4D Time-Lapse Full Waveform Inversion Case Study for SAGD Steam Chamber Imaging

Introduction

Full Waveform Inversion (FWI) initially emerged as an advanced tool for complex velocity model building (Crase et al., 1990; Warner and Guasch, 2014; Kotsi and Malcolm, 2017). The FWI-derived velocity model coupled with advanced imaging algorithms, such as PSDM and RTM, can dramatically improve the subsurface imaging from extremely complicated structures that exhibit abrupt vertical and lateral velocity changes (Zhang and Zhang, 2011; Zhang and Huang, 2013). The oil and gas industry has seen very successful applications of FWI in different geologic settings such as the complex subsalt targets in the offshore Gulf of Mexico. However, FWI has yet to extend its full potential to the land seismic data, especially the 4D time-lapse seismic surveys in the Oil Sands areas. The application of FWI to the land seismic remains challenging mainly due to lacking low frequencies, limited offsets, high amplitude elastic waves, and source wavelet estimation. To mitigate these effects on the time-lapse FWI, the double-difference workflow (Bian et al., 2017) was applied using a cost function mainly targeting the baseline match and the waveform difference match between the baseline and monitor surveys.

Method and Theory

FWI is driven by minimization of the data residual between the real raw shot gathers and the simulated shot gathers by an iterative process that results in a high-resolution velocity model (Figure 1). Two key requirements in the FWI method are efficient forward modeling and local differential computation, which are two major computational costs in the FWI process.

\[ \phi_{FWI} = \|d_s^{obs} - d_s^{pre}\|^2 + \tau_s\|Lm_s\|^2 \]  \hspace{1cm} (1)

\( d_s^{obs} \) and \( d_s^{pre} \) represent the observed seismic waveform data and synthetic data. \( \tau_s \) is the smoothing parameters to balance the data misfit term and a regularization term. \( m_s \) is the velocity model. The gradient of the FWI objective function is defined as the partial derivative of the cost function with respect to the model slowness:

\[ \frac{\partial \phi_{FWI}}{\partial m_s} = \tilde{P}_F P_B + \tau_s L^T Lm_s \]  \hspace{1cm} (2)

where \( \tilde{P}_F \) and \( P_B \) are the forward and backward propagation wavefield for imaging that provides sensitivity impacts and directs waveform inversion.

4D Time-Lapse FWI
The time-lapse of seismic data is often used to detect the reservoir changes which leads to the seismic waveform differences between the baseline and monitor surveys (Lumley, 2001). FWI has been found as an efficient imaging technique because of its capability to produce a high-resolution velocity model (Tarantola, 1984; Zhang and Huang, 2013; Maharramov et al., 2016; Bian et al., 2017; Kotsi and Malcolm, 2017; Peng et al., 2018). There are four FWI schemes in time-lapse studies: a) parallel, b) sequential, c) double-difference, and d) joint inversion workflows. These methods are illustrated in Figure 2.

**Figure 2** Time-lapse FWI schemes: a) parallel, b) sequential, c) double-difference, and d) joint inversion methods.

The parallel workflow (Figure 2a) is equivalent to run FWI separately for each survey, presumably, the starting model and all the parameters of each FWI are the same. The sequential workflow (Figure 2b) is like the parallel workflow except the monitor FWI takes the final FWI model of the baseline survey as a starting model. As the inversion is performed independently, these methods do not require the acquisition geometries to be the same but bearing the pain of non-uniqueness of FWI solutions, they require a significant amount of manual interpretation and quality control. Although the joint inversion (Figure 2d) (Maharramov et al., 2016) can penalize the model difference to stabilize the FWI regularization, we feel it is difficult to isolate the 4D changes to be only around the reservoirs. We propose to perform time-lapse FWI using the double-difference workflow (Fig. 2c) (Bian et al., 2017; Watanabe et al., 2004; Zhang and Huang, 2013), where we can mask the monitor model to be only different from the baseline at the reservoirs. The starting model of the double-difference FWI is the final model of the baselines FWI, and the input data of this workflow is the waveform difference between the monitor and baseline surveys. The waveform difference generated by the elastic property changes between time-lapse surveys can be regarded as the scattered waves. Even though the starting model, which is the baseline model in this scheme, may have its own error, the scattered waves can be migrated to isolated areas around the reservoirs, rather than to distribute the energy to the whole area. The theory of the double-difference FWI is described below.

**Double-Difference FWI**

Consider the following cost function in a joint baseline/monitor FWI:

\[
E(m_{\text{baseline}}, m_{\text{monitor}}) = \| [d_{\text{monitor}} - u_{\text{monitor}}(m_{\text{monitor}})] - [d_{\text{baseline}} - u_{\text{baseline}}(m_{\text{baseline}})] \|^2 = \| [d_{\text{monitor}} - d_{\text{baseline}}] - [u_{\text{monitor}}(m_{\text{monitor}}) - u_{\text{baseline}}(m_{\text{baseline}})] \|^2 \tag{3}
\]

where \(d_{\text{baseline}}\) and \(d_{\text{monitor}}\) are the baseline and monitor seismic waveforms, \(m_{\text{baseline}}\) and \(m_{\text{monitor}}\) are the baseline and monitor models, \(u_{\text{baseline}}\) and \(u_{\text{monitor}}\) are the synthetic waveforms using the exiting baseline and monitor models respectively. The FWI objective is to find a solution for \(m_{\text{baseline}}\) and \(m_{\text{monitor}}\) that can minimize the double differences in the cost function of equation (3).
Assuming a reasonable baseline model can be obtained from a standard baseline FWI, equation (3) can be written as follows:

$$E(\mathbf{m}_{\text{monitor}}) = \|d_{\text{monitor}} - d_{\text{baseline}} + u_{\text{baseline}}(\mathbf{m}_{\text{baseline}}) - u_{\text{monitor}}(\mathbf{m}_{\text{monitor}})\|^2$$

(4)

so, we can minimize the cost function by performing a monitor FWI but replacing the monitor seismic waveform with the input waveform that is the difference between the monitor and baseline waveforms plus the baseline synthetic waveform. The advantage of this method compared with a sequential FWI is that it should guarantee to converge to the baseline model if there is no waveform difference between the time-lapse surveys, so we can safely mask the areas if we believe there shouldn’t be any change from the baseline model.

**Results**

The output from 4D time-lapse FWI is the velocity difference volume between the baseline and monitor surveys. Velocity changes are a function of saturation, temperature, and pressure, with the greatest velocity change associated with a gas phase. As a result, the velocity difference between the baseline and the monitor surveys can be used for the direct interpretation of the developed steam chamber. The preliminary analysis of the inverted 4D time-lapse FWI velocity difference shows a very encouraging image of the steam chamber inside the reservoir which is crucial for understanding the heterogeneity of the reservoir and future development plans. The inverted FWI velocity difference was validated with vertical well temperature logs, top/base steam chamber events from the reflection seismic volume, the time delay map, and the surface heave map.

**Figure 3** A comparison between Kirchhoff migrated Common Image Gathers (CIG’s) generated from the traditional velocity models (a), and FWI velocity models (b). PSTM image using the traditional velocity model (c) and the FWI derived PSDM volume (d).

The FWI process has improved steam chamber imaging in several ways. The Kirchhoff migrated Common Image Gathers (CIG’s) in Figure 3a using the traditional velocity model shows the event flattening is not accurate enough due to the inaccuracy of the velocity model. The CIG’s in Figure 3b using the FWI velocity produce an obvious improvement in the event flattening which will generate focused steam chamber top and base reflectors on the stacked section.

The improved seismic imaging of the steam chamber on the PSDM section compared with the depth converted PSTM image using the traditional velocity model is shown in Figure 3d. On the PSTM image in Figure 3c, the geometry of the steam chamber is not focused, and the steam chamber geometry is less clear. On the PSDM image in Figure 3d, the base of the steam chamber is more focused and clearer.

The validation and analysis of the FWI velocity model involve comparing with time delay map, vertical observation well temperature logs, and production data. The inverted FWI velocity differences (4a) agree with the temperature logs and have a good alignment with the horizontal trajectory. The steam chamber geometry shown on the FWI velocity difference agrees with the PSDM image (4b).

A map view of a depth slice of the FWI velocity difference at 16 meters above the producers reveals a strong velocity drop along the horizontals in Figure 4c.
Figure 4 The inverted FWI velocity differences (a) and the corresponding PSDM image (b). Map view of a depth slice of the FWI velocity difference at 16 meters above the producers (c).

Conclusions

We adapted the FWI methodology for an innovative application that jointly inverts the time-lapse datasets for the SAGD steam chamber interpretation. The steam chamber is a gas phase in the reservoir that presents a low-velocity seismic anomaly created during the bitumen extraction process. This constitutes an interesting target for the FWI process. The velocity difference volume created directly from the raw shot gathers can be used to map the steam chamber geometries and allow for faster decision-making on well placement and production optimization. Applying the FWI derived velocity model to create a PSDM volume can significantly improve imaging quality.

References


Zhang, W., and Zhang, J., 2011, Full waveform tomography with consideration for large topography variations, SEG Expended Abstracts 30, 2539-2542.