Target-oriented high-resolution elastic full waveform inversion using redatumed multi-component data

Introduction

Surface seismic inversion for a deep target zone below a complex overburden can be very challenging, because the strong scattering in the overburden often obscures the target’s reflections of interest. Elastic full waveform inversion (FWI) emerged as a promising technique to estimate the subsurface high resolution elastic properties, as we minimize the data misfits between synthetic and recorded (Vigh et al., 2014; Li et al., 2020a). However, high-frequency elastic FWI is computationally expensive, especially for 3D scenarios, because of the fine spatial and time sampling required to compute the wavefield in a stable manner. Besides, using local optimization to solve the highly nonlinear data-fitting optimization problem often renders models corresponding to local minima. Careful handling of the Hessian matrix is often needed to resolve the deep target zone, which suffers from low amplitude reflections and limited illumination.

Redatuming techniques have been proposed to potentially overcome such challenging issues (Wapenaar and Fokkema, 2006; Guo and Alkhalifah, 2020; Li et al., 2020b). Redatuming has also been applied to elastic data, but only to treat PP reflections (Garg and Verschuur, 2020; Biondi and Barnier, 2020). Considering that converted waves usually deliver essential information for interpreting the elastic properties, we utilize the multi-component recorded data in our elastic redatuming approach. The elastic redatuming process aims to redatum multi-component elastic data to a desired datum level, preferably just above the target zone, by suppressing the wavefield distortions from the overburden (Li et al., 2020c). Using the redatumed multi-component dataset, we will show that target-oriented elastic FWI enables a high-resolution inversion for the target zone in an efficient manner.

Thus, to describe the reservoir of interest with high resolution and high efficiency, we propose an inversion workflow for target-oriented elastic FWI using redatumed elastic data. As suggested by Guo and Alkhalifah (2020), FWI with only low frequencies, and thus, lower cost, is enough to estimate an overburden model. This is justified by the fact that high frequency scattering in the overburden have limited impact on data from the target zone, considering dispersive nature of seismic data, especially at high frequency. We then apply the elastic redatuming to the full band surface multi-component data. Finally, target-oriented elastic FWI using the generated virtual data is implemented to retrieve the elastic properties for the target zone. We demonstrate the performance of this inversion workflow using the Marmousi2 model.

Theory

We extend the waveform redatuming (Guo and Alkhalifah, 2020; Li et al., 2020c) to elastic media. The redatuming process is handled as an optimization problem in which we invert for the virtual elastic dataset (Green’s function) at the datum level using the recorded surface seismic data and a reasonable overburden model, here estimated by low-frequency elastic FWI. The redatumed elastic data can be retrieved by minimizing the following objective function (Alkhalifah and Wu, 2016):

$$\min_{\mathbf{m}} J = \frac{1}{2} \sum_{\mathbf{u}} \left( \mathbf{u}^T \mathbf{A} \mathbf{u} + \mathbf{u}^T \mathbf{B} \mathbf{u} + \mathbf{b}^T \mathbf{u} \right)$$

(1)

where, \( \mathbf{d} \) is the observed multi-component data, \( \mathbf{m} \) is the overburden model, \( \mathbf{g}^b \) denotes the unknown Green’s function at the datum level, \( \mathbf{u} \) refers to the elastic wavefield satisfying elastic wave equation. \( \mathbf{u}^b \) is simulated based on the following datum-based modelling operator:

$$\mathbf{F} \mathbf{u}^D_{\mathbf{x}_s} = \int \mathbf{u}_{\mathbf{x}_o} \otimes \mathbf{h}_{\mathbf{x}_s} \cdot t \delta (\mathbf{x} - \mathbf{x}_{so} + \mathbf{h}) \mathrm{d} \mathbf{x}_{so}$$

(2)

where, \( \mathbf{F} \) is the elastic wave modeling operator, \( \mathbf{h} \) is the subsurface offset vector pointing from the virtual source \( \mathbf{x}_{so} \), \( m \) and \( n \) refer to x- or z-component of the elastic wavefield. The upgoing wavefield \( \mathbf{u}^D_{\mathbf{x}_s} \) is generated from the secondary source, located at the datum level, given by the convolution of the downgoing wavefield \( \mathbf{u}^D_{\mathbf{x}_o} \) with the Green’s function \( g^D_{\mathbf{x}_o} \).
The gradient of the objective function with respect to the redatumed data \((g^p)\) is defined as:

\[
\frac{\partial J}{\partial g^p_{mn}}(x_\nu+h,x_\nu,t) = -\sum \langle u^r_{\nu}(x_\nu,x,t), u^l_{\nu}(x_\nu+h,x,t) \rangle_t,
\]

where, \(u^r\) is the backward propagating wavefield from the adjoint source at the receivers. We can compute the gradient for the redatumed z- or x-component data \((g^z_{mn}/g^x_{mn})\) by cross-correlating the forward \(z\)-component wavefield and the backward \(z\)- or \(x\)-component wavefield, respectively, at the datum level followed by a summation over the sources. Once the \(z\)- and \(x\)-component data are redatumed, we then perform a target-oriented elastic FWI. Overall, the inversion workflow is summarized as: (1) We perform an elastic FWI using a low-pass filtered data to estimate the model on a coarse grid; (2) We then redatum the full-band elastic data to the datum level using the inverted overburden, where a fine grid is used to adapt to the high-frequency wavefield simulation; (3) We implement an elastic FWI for the target zone using the redatumed data to recover its high-resolution elastic properties.

**Example**

We test the proposed inversion method on the modified Marmousi2 elastic model. The P-wave velocity model is shown in Figure 1a. We build the S-wave velocity model (Figure 1b) from the P-wave velocity model using a relationship of \(V_s = V_p/\sqrt{3} + 0.1*(V_p-2.4)\). There is a hydrocarbon reservoir at a depth of 2.8 km in the deep anticlinal structure. We set the datum level at a depth of 2.2 km (shown by the red dashed line in Figure 1a), just above the reservoir zone of interest. We only need to apply the high frequency elastic FWI on the small target zone, shown by the box in Figure 1a.

![Figure 1](image_url)  
*Figure 1 The elastic Marmousi2 example: the true Vp (a) and Vs (b) and the initial Vp and Vs models.*

A Ricker wavelet with a peak frequency of 20 Hz is used as the source wavelet. We deploy 91 shots and 471 receivers evenly sampled at depth 20 m to simulate the elastic multi-component data. Figures 1c and 1d show the initial model. We first conduct the conventional elastic FWI using two frequency bands 2-5 and 2-8 Hz, sequentially. The spatial and time sampling are set to 20 m and 2 ms, respectively, to simulate the elastic wave propagation. The inverted P- and S-wave velocities are shown in Figure 2. We then discretize the inverted model using a finer grid to provide the overburden model for the elastic redatuming and the starting model for target-oriented high-resolution elastic FWI. Specifically, a spatial interval of 5 m and a time sampling of 0.5 ms are required to stabilize the high-frequency simulation (up to 40Hz). Given the overburden model, we then apply the elastic redatuming scheme to the recorded full-band data. We use 58 virtual shots evenly sampled from 4 to 8.56 km at the datum level and 401 virtual receivers for each virtual shot with maximum offset 1 km. The virtual \(z\)- and \(x\)-components shot gathers are shown in Figures 3a and 3b. For comparison, we also simulate the true elastic data for the virtual survey. A side-by-side comparison of the redatumed and simulated shot gathers are shown in Figures 3c and 3d, where the left and right half of each shot gather represents the redatumed and simulated data, respectively. We can see that the retrieved reflections from redatumed data match the simulated ones well. This demonstrates that elastic redatuming is capable of retrieving the reflections, representing the underlying model, even with the inexact overburden model estimated from low-frequency FWI.
Figure 2 The conventional elastic FWI result using 2-8 Hz. The inverted Vp (a) and Vs (b).

Figure 3 The redatumed z- (a) and x-components (b) shot gathers; A side-by-side comparison of the redatumed and simulated shot gathers for z- (c) and and x-component (d) data.

At last, we perform the target-oriented elastic FWI using the redatumed multi-component data to recover the high-resolution elastic properties for the target zone. With a starting model extracted from the full model low frequency FWI shown in Figures 4a and 4b, we recover the P- and S-wave velocities shown in Figures 4c and 4d. We also include a TV regularization in the inversion to preserve the sharp boundaries better, and the resulting inverted Vp and Vs are shown in Figures 4e and 4f. Figures 4g and 4h show the estimated Vp and Vs in the target zone using a conventional elastic FWI with surface full-band data on the whole model. The true Vp and Vs are also given in Figures 4i and 4j for comparison. Obviously, the target-oriented inversion results show higher resolution and accuracy compared to the conventional elastic FWI result. The comparison of the horizontal profile at a depth of 2.9 km, shown in Figure 5, further proves that. The cost of the proposed approach is less than 15% of the cost of the full model FWI of the full band data. We will share real data results corresponding to ocean bottom cables at the meeting.
Figure 5 Comparison of the horizontal profiles at a depth of 2.9 km for Vp (a), and Vs (b). Black line: the true model shown in Figures 4i and 4j; cyan line: the target model shown in Figures 4a and 4b; green line: the inversion result shown in Figures 4g and 4h; red line: the target-oriented inversion result shown in Figures 4c and 4d; blue line: the target-oriented inversion result using a TV regularization shown in Figures 4e and 4f.

Conclusions

We develop a target-oriented high-resolution elastic FWI scheme using the redatumed multi-component data. Using a velocity model obtained from a cheaper low-frequency elastic FWI, we redatumed the full-band multi-component data to datum level just above a target zone. We then could apply a high frequency elastic FWI on the small target zone. This target-oriented strategy reduces the computational cost considerably for high-frequency elastic FWI. The Marmousi2 example shows that the proposed inversion scheme retrieves the elastic properties in the deep target zone with higher resolution, accuracy and efficiency.

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References