An optimal anisotropic full-waveform inversion for marine seismic data

Ju-Won Oh [(1)*], Youngjae Shin [(2)], Jongha Hwang [(2)], and Dong-Joo Min [(2)]

[(1)] Chonbuk National University
[(2)] Seoul National University.

Abstract: Recently, the full-waveform inversion (FWI) has been widely studied due to its main advantage that it enables us to indirectly estimate subsurface parameters from surface seismic data. However, for more accurate estimation of subsurface parameters, anisotropic multi-parameter FWI should be considered because seismic anisotropy is an important physical phenomenon that significantly affects wave propagation in complex sedimentary basins. For such anisotropic full-waveform inversion, finding an optimal parameterization and an optimal FWI strategy is crucial to mitigate parameter trade-offs and to reduce the Null space. In this study, we first analyze the radiation pattern of partial derivative wavefields from each model parameter perturbations considering multi-channel streamer and ocean bottom seismometers. Based on the radiation pattern analysis, we analyze the sensitivity of each model parameter to the marine seismic data and the trade-offs between model parameters. Finally, we suggest an optimal FWI strategy to build anisotropic Earth model more correctly.

1. Introduction

Full-waveform inversion (FWI) has grown to be one of the most attractive imaging techniques because it provides subsurface velocity model at reasonably high resolution (Virieux and Operto, 2009). In the multi-parameter FWI considering subsurface anisotropy, the choice of an optimal parameterization is essential for the successful inversion of the medium parameters to avoid the trade-off between parameters (Operto et al., 2013). Alkhalifah and Plessix (2014) compared several acoustic VTI (Vertical Transverse Isotropic) parameterizations and concluded that the choosing horizontal P-wave velocity and two anisotropic parameters (ε and η) can be the most optimal solution to recover P-wave velocity in the presence of diving waves. In this work, we extend this idea to elastic orthorhombic inversion and show how we can build subsurface anisotropic Earth model with less trade-offs (Oh and Alkhalifah, 2016; Oh and Alkhalifah, 2018; Oh and Alkhalifah, 2019).

2. The multi-parameter inverse problem

The gradient direction of model parameter vector (p) with the l_2 norm of residuals between modelled (u_s) and field (d_s) data in the time domain can be expressed as (Tarantola, 1986)

$$\frac{\partial E}{\partial p_{m,n}} = \sum_s \sum_r \int \left\{ u_{s,m,n}^{pdw}(r,t) \left[d_s(r,t) - u_s(r,t) \right] \right\} dt \quad (1)$$

where r, t and s denote the receiver, time and source, respectively. The term $u_{s,m,n}^{pdw}(r,t)$ is the partial derivative wavefields with respect to a desired model parameter class (m) at n^{th} nodal points (Pratt et al., 1998). Because the gradient direction is the zero-lag cross-correlation of partial derivative wavefields and residual wavefields, the radiation pattern of partial derivative wavefields is an important factor to determining the FWI performance of each model parameter.

3. Radiation pattern analysis

The angular dependency of PDW from the incidence P-wave in an isotropic background medium can be approximated as follows (Aki and Richards, 1980; Oh and Alkhalifah, 2016):

$$R_m^{P-P} = \mathbf{e}_P^T \mathbf{M}_m^P \mathbf{e}_P \quad (2)$$

and

$$R_m^{P-SV} = \mathbf{e}_{SV}^T \mathbf{M}_m^P \mathbf{e}_P \quad (3)$$

where

$$\mathbf{e}_P^T = \begin{pmatrix} \sin\theta_d \cos\varphi_d & \sin\theta_d \sin\varphi_d & \cos\theta_d \end{pmatrix} \quad (4)$$

and

$$\mathbf{e}_{SV}^T = \begin{pmatrix} \cos\theta_d \cos\varphi_d & \cos\theta_d \sin\varphi_d & -\sin\theta_d \end{pmatrix}. \quad (5)$$

The two angles, θ_d and φ_d, are scattering angle and azimuth angle of the scattered waves. The matrix $\boldsymbol{M}$ is the moment tensor form of the virtual source (Oh and Alkhalifah, 2016) for each parameter.

Oh and Alkhalifah (2016) suggested a hierarchical parameterization that contains two seismic velocities, three VTI parameters (ε_1, η_1, γ_1) and four parameters (ε_D, η_D, γ_D and δ_3) to decide azimuthal variation. Figure 1 shows the P-P and P-SV radiation patterns of the parameters with the hierarchical parameterization. The P- and S-wave velocities in the hierarchical parameterization have the same angular coverage as P- and S-wave velocities in isotropic media. In addition, three VTI parameters in the hierarchical parameterization also have the same angular coverage as those parameters in VTI media. Thanks to this hierarchical feature, we can build our Earth model from isotropic to VTI to orthorhombic model by updating only seismic velocities on initial stage and then by adding VTI and orthorhombic parameters sequentially.

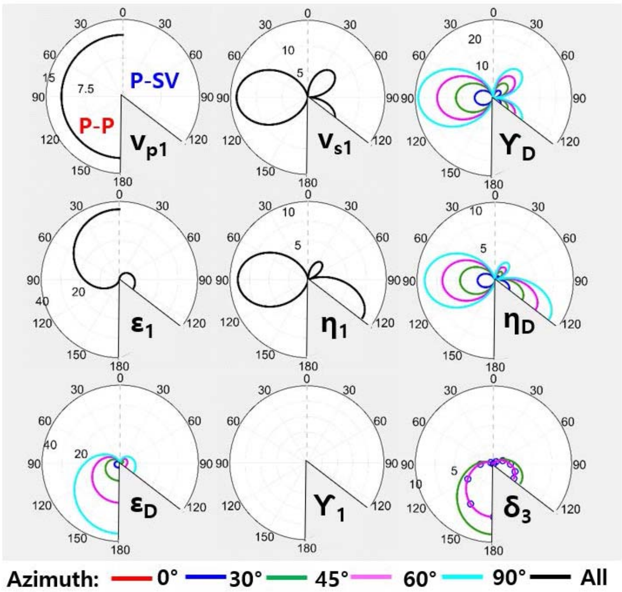

Fig. 1. The P-P (left hemisphere) and P-SV (right hemisphere) radiation pattern for nine independent parameters in the hierarchical parameterization (Oh and Alkhalifah, 2019). The angle around each circle is defined as the opening angle satisfying the Snell's law from a horizontal reflector. The Poisson's ratio is assumed to be 0.25.

4. Trade-off analysis

To verify our observation from theoretical radiation patterns, we numerically compare the gradient direction of different anisotropic parameters for a simple synthetic model (so-called hockey-puck model in Figure 2). As we expected from the radiation pattern analysis in Figure 1, P-wave velocity have the strongest influence on the data thus all model parameters are affected by the trade-off artifacts from the P-wave velocity perturbation. From the hydrophone data, P- and S-wave velocities have strong trade-off because their radiation patterns are overlapped in PP mode.

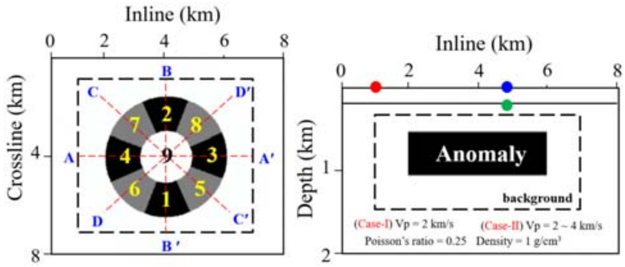

Fig. 2. The horizontal and vertical slices of the hockey-puck model. The model has an anomalous layer, which has hockey-puck-shaped parameter perturbations horizontally. The horizontal and vertical slices in Fig 3 are extracted within the black dashed area and along red dashed lines (AA', BB', CC', DD'), respectively (Oh and Alkhalifah, 2019).

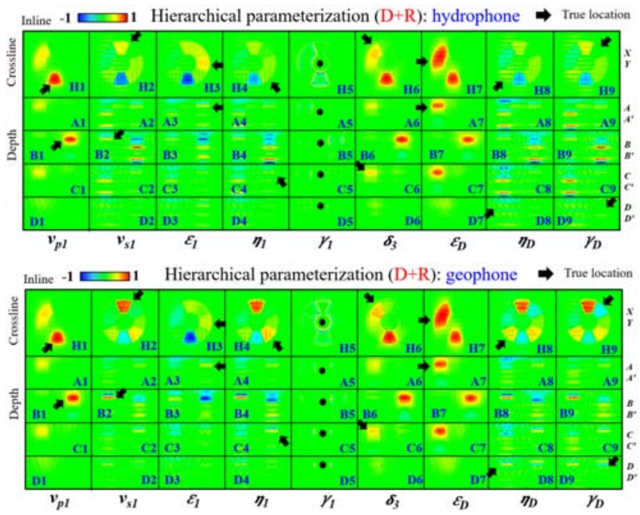

Fig. 3. The horizontal slices (H: at top of anomaly) and 4 vertical slices (A:AA', B:BB', C:CC', D:DD' in Fig. 2) of the gradient directions from hydrophone and geophone data for nine elastic orthorhombic parameters in the hierarchical parameterization (Oh and Alkhalifah, 2019). In this example, background velocity is linearly increasing thus seismic data have both diving wave (D) and reflections (R).

On the other hand, the trade-off between P- and S-wave velocities can be mitigated if we have PS waves from the geophone data. The parameter ε_1 detects high wavenumber features, while the parameter ε_D detects low wavenumber features as supported by their radiation patterns. The parameter γ_1 has the poorest sensitivity because this parameter has no P-P and P-SV reflection energy (Figure 1). We also observe strong trade-offs between the four parameters (v_{s1}, η_1, η_D and γ_D) because their radiation patterns are severely overlapped.

5. An optimal FWI strategy

From the observations in radiation pattern and trade-off analyses, we find that anisotropic parameters η_1, η_D, and γ_D are hard to be recovered due to trade-offs with S-wave velocity and γ_1 has week sensitivity. In addition, the parameter δ_3 is also overlapped by ε_D thus it is better to ignore δ_3 in the case of orthorhombic inversion. Based on these observations, we suggest that P- and S-wave velocities, ε_1 and ε_D are the most effective parameters in anisotropic FWI for the marine seismic data. With these four parameters, we can build isotropic Earth model first by updating only P- and S-wave velocities. Then we can add ε_1 in FWI procedure to estimate velocity ratio along horizontal and vertical directions. Finally, when the orthorhombic FWI is needed and long-offset wide azimuth dataset is available, we can add ε_D in FWI procedure to estimate velocity variations along two horizontal directions.

6. Conclusions

To make the complex anisotropic full-waveform inversion more practical on marine seismic data, we analyzed radiation patterns of partial derivative wavefields for anisotropic model parameter perturbation and trade-offs between parameters in the gradient direction. Through the radiation pattern analysis and trade-off analysis from a hockey-puck model, we derived an optimal FWI strategy, in which we update P- and S-wave velocities first and then add anisotropic parameters sequentially. The synthetic examples and real data examples will be shown in the presentation.

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