Time-Lapse Seismic Full Waveform Inversion Using Improved Cascaded Method

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

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

Summary

Having a good knowledge about changes in the subsurface can improve the efficiency either in petroleum production or CO 2 sequestration. Time-lapse Full waveform inversion (TL-FWI) is an efficient tool that can provide high-resolution images of the changes in subsurface. As TLFWI is a highly ill-posed problem, the initial model has significant effects on the final results. Although the cascaded inversion method has been used to address this problem, there are still artifacts in the result that can be avoided by using better strategies such as sequential and central-difference inversion.

In this study, the improved cascaded inversion is presented to address this problem more efficiently. This method provides the final result as a weighted average of reverse and forward bootstraps to improve the quality of output. In this way, the artifacts cancel each other out. Besides, varying weights allows differentiating the anomalies and artifacts. In addition to increasing the interpretability of the results, the improved cascaded strategy needs three FWI runs instead of four in the case of sequential and central-difference methods. Thereby, the improved cascaded method reduces the computation time while providing more accurate results.

Introduction

Monitoring the Earth's properties is an important problem that could help for better understanding the interactions under the surface. Having a good knowledge about changes in these properties can improve the efficiency either in petroleum production or CO_2 sequestration. To obtain a high resolution image of the subsurface, full-waveform inversion (FWI) has shown convincing results (Tarantola 1984). FWI can be implemented in a time-lapse manner to image changes in the properties of the subsurface (Plessix et al. 2010). For example, Watanabe et al. (2005) used time-lapse crosswell seismic data at the Mallik test site during the gas production test from the hydrate layer. Rankes et al. (2013) applied time-lapse FWI on a field in the North Sea to detect the changes from 1988 to 1990. Hicks et al. (2016) used 4D FWI to study the Grane PRM system located in the North Sea to recover P-wave velocity changes related to gas replacing oil. Fabien-Ouellet et al. (2017) used 4D FWI to estimate velocity and attenuation changes for monitoring CO_2 sequestration. Zhou and Lumley (2021) apply time-lapse FWI to SEAM data.

Several studies have been done based on different 4D FWI methods. These methods include the parallel scenario (Plessix et al. 2010), in which the result of the inversion of the baseline and monitor models are subtracted. Another scheme is cascaded inversion (Routh et al. 2012). In this method, the inversion of the baseline is used as the initial model for the inversion of the monitor model and finally, the models are subtracted. This scheme and double difference method (Watanabe et al. 2005) attempt to couple different vintages. Maharramov and Biondo (2014) presented a sequential difference method to reduce the effects of the initial model which needs applying FWI four times. Zhou and Lumley (2021) proposed the central-difference strategy, which uses two independent cascaded inversions to get two bootstraps (forward and backward). The average of the two bootstraps gives the most accurate estimation of the changes.

Cascaded inversion cannot estimate the changes very well because of the difference in the level of convergence of baseline and monitor model (Hicks et al. 2016). In this study, we propose a modified version of the cascaded method. This method provides a better estimation in comparison to conventional cascaded and sequential difference methods. Although the obtained result is comparable with central-difference approach, the algorithm needs to implement the FWI procedure three times, instead of four in the case of sequential and central-difference inversion strategies. Thereby, the proposed method decreases the computational cost significantly and still provides high-quality results.

Methodology

We implement the inversion in the time domain by minimizing the L2 norm-based objective function as

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

where F denotes the forward modelling operator and d is observed data (baseline or monitor). $\mathbb{M}$ represents the model space with an initial model, m_0, which gets updated through the iterations. The 4D changes of model can be obtained by the cascaded method (Figure 1a). In this method, we first update the initial model to get the baseline model (m_b). Then, the monitor data are inverted with the baseline model as the initial model ($m_0 = m_b$). The velocity changes are obtained as the difference between the monitor and baseline models. One issue with this approach is that if it is performed with a different order of inversion (monitor-baseline instead of baseline-monitor), the result changes dramatically. To avoid this problem and decrease the effects of the initial model, Maharramov and Biondo (2014) proposed the sequential (cross update) inversion (Figure 1b). Sequential inversion uses conventional cascaded method to get a baseline (m_b) and a monitor (m_m) model. Then, a second baseline model is obtained by using the inverted monitor model as the initial model ($m_0 = m_m$). Then that baseline model is used to estimate again the monitor model ($m_0 = m'_b$). Thereby, this method needs two more inversions after implementing the cascaded method to estimate the second baseline and monitor models (m'_m). The velocity changes are obtained by calculating the difference between these two models. Zhou and Lumley (2021) propose a different approach called central-difference time-lapse FWI (Figure 1c), which starts from an initial model and gets the first set of baseline and monitor models. Then those models are considered as initial

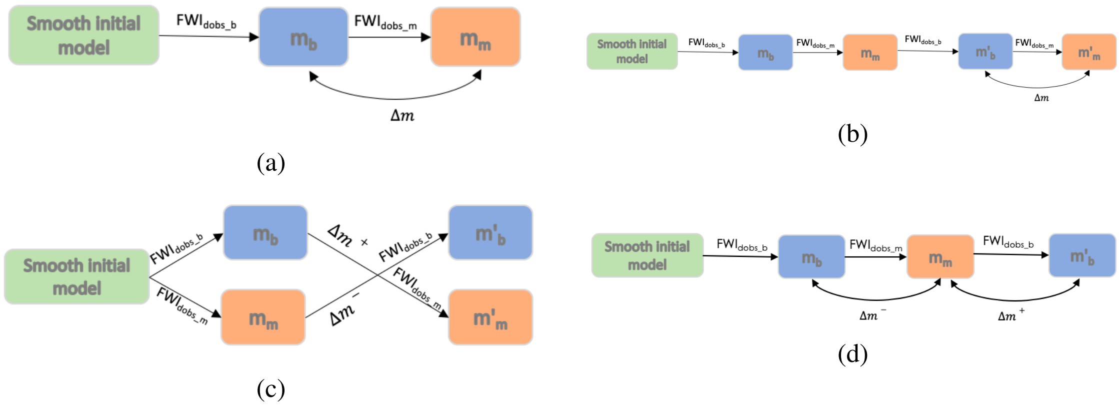


Figure 1: *Algorithms of (a) conventional cascaded, (b) sequential difference, (c) central difference, and (d) improved cascaded time-lapse inversion. The subscripts denote the baseline and monitor surveys.*

model to estimate the monitor and baseline, respectively. These two final FWIs provide forward and backward bootstraps and their average is considered as the output of the method.

Inspired by the central-difference strategy, we implement a new version of cascaded inversion which provides a better result than the original cascaded and sequential inversion. The estimated result is also comparable with the central-difference method, but needs performing one less inversion run than sequential or central-difference inversion.

In the proposed method, after estimating the first monitor model by using the baseline as the initial model, we run our FWI one more time to invert again the baseline data by using the monitor model as the initial guess (Figure 1d). In this way, we have two different estimated changes in our model. These two models have mostly the same artifacts with different sign. Hence, by taking the average of forward and backward estimations, we can suppress most of these artifacts and get a better estimation of changes in the property of the subsurface. As the backward estimation usually contains greater artifacts, we calculate the average of two models by giving a weight to the backward bootstrap, such that

$$\Delta m = \frac{\alpha \Delta m^- + \Delta m^+}{1+\alpha} \tag{2}$$

where α is a weight used to analyse the artifacts and

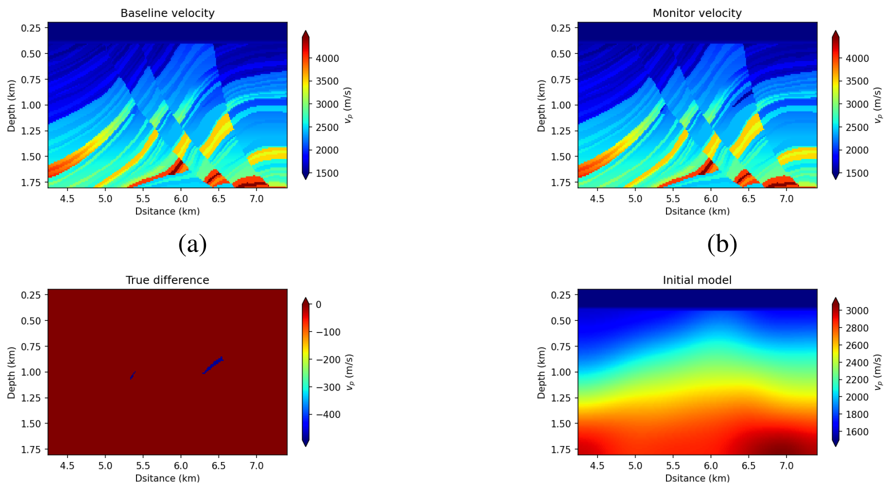
$$\Delta m^- = m_m - m_b, \tag{3a}$$
$$\Delta m^+ = m_m - m'_b \tag{3b}$$

where m'_b is the second estimated baseline. The parameter α mostly affects the artifacts and makes them more or less noticeable. Hence, changing this parameter and comparing the results is a good detector of the true anomalies which are sought.

Results

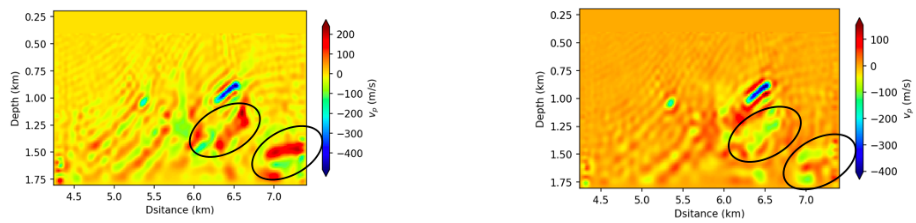
To analyse the efficiency of the proposed method, we compare different time-lapse strategies on a portion of the Marmousi model. A modified version of the Marmousi model is used as the baseline and the targets are two gas sand traps in the monitor line as shown in Figure 2.

The initial model for this study is shown in Figure 2d. If we consider the algorithm presented in Figure 1a as backward 4D FWI, we can implement FWI to estimate another baseline model (m'_b) using $m_0 = m_m$ to obtain forward bootstrap (Figure 1d). These two estimations are shown in Figure 3.



(a) (b) (c) (d)

Figure 2: *(a) Baseline, (b) monitor model, (c) their difference, and (d) the initial model which is smoothed version of true baseline.*



(a) (b)

Figure 3: *Result of cascaded inversion changes for different order of inversion, (a) Backward (Δm^{-}) and, (b) Forward bootstraps (Δm^{+}). Note that the artifacts have different sign as shown by black ovals.*

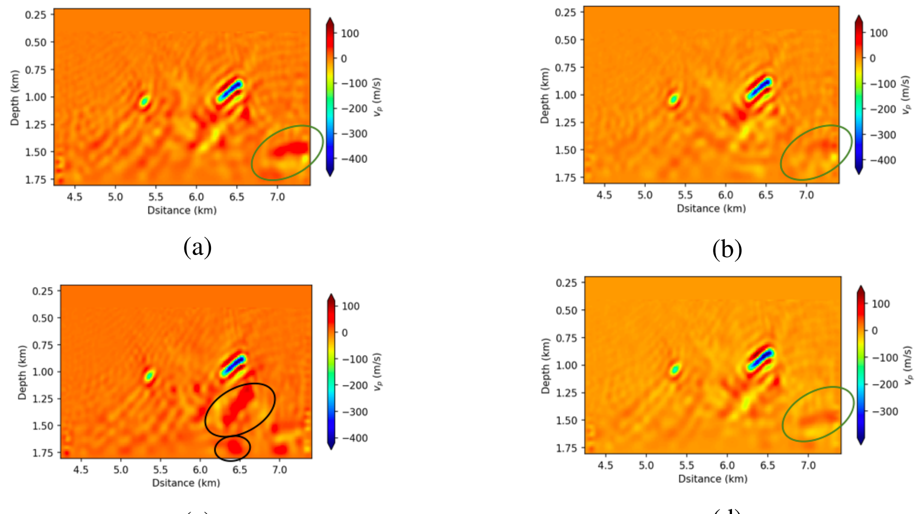
Figure 4 shows the velocity changes obtained by applying the proposed methodology (equation 2) with different alpha values. This figure also shows the estimations obtained by implementing the sequential and central-difference time-lapse inversions. The sequential inversion method yields the largest artifacts of the three methods tested here. Note that our proposed methodology matches the quality of the central difference method at a lesser cost of three FWI runs instead of four.

To analyse the effects of noise, we applied the proposed method on data with 7 dB SNR. Figure 5 shows the estimated changes obtained by the forward, the backward and the proposed method. Comparing the results shows that the proposed method improves the quality of inversion on the noisy data as well.

Conclusions

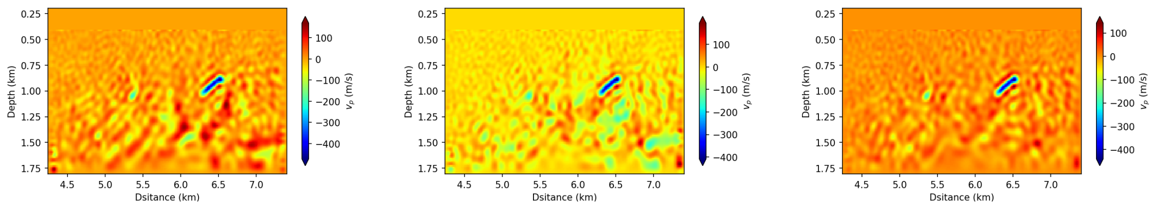
In this study, we proposed a modified cascaded inversion and compared its performance with the sequential and the central difference methods. As can be shown, based on the order of inversion, two different estimations can be obtained. By comparing the results of forward and backward bootstraps, we showed that the true changes have the same sign, which is not the case for large artifacts. Thus the average of forward and backward inversions can improve the result of 4D FWI. We use weighted averaging to put less accent on the backward inversion. Changing that weight causes the artifacts to cancel out each other better (as they have different sign) and it does not affect the true anomalies significantly.

By comparing this method with sequential inversion, we concluded that the proposed method can provide a better result with less computation. Although the central-difference method provides comparable results, the proposed method is faster as it needs one less FWI run than the central-difference method.



(a) (b) (c) (d)

Figure 4: *Results of proposed method with (a) $\alpha = 1$, (b) $\alpha = 0.5$, (c) sequential and (d) central-difference inversion show that beside the cost of computation, the proposed methodology in this study can have superiority in the precision of the results as well. The strong artifacts in the sequential method are shown by black ovals. The green ovals show how α can improve the result and clear it from the artifacts of central-difference method.*



(a) (b) (c)

Figure 5: *(a) Backward and (b) forward bootstraps, and (c) proposed method with $\alpha = 1$ in noisy data.*

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