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Looking Ahead of a Tunnel Boring Machine with 2-D SH Full Waveform Inversion

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SUMMARY

In the near-surface with unconsolidated soils, shear properties can be well imaged, sometimes better than P-wave properties. To facilitate ground prediction ahead of a tunnel boring machine (TBM), active 'surveys' with shear-wave vibrators are carried out during boring. In such surveys, only a few shear-wave vibrators can be placed in front of the machine's cutter head. The vibrators inject a force in the direction perpendicular to the drilling path. We use a vibrator that is capable of exciting low frequencies. Therefore, a full waveform inversion (FWI) approach can be used, which would make the imaging more automatic. Imaging with conventional migration methods suffers from artifacts caused by incomplete aperture and inadequate velocity analysis. In this abstract, we examine the potential of 2-D SH FWI to reconstruct anomalies. In contrast to FWI for hydrocarbon exploration, we have access to reliable low frequencies in the data and are working in the near-field regime. The very limited maximum offset causes diving waves to be absent. This lack of aperture makes it difficult to reconstruct the shear-wave velocity away from the source-receiver array even in the presence of low frequencies. Our study shows that FWI with SH waves should offer a valuable look-ahead capability.

Introduction

Quantitative imaging of various near-surface elastic parameters is essential in many civil engineering applications. For example, inversion of seismic data for various subsurface parameters can reduce the risk of collapses during underground tunnel construction. Several authors (Haines and Ellefsen, 2010) demonstrated the advantages of using shear waves in these applications. In unconsolidated soft soils, the shear waves are hardly affected by the partial fluid saturation. Hence, the estimated shear wave velocity correlates well with subsurface lithology. Also, the propagating shear waves often have a shorter wavelength in these soils compared to that of P-waves (Ghose et al., 1998; Haines and Ellefsen, 2010). This results in better resolution when imaging with shear waves. In the case of layered media, the horizontally polarized shear (SH) waves are decoupled from P, SV, and Rayleigh waves. Our objective is to demonstrate the usefulness of SH waves in unconsolidated soils typically encountered in the shallow subsurface. Since data need to be processed in nearly real time with current computing technology, we have to simplify the SH inversion problem to 2D. This implicitly assumes invariance in the out-of-plane direction, which will be denoted by y . Shear vibrators and receivers are placed on the soil in front of the cutter head to generate and record only the SH wavefield. We assume a vibrator that can excite signals down to 5 Hz, a low frequency for shallow shear-wave surveying. The ground force is primarily injected in the y -direction and the inline receivers record only y -component particle velocity. Due to the limited space on a TBM, only a few source and receiver positions can be used. Conventional imaging techniques for near-surface exploration suffer from various pitfalls (Steeple and Miller, 1998). Incomplete aperture and inadequate velocity analysis cause artifacts in the images. In order to partially overcome these difficulties, we use full waveform inversion (FWI) (Tarantola, 1986; Virieux and Operto, 2009), a nonlinear data fitting procedure that minimizes the least square misfit between the recorded and modelled seismic data to estimate the subsurface parameters. FWI should exploit reliable low-frequency information in the data for automatic velocity model building. Also, the least-squares imaging condition can suppress some of the acquisition-related artifacts (Nemeth et al., 1999).

This paper is organized into the four sections. The first reviews the FWI algorithm. In the second and third sections, we demonstrate its application to synthetic and field data, respectively. The last section summarizes the paper.

Modelling and inversion

The SH wavefield is not sensitive to the compressional properties of the subsurface. It obeys the 2-D wave equation, $Lu = f_0$, with $L = \rho \frac{\partial^2}{\partial t^2} - \nabla \cdot \rho V_s^2 \nabla$. Here, u denotes the y -component of the particle velocity, $\nabla = (\frac{\partial}{\partial x}, \frac{\partial}{\partial z})^T$ and f_0 is the source term. We use a time-domain staggered-grid finite-difference code for the SH wave equation to model the data and to perform the adjoint wavefield computations required for inversion. We perform a multi-parameter SH full-waveform approach with a (V_s, ρ) -parametrization. The objective function for the inversion is

$$J = \sum_{i=1}^{N_r} \sum_{j=1}^{N_s} \sum_{\tau} \left(\sum_{\tau} u_{ij}(\tau) f_j(t - \tau) - u_{ij}^0(t) \right)^2,$$

where u_{ij} and u_{ij}^0 denote the modelled and observed wavefields due to j^{th} source at i^{th} receiver. There are a total of N_s sources and N_r receivers. The convolutional filter, f_j , accounts for the unknown wavelet corresponding to the j^{th} source. The unknowns in the inversion are the shear wave-speed, V_s , density, ρ , and source signatures, f_j . With limited offset-dependent information, the inverse problem of estimating V_s and ρ separately is non-unique. The offset-dependent information decreases with the distance from the source-receiver array and, therefore, the properties close to the array can be better determined. Also, it has to be noted that the long-wavelength information of the density model can never be reconstructed. We use a smoothing regularization to avoid short-wavelength artifacts in the models.

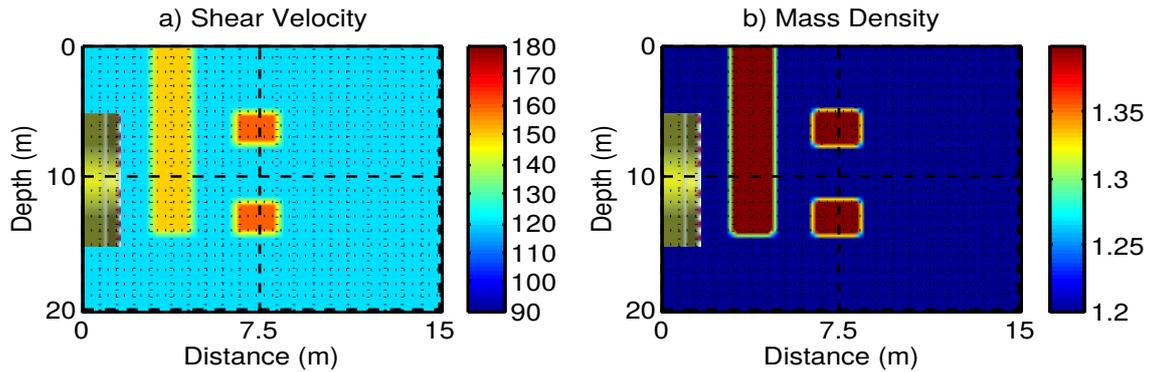


Figure 1: A synthetic Earth model with blocky perturbations ahead of the tunnel boring machine.

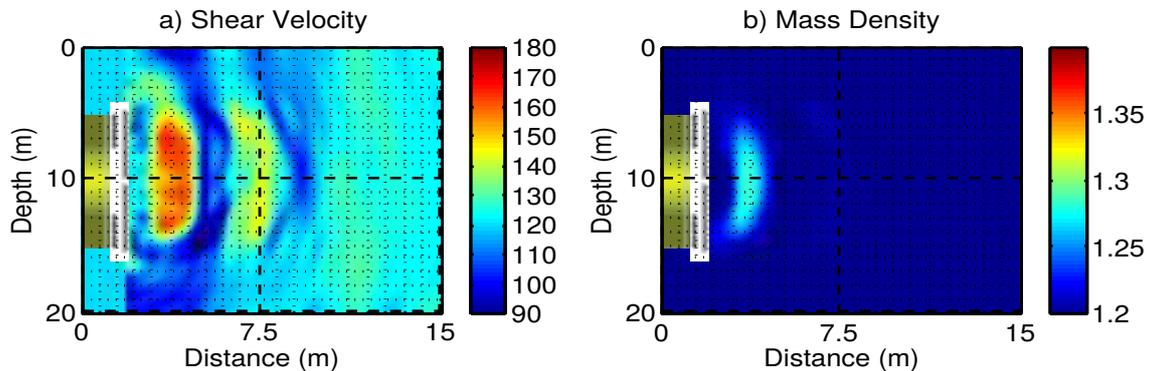


Figure 2: Shear wave velocity and mass density models after inversion for data generated with the models in Figure 1. The source and receiver positions on the tunnel boring machine are also plotted.

Synthetic Example

Figure 1 depicts an assumed near-surface Earth model with 3 blocky perturbations. The background medium is soft clay with $V_s=120\text{m/s}$. The blocks have a slightly higher velocity ($V_s=150\text{m/s}$). The aim is to image the blocks with 10 sources and 20 receivers on the tunnel boring machine (acquisition geometry in Figure 1). We used a 4–7–30–40Hz Ormsby wavelet to model the seismic data for 1.5s. Then the starting model is homogeneous with $V_s=120\text{m/s}$ and $\rho=1.2\text{g/cc}$. We applied multi-scale FWI by first inverting the data between 4–12Hz, followed by three bands: 4–20Hz, 4–28Hz and 4–36Hz. In each frequency band, we estimate the source signature, followed by at most 30 conjugate-gradient iterations to update the medium parameters. Figure 2 depicts the resulting velocity and density models. The vertical beam in front of the TBM is well resolved. The offset dependent information in the data, necessary to update the medium properties, decreases with distance from the TBM. Therefore, the blocks away from the TBM are not well resolved due to lack illumination.

Field test

We conducted a field test on a clay field in the Netherlands, using a shear-wave vibrator that allows to generate the low frequencies. The goal of this test is to see whether the FWI approach allows automatic (e.g., without any picking) subsurface model generation. To acquire data, we placed 24 receivers evenly spaced at 0.5 m along a single transect on the surface ($z = 0\text{m}$) starting from $x = 0\text{m}$ to 11.5m. They measure the y -component of particle velocity. We generated SH waves by placing the vibrator on the surface at 12 different positions in between the receivers from $x = 0.25\text{m}$ to 11.25m. A 1–200Hz tapered sweep signal of 12-s length is input at each source position. A shot gather of the recorded data after cross-correlation with the sweep signal is plotted in the Figure 3a. The auto-correlation of the

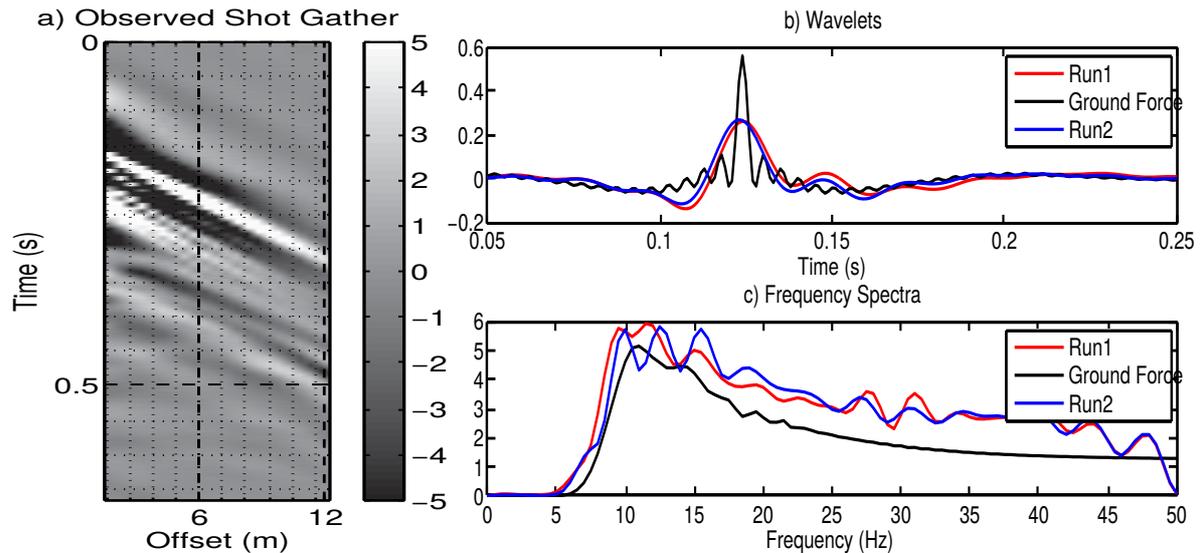


Figure 3: Field experiment. An observed shot gather is plotted in (a), which is clipped at 2% of its maximum amplitude. The vibrator ground force is compared with the estimated source wavelets in (b) and (c).

vibrator's ground force is plotted in Figure 3b. **Run1:** First, we tried to fit the recorded shot gathers starting from a homogeneous Earth model of $V_s=70\text{m/s}$ and $\rho=1.2\text{g/cc}$. We applied multi-scale FWI by first inverting the data between 1 and 3 Hz, followed by the bands 1–5 Hz, 1–10 Hz, 1–20 Hz and 1–50 Hz. The optimization was performed by a preconditioned conjugate-gradient method with smoothing regularization. In each frequency band, the source signature, f , was first estimated, followed by updating the medium parameters V_s and ρ . The final estimated shear properties are shown in Figure 4, explaining about 63% of the observed data energy. Figure 3b also plots the estimated source wavelet during the inversion. We notice the presence of two reflectors, marked R1 and R2 in Figure 4, around 7 m and 10 m depth respectively. The inversion tends to decrease the intermediate velocity of the top layer to about 50 m/s (dashed triangle in Figure 4). Since the only reliable medium parameters are inside the dashed triangle, which is better illuminated, a second run is started with a model that has medium properties corresponding to that triangle. **Run2:** We restarted the inversion from an initial model of $V_s=50\text{m/s}$ and $\rho=1.2\text{g/cc}$. The output models after this run are plotted in Figure 5, explaining about 75% of the observed data energy. The estimated source wavelet is plotted in Figures 3b. The location of R1 is now $z=6.5\text{m}$ and R2 is positioned at $z=8\text{m}$. We conclude that the intermediate velocity of the top layer is about 50 m/s. The maximum offset in the data is 12 m and the inversion result is not very reliable between R1 and R2, despite the availability of low frequencies. Still, a discontinuity is imaged, although not at an accurate depth. The offset dependent information in the data, necessary to update the velocity, decreases with depth in this case.

Conclusions

We investigated the potential of 2-D SH full waveform inversion for imaging in front of a TBM, in the case of unconsolidated soils. The presence of reliable low frequencies in the data enables us to perform automatic velocity analysis to update low-wavenumber features in the model. Least-squares fitting of the data results in images that have less acquisition related artifacts compared to conventional imaging techniques.

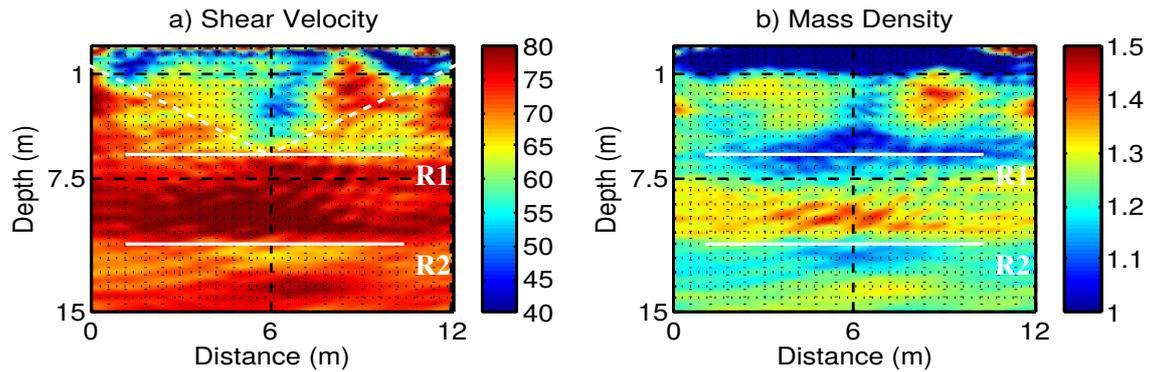


Figure 4: Shear wave velocity and mass density models estimated from the field data, starting from a homogeneous Earth model with $V_s = 70$ m/s and $\rho = 1.2$ g/cc. The models explain approximately 63% of the observed data energy.

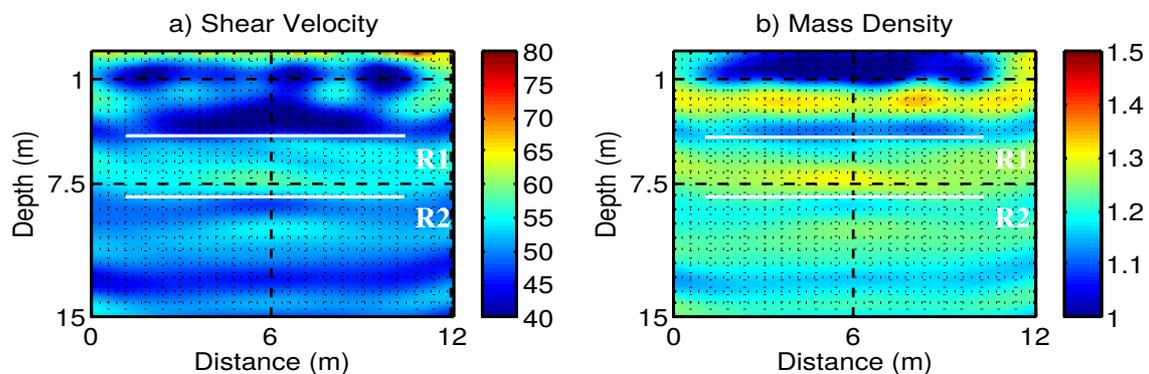


Figure 5: Shear wave velocity and mass density models estimated from the field data starting from a homogeneous Earth model with $V_s=50$ m/s and $\rho=1.2$ g/cc. The models now explain approximately 75% of the observed data energy.

Acknowledgements

This work was carried out as part of the NeTTUN project, funded from the European Commission's Seventh Framework Programme for Research, Technological Development and Demonstration (FP7 2007-2013) under Grant Agreement 280712.

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