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Parameterization analysis in elastic full-waveform inversion of multi-component seismic data

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Main objectives

This study analyses the influence of different model parameterizations in the elastic full-waveform inversion of multi-component ocean-bottom seismic data, so as to design an effective FWI workflow to reconstruct P- and S-wave velocity models of the subsurface jointly and robustly, applicable in scenarios of both weak and strong elastic effects.

New aspects covered

We analyse the pros and cons of three different model parameterizations in the elastic full-waveform inversion and build hierarchical FWI workflows over different parameter classes and data components for multi-component ocean-bottom seismic data. Poisson's ratio is used as the indicator to design the overburden models that produce elastic effects varying from weak to strong in the robustness test of the proposed inversion workflows. An effective hierarchical elastic FWI workflow is found for reconstructing P- and S-wave velocity models jointly and robustly in scenarios of both weak and strong elastic effects.

Summary (200 words)

In marine surveys, multi-component seismic data can be acquired by placing 4-component sensors (hydrophone plus three-component geophone) on the seafloor. One benefit of such acquisitions is the source-receiver decoupling which makes it possible to increase the maximum offset and azimuth coverage. Another one is the direct S-wave recording through geophones that offers the possibility to better measure the elastic properties for lithology and reservoir characterization. Multi-parameter elastic full-waveform inversion (FWI) is a promising technique to reconstruct P- (V_p) and S-wave velocity (V_s) models jointly. Its success depends upon several factors, and one is the choice of the subsurface parameterization over proper data components. This study analyses three different elastic model parameterizations in terms of data sensitivity and model gradient feature. A fluid-solid coupled time-domain FWI engine is employed for an accurate modelling of the acoustic and elastic wavefields in the water and subsurface, respectively. FWI tests are performed on a series of overburden models with increasing elastic effects and a realistic synthetic model, revealing a robust and reliable V_p and V_s reconstruction can be achieved by inverting hydrophone data with (V_p , V_p/V_s ratio) parameterization first and then three-component geophone data with (V_p , V_s) parameterization in a two-step workflow.

Parameterization analysis in elastic full-waveform inversion of multi-component seismic data

Introduction

A quantitative estimation of elastic properties from seismic data is crucial for subsurface lithology and reservoir characterization. The V_p/V_s ratio is usually used for identifying fluid type and estimating porosity and saturation in hydrocarbon reservoirs through several empirical relationships (Hamada, 2004). Full-waveform inversion (FWI) has been proposed for extracting high-resolution quantitative physical parameters of the subsurface by fitting the full information in the seismogram. In marine exploration, FWI is mostly used to derive P-wave velocity models in the acoustic approximation (anisotropy/attenuation potentially as passive parameters) using hydrophone or vertical component data.

Ocean-bottom acquisitions give access to multi-component seismic data by placing 4C sensors (hydrophone plus 3C geophone) on the seafloor. Elastic effects can thus be easily captured through the direct recording of S waves by 3C geophones, especially in the horizontal components. Reconstructing P- and S-wave velocity models jointly needs the use of multi-parameter FWI based on an elastic wave modelling solver. Besides the computational cost challenge, the strong nonlinearity and parameter trade-offs in multi-parameter elastic FWI make a suitable data- and model-driven workflow become necessary (Sears et al., 2010; Wang et al., 2021). To maintain the efficiency and accuracy, our elastic FWI study is performed with a fluid-solid coupled modelling solver, based on the acoustic-elastic coupled wave equation and spectral-element discretization. To reconstruct reliable P- and S-wave velocity models, we build a robust hierarchical FWI workflow applicable in both weak and strong elastic-effect scenarios, through analysing the data sensitivity and model gradient corresponding to different model parameterizations.

3D fluid-solid coupled elastic FWI and model parameterization

We define the misfit function in the FWI of multi-component seismic data as

$$J(\mathbf{m}) = \frac{1}{2} \sum_{shots} (\lambda \|\mathbf{d}_p^{syn}(\mathbf{m}) - \mathbf{d}_p^{obs}\|^2 + (1 - \lambda) \|\mathbf{d}_u^{syn}(\mathbf{m}) - \mathbf{d}_u^{obs}\|^2), \quad (1)$$

where \mathbf{m} denotes the set of subsurface model parameters, \mathbf{d}_p^{obs} and \mathbf{d}_u^{obs} are observed hydrophone and 3C geophone data, respectively, and their corresponding synthetic data \mathbf{d}_p^{syn} and \mathbf{d}_u^{syn} can be modelled by a 3D fluid-solid coupled elastic modelling solver (Cao et al., 2021). λ takes the value 0 or 1 to decide which data type is inverted. The minimization of $J(\mathbf{m})$ requires access to the gradient of $J(\mathbf{m})$ obtained from the zero-lag correlation of the incident and adjoint wavefields.

Seismic velocity (V_p, V_s) is a common used model parameterization in elastic FWI (Sears et al., 2010). Based on their gradients and the chain rule, we can derive the gradient expressions with respect to V_p/V_s ratio (R) and Poisson's ratio (σ) to explore two alternative model parameterizations (V_p, R) and (V_p, σ):

$$\frac{\partial J(\mathbf{m})}{\partial R} = V_s \left(\frac{\partial J(\mathbf{m})}{\partial V_p} - \frac{\partial J(\mathbf{m})}{\partial V_s} \frac{1}{R} \right), \quad \frac{\partial J(\mathbf{m})}{\partial \sigma} = V_s \left(\frac{\partial J(\mathbf{m})}{\partial V_p} - \frac{\partial J(\mathbf{m})}{\partial V_s} \frac{1}{R} \right) / \left(4 \sqrt{\frac{1-\sigma}{0.5-\sigma}} (0.5 - \sigma)^2 \right). \quad (2)$$

To analyse the data sensitivity in different model parameterizations, we calculate radiation patterns of the partial derivative wavefield modulus associated with one parameter perturbation point in the center of a 2D model. As shown in Figure 1, variations of the calculated modulus in different diffraction modes (P-P, P-S, S-P and S-S) reveal how a specific model parameter can be inferred from the data. For the V_p model (Figure 1a), its reconstruction only relies on P-P diffracted waves in the (V_p, V_s) parameterization, the same as the one in the acoustic FWI, implying why the acoustic FWI can succeed in the V_p reconstruction when elastic effects have a relatively weak imprint in the data or can be mitigated by a data pre-processing. In contrast, additional S-related wave modes are involved in the V_p reconstruction for the (V_p, R) and (V_p, σ) parameterizations, making S-waves can also be used to constrain the V_p reconstruction. Typically, a parameterization with less overlapping of radiation patterns over the scattering angles would be chosen to mitigate the impact of interparameter trade-off in the inversion, such as the (V_p, V_s) parameterization where the trade-off only happens in the P-P mode at intermediate scattering angles. However, when inverting the hydrophone data, the introduction of S-related wave modes in the V_p reconstruction can be vital for avoiding misinterpreting P-to-S-to-P converted waves as P-P reflected waves. For the V_s -related model, Figure 1b shows parameters of V_s, R and σ have the same patterns in terms of wave modes and scattering angles, revealing the same data sensitivity. However, their corresponding FWI gradient expressions are different, since gradients for R and σ consist of contributions from gradients for V_p and V_s (Eq. 2). Although this mixture has a negative influence on an isolated V_s reconstruction, especially for the case that gradient term of V_p is greater than the one for V_s , it can create a binding effect from V_p to stabilize the V_s reconstruction when data have no/relatively weak energy of reliable S-waves, such as the hydrophone data. Based on the above analysis and the wave dominance in

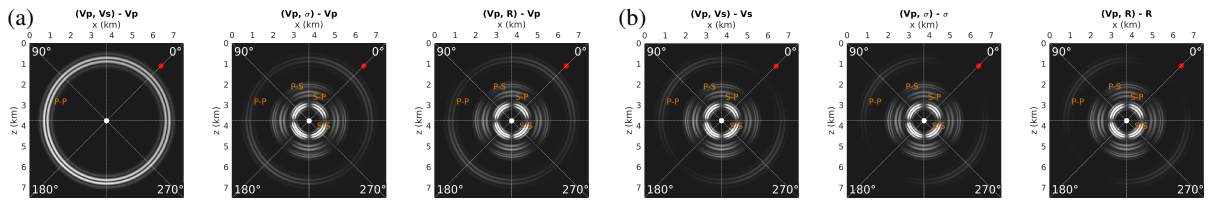


Figure 1: Radiation patterns of the partial derivative wavefield modulus parametrized by (V_p, V_s) , (V_p, σ) and (V_p, R) . (a) V_p perturbation with fixed V_s , σ and R , (b) V_s , σ and R perturbations with fixed V_p . The incident source and the parameter perturbation point are denoted in red and white, respectively.

multi-component seismic data, we consider using a two-step hierarchical strategy in elastic FWI:
 Step 1: Invert P-wave dominated hydrophone data with (V_p, R) or (V_p, σ) to introduce constraints from converted S-waves in the V_p reconstruction and stabilize the V_s reconstruction with the V_p gradient term;
 Step 2: Invert S-wave dominated 3C geophone data with (V_p, V_s) and the resulting V_p and V_s from Step 1 as the starting models, where the weak interparameter trade-off in this parameterization contributes to reconstructing V_s directly from reliable S-waves and mitigating V_p imprint artifacts.

Numerical examples

To investigate the feasibility of the proposed two-step hierarchical strategy for multi-component data inversion, we perform FWI tests on two synthetic models with increasing complexity.

In the first example, we use Poisson's ratio σ as the indicator to design a series of 3D overburden models that produce elastic effects varying from weak to strong. As shown in Figure 2a, the main model structure is one high-velocity thick layer overlying a small-scale low-velocity anomaly mimicking a hydrocarbon reservoir. The S-wave velocity models are constructed based on the values of V_p and σ . Except for the high-velocity overburden, a constant $\sigma = 0.45$ is used everywhere to build a more natural soft-seabed environment. Different elastic effects are produced at the high-velocity overburden with varying σ from 0.45 to 0.25 (see models M_1 to M_5 in Table 1). A constant density is taken for all those models to make the inversion study focus on the velocity reconstruction. The observed multi-component datasets for models $M_1 - M_5$ are generated with a 5 Hz Ricker wavelet source-time function and an ocean-bottom node (OBN) acquisition geometry including 20 4C receiver nodes and 25 shooting lines at 5 m water depth (Figure 2a). Figure 2b shows the initial V_p model, and the initial V_s model is constructed based on it with a constant $\sigma = 0.45$. By applying the two-step hierarchical elastic FWI, Figure 3 displays the V_p and V_s profiles obtained at the two stages. Thanks to the additional constraint from converted S-wave modes, (V_p, σ) and (V_p, R) parameterizations both achieve a robust V_p reconstruction at Stage 1 for all the models with weak and strong elastic effects (Figure 3a). As a comparison, a V_p reconstruction with (V_p, V_s) parameterization is also performed and shows a bias with the elastic effect increasing as indicated by black arrows. The reason can be due to the P-to-S-to-P converted phase occurring at the overburden top edge. When a strong elastic effect exists, the energy of this converted wave can be competitive with the reflected P-waves, making it interpreted as a $P - P$ reflection mode coming from the overburden bottom edge. Moreover, in Figure 3a, we can also observe how the gradient expressions for σ and R influence the V_s reconstruction: the non-linear σ scaling in the σ gradient makes its V_s model suffer from instability issues in the small σ area, while the V_p and V_s gradients mixture in the R gradient produces a compensation effect from the V_p model. When moving to Stage 2, the resulting V_p and V_s from Stage 1 are used as the starting models, and the final FWI results are shown in Figure 3b. At this stage, the V_s model is mainly updated compared with the V_p model, because of the dominance of S-waves and a good separation between P- and S-wave modes in the (V_p, V_s) parameterization. The V_p bias of the overburden in strong elastic-effect scenarios from (V_p, V_s) parameterization is not mitigated by Stage 2, and consequently influences a correct V_s recover of low-velocity anomaly. In contrast, by combining (V_p, R) and (V_p, V_s) parameterizations in the workflow, a robust and reliable V_p and V_s joint reconstruction is achieved in both weak and strong elastic-effect scenarios.

The second example is based on the Valhall synthetic model which has a challenging soft-seabed environment and gas cloud with strong elastic effects (extremely low Poisson's ratio). To run with 3D FWI, this 2D model is extended in the y -direction constantly. The observed multi-component dataset is generated based on the true V_p , V_s and density models illustrated in Figures 4a-4c, using a similar OBN acquisition geometry (19 4C receiver nodes and 16 shooting lines at 5 m water depth) and a 5 Hz Ricker wavelet source-time function. The free-surface boundary condition is applied at the water top.

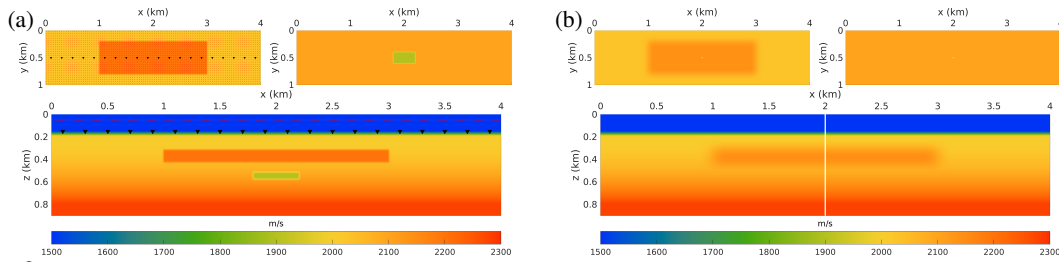


Figure 2: Horizontal and vertical slices of 3D overburden models: true (a) and initial (b) V_p model. Red dots and black triangles in (a) are shots and OBNs. White line in (b) indicates the location for extracting velocity profile.

To build a more realistic FWI configuration, we remove the energy less than 2.5 Hz in the observed data and estimate the source wavelet from the data based on the initial models (Figures 4d-4f). The two-step hierarchical strategy is used for the V_p and V_s model reconstruction, without a density update. Figure 5 illustrates the reconstructed V_p and V_s models from two stages, and the results from three different FWI workflows are compared. The details of three FWI workflows are

Stage 1: invert hydrophone data, by three different FWIs: 1) acoustic FWI on primary P waves (Scholte wave and P-to-S-to-P converted wave are muted), 2) elastic FWI with (V_p, V_s) parameterization on the full data, 3) elastic FWI with (V_p, R) parameterization on the full data;

Stage 2: invert 3C geophone data (Scholte-wave muted and data weighted by the source-receiver offset to the power of 2), by elastic FWI with (V_p, V_s) parameterization and different starting models obtained from Stage 1: 1) V_p from acoustic FWI and initial V_s in Figure 4e, 2) V_p and V_s from elastic FWI with (V_p, V_s) parameterization, 3) V_p and V_s from elastic FWI with (V_p, R) parameterization.

As expected, after effectively mitigating the elastic effects from the data, the acoustic FWI can be applicable for a reliable V_p reconstruction, but suffers from oscillating artifacts resulting from a wrong AVO (Figure 4a) and less update in the shallow part due to a sacrifice of near-offset information in the mute, leading to the V_s reconstruction at the second stage trapped into the shallow part for compensation (Figure 4d). With an elastic approximation, these issues do not appear in V_p models from two elastic FWIs, and we can find the most robust and reliable V_p and V_s reconstruction comes from the workflow with a combination of (V_p, R) and (V_p, V_s) parameterizations (Figures 4c and 4f). The V_p model only using (V_p, V_s) parameterization shows a similar bias in the gas cloud area (Figure 4b) as in the M_5 overburden model, and consequently impacts the correctness of V_s reconstruction below it (Figure 4e).

Conclusions

This study presents the influence of model parameterization and hierarchical design in the elastic FWI of multi-component ocean-bottom data. Three different model parameterizations are analysed from the aspects of the data sensitivity and the model gradient feature. With the help of radiation pattern calculation, the data sensitivity analysis reveals that (V_p, R) and (V_p, σ) parameterizations provide additional contribution from S-waves to constrain the V_p reconstruction for interpreting P-to-S-to-P converted waves. The mixture of contributions from gradients for V_p and V_s in the R and σ gradient expressions can create a binding effect from V_p to stabilize the V_s reconstruction when data have no/relatively weak energy of reliable S-waves (hydrophone data). When S-wave dominant in the data (geophone data), the (V_p, V_s) parameterization can focus on the V_s reconstruction due to its weak trade-off between V_p and V_s . Based on those analyses and the wave dominance in the multi-component data, a two-step hierarchical elastic FWI workflow is designed by combining (V_p, R) and (V_p, V_s) parameterizations. Its robustness and reliability in the V_p and V_s joint reconstruction are illustrated by numerical tests on overburden models with elastic-effect increasing and a realistic Valhall synthetic model.

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	M_1	M_2	M_3	M_4	M_5
V_p (m/s)			2200		
σ	0.45	0.4	0.35	0.3	0.25
V_s (m/s)	663.33	898.15	1056.85	1175.95	1270.17

Table 1: Physical parameters in the high-velocity overburden of Figure 2a, as used to design the true V_s models M_1 to M_5 .

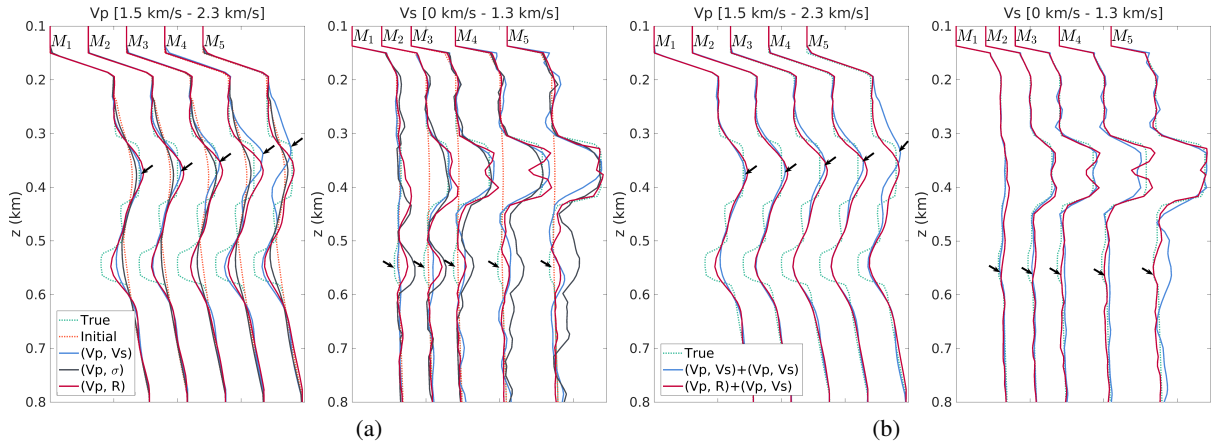


Figure 3: Vertical velocity profiles for comparing the reconstructed V_p and V_s of the models M_1 to M_5 . (a) Invert hydrophone data with (V_p, V_s) , (V_p, σ) and (V_p, R) parameterizations, (b) invert 3C geophone data using the V_p and V_s from (a) as the starting models, with (V_p, V_s) parameterization. Anomalies are highlighted by black arrows.

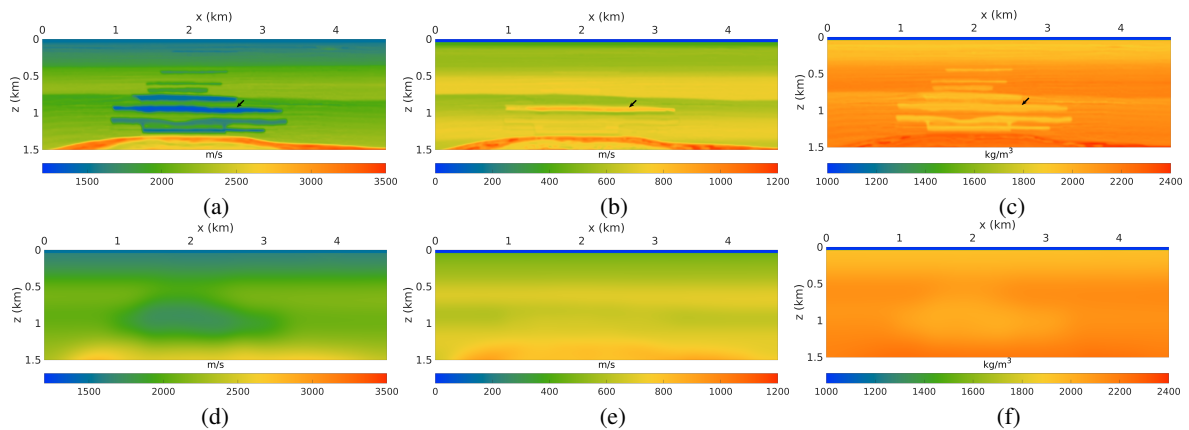


Figure 4: Valhall synthetic models (a, b, c) and corresponding initial models for FWI (d, e, f). Figures from left to right indicate models of V_p , V_s and density, respectively. Black arrows highlight the location of gas cloud which has an extremely low Poisson's ratio ($\sigma = 0.125$) compared with the value of background (around $\sigma = 0.466$).

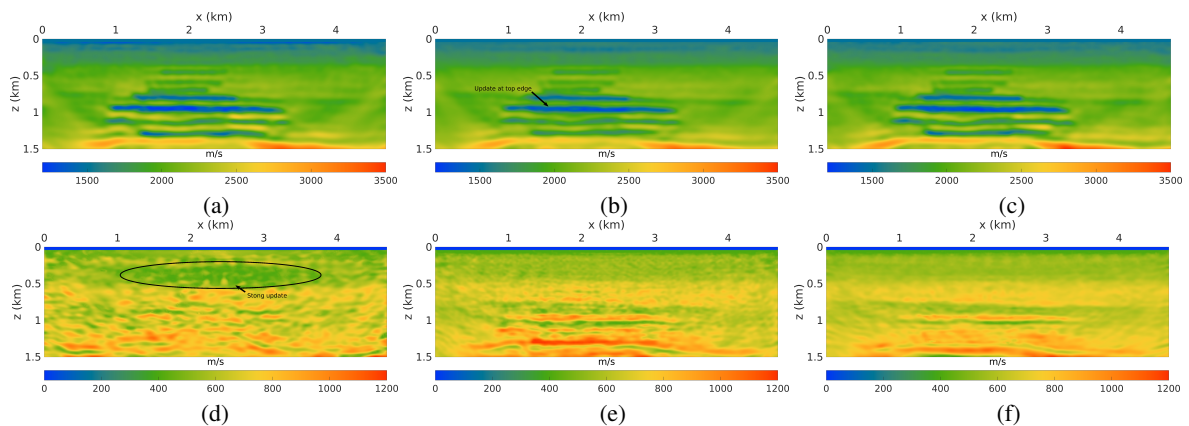


Figure 5: Reconstructed V_p and V_s models from three different two-step FWI workflows. Step 1: only invert hydrophone data to get V_p models using acoustic FWI (a), elastic FWI with (V_p, V_s) parameterization (b), and elastic FWI with (V_p, R) parameterization (c), respectively. Step 2: apply elastic FWI with (V_p, V_s) parameterization to invert 3C geophone data to get V_s models using the starting models: V_p in (a) and V_s in Figure 4e (d), V_p in (b) together with its updated V_s from Step 1 (e), and V_p in (c) and $V_s = V_p/R$ with the inverted R from Step 1 (f).