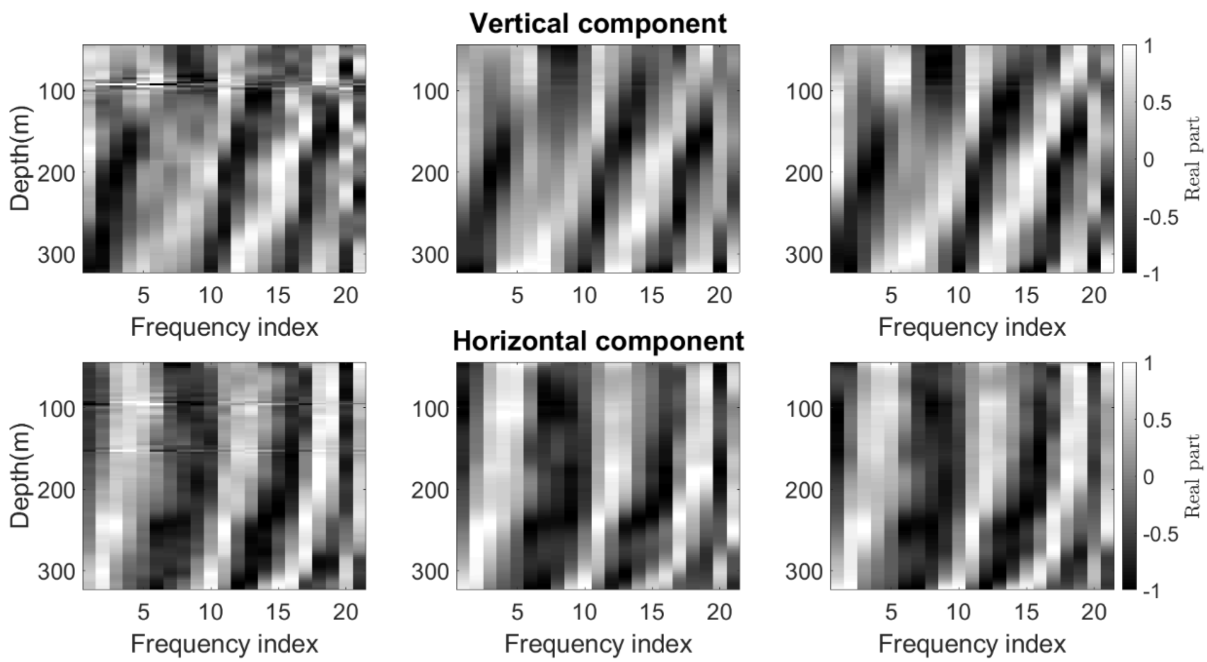

Figure 1. Real part of frequency domain data for shot at 450 m offset. Top row: vertical component of measurements. Bottom row: horizontal component of measurements. Left column: Measured data. Middle column: Modeled data after effective source estimation (no elastic property updates). Right column: Modeled data after simultaneous inversion for effective source and elastic properties. Frequencies are arranged from lowest to highest used in the inversion.

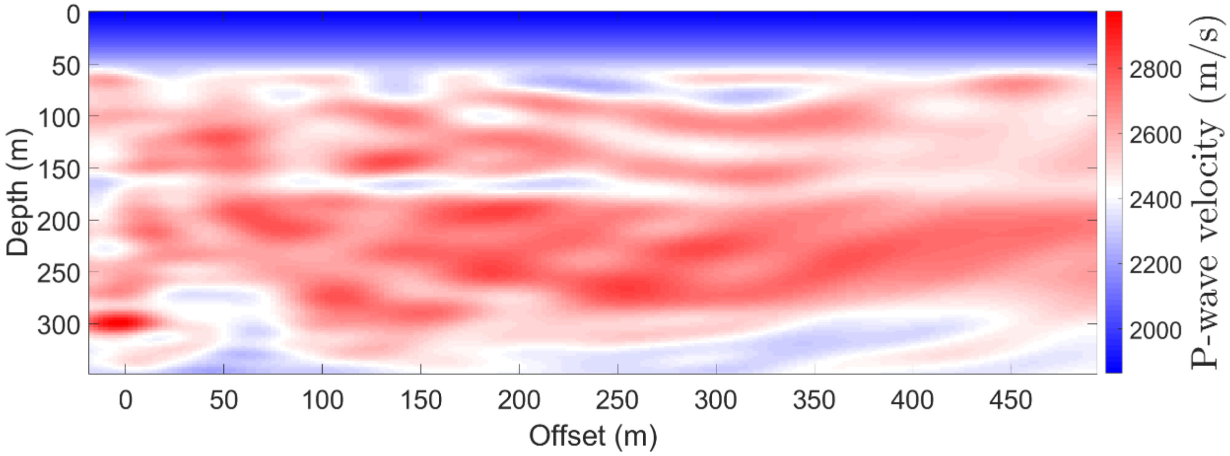

Figure 2. P-wave velocity of the inversion output. Horizontal positions are measured relative to the well-head.

Conclusions

Here, we performed a two dimensional full waveform inversion on a subset of the 2018 CaMI VSP dataset in order to help establish a baseline model for later time-lapse inversion. Because the near surface can often introduce significant challenges in an FWI workflow, we employed an extended model strategy in which the near surface was bypassed by inverting for both the wavefield at chosen depth and the elastic properties below that depth. The inversion result achieved a good match to the measured data, suggesting a good representation of the true subsurface in the region.

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