TIME-LAPSE FULL-WAVEFORM INVERSION FOR MONITORING THE ﬂUID SATURATION

A. Mardan[1], B. Giroux[1], G. Fabien-Ouellet[2]

[1] INRS-ETE; [2] Polytechnique de Montréal

Summary

Monitoring the saturation of fluids in reservoirs is an important tool to improve the management of petroleum and CO2 storage reservoirs. Full-waveform inversion (FWI) has been increasingly used for monitoring the (visco)elastic moduli due to its capacity to estimate these moduli at high resolution. However, monitoring the rock-physics properties has been carried out using rock-physics inversion which relies on linearized amplitude variation with offset (AVO), but this technique has its limitations (using only the reflected events, uncertainties in data processing, and so on). In this study, we examined the possibility of monitoring the rock-physics parameters (e.g. water saturation, Sw) in reservoirs directly from time-lapse FWI (TL-FWI). We also present the required formulation to implement FWI for updating Sw. Based on this study, rock-physics parameters can be monitored directly from seismic data using TL-FWI. It should be known that this technique requires good knowledge about the rock physics of the area of study.

Time-lapse full-waveform inversion for monitoring the fluid saturation

Introduction

Having a good knowledge about the distribution of fluids in reservoirs is a crucial parameter in both the production from and the injection to the reservoirs. For that purpose, a variety of seismic-based methods have been proposed to monitor the changes in the physical properties inside the reservoir. Estimating and monitoring the rock-physics properties from seismic data has been either carried out directly by taking the advantage of the Bayesian inversion approach (Lang and Grana, 2019) or sequentially (Queißer and Singh, 2013; Dupuy et al., 2016a,b). However, these methods rely on the amplitude variation with offset (AVO) and convolutional model which have limitations (Hu et al., 2021). To address this, Hu et al. (2021) proposed a direct inversion for rock-physics properties using full-waveform inversion (FWI). FWI is a high-resolution seismic imaging technique that uses the entire information of seismograms (Virieux and Operto, 2009). Because of its capacity to recover changes of (visco)elastic modulus at high resolution, FWI has been increasingly applied to seismic data for monitoring the elastic properties and a variety of methods are provided to obtain accurate estimates (Fabien-Ouellet et al., 2017; Asnaashari et al., 2015; Mardan et al., 2022b).

In this study, we examine the feasibility of applying time-lapse FWI (TL-FWI) to monitor the rock-physics properties, directly from the seismic data. To estimate the rock-physics changes from different vintages of the seismic data, an efficient link between the rock-physics properties and the seismic changes is required. Rock-physics models can provide this connection based on the different conditions in the area of study (Mavko et al., 2020).

Generally, fluid saturation and effective pressure are the two main properties that change after fluid substitution (other parameters change based on these two). Increasing the saturation of water (decreasing the saturation of hydrocarbon) increases the P-wave velocity and density (water has higher bulk modulus and density). On the other hand, this replacement decreases the S-wave velocity. In addition to the changes in fluid saturation, fluid substitution also varies the effective pressure. As a general rule, by increasing the effective pressure, P-wave and S-wave velocities increase. However, this parameter does not affect the density significantly (Lang and Grana, 2019).

The objective of this study is to monitor the saturation of water (S_w) during a fluid substitution using TL-FWI. In the next section, we discuss the FWI formulation for estimating S_w. Then a brief discussion about the TL-FWI is followed by analyzing the application of rock-physics TL-FWI to the Marmousi model. To perform the FWI in this study, we used PyFWI which is an open-source Python package (Mardan et al., 2022a).

Methodology

FWI can be implemented in the time domain by minimizing the difference between the observed and the estimated seismic data. The cost function of this problem, $\chi(\mathbf{m})$, can be expressed as

$$\min_{m \in \mathbb{M}} \chi(\mathbf{m}) = \frac{1}{2} \|F(\mathbf{m}) - d\|_2^2, \tag{1}$$

where F is the forward modeling operator, d represents the observed data and $\mathbf{m}$ denotes the Earth's properties belonging to the model space $\mathbb{M}$. To minimize equation 1, implementing an efficient adjoint-state method is required to estimate the gradient of the cost function with respect to each parameter class. Common parameterizations of FWI usually rely on elastic modulus, velocities or imepdance, such as density-Lamé modulus (DM), $\mathbf{m} = [\rho, \lambda, \mu]$, and density-velocity (DV), $\mathbf{m} = [\rho, V_P, V_S]$. To invert for rock-physics properties, a different set of parameterization is required which relates either DM or DV to the desired parameters for inversion. As the goal of this study is monitoring the saturation during the fluid substitution and the changes in the effective pressure are not considered, we choose three parameters that are less affected by effective pressure and two of these parameters tend to remain constant during the procedure of fluid replacement. For this reason, porosity (ϕ), clay content (C), and

S_w (PCS) are chosen to form the new parameterization. To establish a link between PCS and DV, a rock-physics model is required which can vary from one field to the other. In this study, the Han empirical model is used (Han, 1987),

$$\begin{aligned} V_P &= a_1 - a_2\phi - a_3C, \\ V_S &= b_1 - b_2\phi - b_3C, \end{aligned} \tag{2}$$

where $a_1 = 5.5$, $a_2 = 6.9$, $a_3 = 2.2$, $b_1 = 3.4$, $b_2 = 4.7$, and $b_3 = 1.8$ (Hu et al., 2021). Density is calculated as the weighted average of the density of the solid matrix and the fluid components

$$\begin{aligned} \rho &= (1-\phi)\rho_m + \phi\rho_f, \\ \rho_m &= \rho_c C + \rho_q(1-C), \\ \rho_f &= \rho_w S_w + \rho_h(1-S_w), \end{aligned} \tag{3}$$

where subscripts m, f, c, q, w, and h represent the solid matrix, fluid, clay, quartz, water, and hydrocarbon, respectively. Using equations 2 and 3, the gradient of the cost function can be calculated for the PCS parameterization as

$$\begin{bmatrix} \frac{\partial\chi}{\partial\phi} \\ \frac{\partial\chi}{\partial C} \\ \frac{\partial\chi}{\partial S_w} \end{bmatrix} = \begin{bmatrix} -a_2 & -b_2 & \rho_f - \rho_m \\ -a_3 & -b_3 & (1-\phi)(\rho_c - \rho_q) \\ 0 & 0 & \phi(\rho_w - \rho_h) \end{bmatrix} \begin{bmatrix} \frac{\partial\chi}{\partial V_P} \\ \frac{\partial\chi}{\partial V_S} \\ \frac{\partial\chi}{\partial\rho} \end{bmatrix}. \tag{4}$$

Having the gradient of the cost function (equation 1) in PCS, we are able to implement FWI to estimate the rock-physics properties. Thereby, in addition to the coefficients in the Han model (equation 2), the density of the minerals and fluid should be known which is not far-fetched in a developed field.

For TL-FWI, the simultaneous TL-FWI is an efficient method which is based on the joint minimization of the baseline and monitor models (Maharramov and Biondi, 2014). The cost function of the simultaneous TL-FWI is defined as

$$\begin{aligned} \min_{\mathbf{m}_m,\mathbf{m}_b} \mathcal{C}(\mathbf{m}_m,\mathbf{m}_b) = &\frac{1}{2}\|F(\mathbf{m}_b) - \mathbf{d}_b\|_2^2 + \frac{1}{2}\|F(\mathbf{m}_m) - \mathbf{d}_m\|_2^2 \\ &+ \frac{\gamma}{2}\|\mathbf{m}_m - \mathbf{m}_b\|_2^2, \end{aligned} \tag{5}$$

where subscripts b and m denote the baseline and monitor surveys, respectively and γ is the regularization parameter.

Example

To examine the effectiveness of the presented strategy, we use a portion of the Marmousi model and convert it to PCS (Figures 1a-c). To generate the monitor model, the saturation in the reservoir is filled with its background (Figure 1d), while the porosity and the clay content remain the same (Figures 1a and b). We assume that parameters of the rock physics model have been well calibrated, as monitoring is usually performed in fields under production or injection which requires a good reservoir characterization. Thereby, we use a slightly smoothed version of porosity and clay content as the initial model (Figures 1e and f), and a highly smoothed model of the saturation (Figure 1g). Figure 1h represents the time-lapse changes of the water saturation.

The observed data are obtained with 10 isotropic explosive sources at the surface considering a perfectly matched layer (PML) around the model. For this study, we used a Ricker wavelet with a peak frequency of 15 Hz. One observed shot gather from the central source of the baseline and monitor data and their difference (multiplied by 5) are shown in Figure 2.

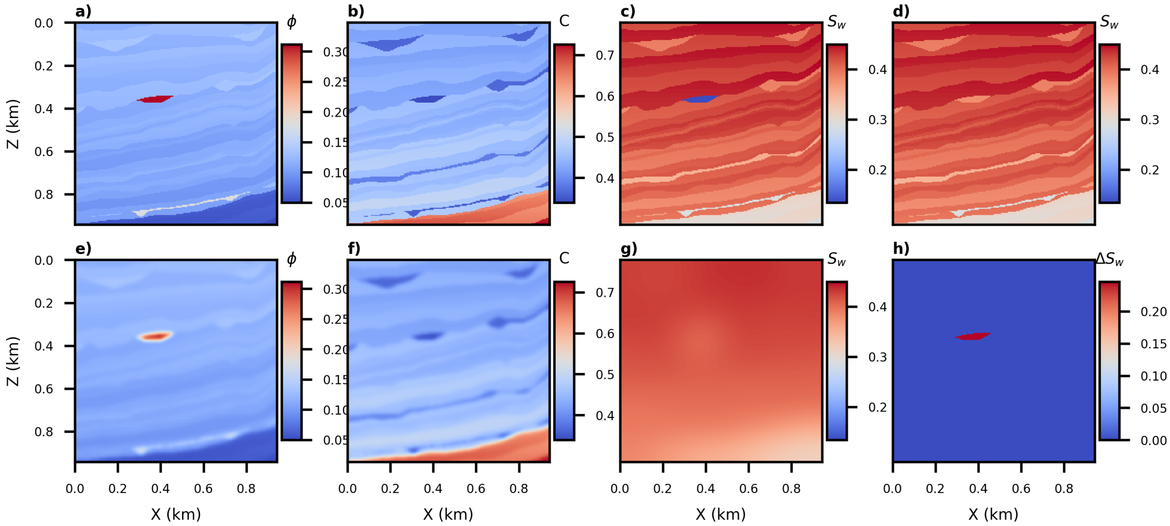

Figure 1 *Marmousi model is used to study the feasibility of direct estimation of time-lapse rock-physics properties from the seismic data. (a-c) Baseline and (a, b, and d) monitor models. (e-g) The smoothed initial model. (h) The true changes in the water saturation.*

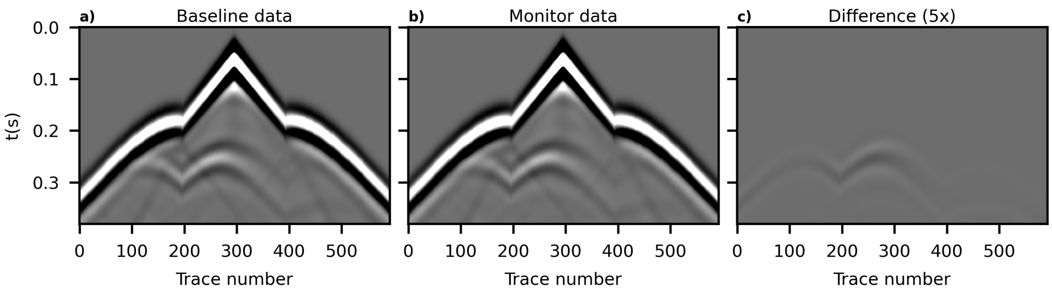

Figure 2 *The observed data from (a) baseline, (b) monitor models, and (c) their difference. For better visualization, the difference is amplified by a factor of 5.*

Results

The datasets shown in Figure 2 are inverted with simultaneous time-lapse inversion to assess the possibility of estimating time-lapse changes of S_w by TL-FWI. To implement this algorithm, the cost function (equation 5) is regularized by ℓ^2-norm of the difference between the baseline and monitor model with $\gamma = 1e-6$. The result and the root mean square error (RMSE) of its discrepancy from the true 4D anomaly (Figure 1h) are presented in Figure 3. The estimated 4D saturation shows the capacity of TL-FWI for estimating the time-lapse rock-physics properties. However, good rock-physics modeling has to be carried out before implementing FWI to provide an accurate relationship between rock-physics properties of the area and the elastic properties. This knowledge is not far-fetched as monitoring usually takes place in well-characterized fields. Besides, choosing an appropriate set of rock-physics property (e.g. ϕ, C, and S_w in this study) is important as this parameterization can reduce the problem of the cross-talk during the FWI.

Conclusions

In this study, the feasibility of direct monitoring of rock-physics properties using TL-FWI is analyzed. We show with a parameterization based on porosity, clay content, and water saturation, that we can estimate an accurate 4D image of the water saturation. The estimated image shows the potential of

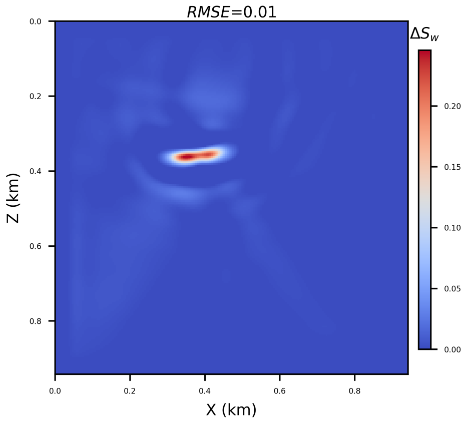

Figure 3 *The estimated time-lapse water saturation with RMSE* $= 0.01$.

the direct monitoring of rock-physics properties using time-lapse full-waveform inversion. However, we should notice that the accuracy of this strategy rely on the knowledge of an accurate relationship between rock-physics and elastic properties for the study area.

Acknowledgments

This project was supported by a NSERC Discovery Grant to BG (RGPIN-2017-06215). The authors thank Qi Hu for providing the Marmousi model in PCS parameterization as used for the baseline model.

References

Asnaashari, A., Brossier, R., Garambois, S., Audebert, F., Thore, P. and Virieux, J. [2015] Time-lapse seismic imaging using regularized full-waveform inversion with a prior model: which strategy? *Geophysical Prospecting*, **63**(1), 78–98.

Dupuy, B., Garambois, S., Asnaashari, A., Balhareth, H.M., Landrø, M., Stovas, A. and Virieux, J. [2016a] Estimation of rock physics properties from seismic attributes — Part 2: Applications. *Geophysics*, **81**(4), M55–M69.

Dupuy, B., Garambois, S. and Virieux, J. [2016b] Estimation of rock physics properties from seismic attributes — Part 1: Strategy and sensitivity analysis. *Geophysics*, **81**(3), M35–M53.

Fabien-Ouellet, G., Gloaguen, E. and Giroux, B. [2017] Time domain viscoelastic full waveform inversion. *Geophysical Journal International*, **209**(3), 1718–1734.

Han, D.H. [1987] *Effects of porosity and clay content on acoustic properties of sandstones and unconsolidated sediments*. Ph.D. thesis, Stanford University.

Hu, Q., Keating, S., Innanen, K.A. and Chen, H. [2021] Direct updating of rock-physics properties using elastic full-waveform inversion. *Geophysics*, **86**(3), MR117–MR132.

Lang, X. and Grana, D. [2019] Rock physics modelling and inversion for saturation-pressure changes in time-lapse seismic studies. *Geophysical Prospecting*, **67**(7), 1912–1928.

Maharramov, M. and Biondi, B. [2014] Robust joint full-waveform inversion of time-lapse seismic data sets with total-variation regularization. *arXiv: Geophysics*.

Mardan, A., Giroux, B. and Fabien-Ouellet, G. [2022a] PyFWI: A Python package for Full-Waveform Inversion (FWI).

Mardan, A., Giroux, B. and Fabien-Ouellet, G. [2022b] Time-Lapse Seismic Full Waveform Inversion Using Improved Cascaded Method. In: *2nd EAGE Conference on Seismic Inversion 2022*, 2022. European Association of Geoscientists & Engineers, 1–5.

Mavko, G., Mukerji, T. and Dvorkin, J. [2020] *The rock physics handbook*. Cambridge university press.

Queißer, M. and Singh, S.C. [2013] Full waveform inversion in the time lapse mode applied to CO2 storage at Sleipner. *Geophysical Prospecting*, **61**(3), 537–555.

Virieux, J. and Operto, S. [2009] An overview of full-waveform inversion in exploration geophysics. *Geophysics*, **74**(6), WCC1–WCC26.