Salt Structure Velocity Model Building Based on Signed Multi-Scale Direct Envelope Inversion

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Salt structure velocity model building based on signed multi-scale direct envelope inversion

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Summary

Large-scale salt dome is an important problem in salt structure exploration. The envelope-based inversion method decouples the amplitude and polarity information of the seismic data and improves the convexity of the full waveform inversion objective function by using the envelope alone. However, the lack of polarity information will result in the inversion not able to accurately identify the velocity variation. In order to solve the problem caused by the missing polarity information of the envelope, signed demodulation method has been proposed and developed into a signed multi-scale direct envelope inversion method. In the signed multi-scale direct envelope inversion, the direct envelope derivative improves the linearity between the envelope and model parameters, and the multi-scale inversion strategy increases the convergence of the inversion. The results of numerical experiments on the SEG/EAGE 2-D Salt model and Sigsbee2A model using low-cut source (frequency components below 4 Hz were truncated) verify the promising potential of the method.

Introduction

Salt structure is a potential exploration target for oil and gas reservoirs. However, large-scale salt domes present a challenge to salt structure exploration. Recently, several new methods have been proposed to improve the effect the full waveform inversion (FWI) on the salt structure: the level set method was introduced into the FWI to identify salt dome boundaries (Lewis et al., 2012). Esser et al. (2015) developed a regularization method by using total variation constraints to the adaptive waveform inversion misfit function to obtain a high fidelity salt model. FWI using the optimal transport distance achieved good performance in the salt structure inversion (Métivier et al., 2016; Yang and Engquist, 2017). Large salt domes bring us the difficulty in the salt structure inversion while providing us the possibility to solve the problem: a large salt dome makes the events in the seismic record sparse and isolated. Based on the sparse characteristics of the observed data from the salt structure, multi-scale direct envelope inversion (MSDEI) that using the direct envelope Fréchet derivative and multi-scale strategy to reconstruct the long wavelength components of the salt structure was proposed (Wu and Chen, 2017; Chen et al, 2017, 2018a, 2019). In order to further improve the inversion quality of the subsalt structure, Chen et al. introduced the wavefield decomposition and migration/de-migration strategy in the reflection waveform inversion into the MSDEI, reducing the dependence of MSDEI on the long-offset seismic data (Chen et al, 2018b). Roberts (2018) validated the effectiveness of the MSDEI using field data from Argentina.

In the MSDEI, demodulation operation was used to extract the low frequency information of the seismic data. However, using only the amplitude demodulation will result in the loss of seismic data polarity information, resulting in the FWI not able accurately identify the velocity variation, thus increasing the possibility of inversion to obtain multiple solutions. Signed demodulation method that contains both the amplitude and polarity information of the envelope. We applied the signed demodulation in the MSDEI and obtained a new inversion method: signed multi-scale direct envelope inversion (S-MSDEI). In the numerical tests, the new inversion method was applied to the SEG/EAGE 2-D Salt model and Sigsbee2A model using low-cut source (frequency components below 4 Hz are truncated).

Multi-scale direct envelope inversion

Envelope are the energy pulse records that contain the coarse scale perturbation information of subsurface. The envelope has a better linear relationship with the model parameters than the strong nonlinearity between the seismic data and the model parameters (Chen et al., 2019). The misfit function of the MSDEI can be written as

$$\begin{aligned} \sigma_W &= \frac{1}{2}\sum_{SRT} \mathrm{r}_W^*(t)\mathrm{r}_W(t) \\ \mathrm{r}_W(t) &= \frac{1}{W}\int_{-W/2}^{W/2} dt'\mathbf{W}(t-t')\left[e_{syn}^2(t)-e_{obs}^2(t)\right] \\ e_{syn}(t) &= \sqrt{y^2(t)+y_H^2(t)} \quad e_{obs}(t)=\sqrt{u^2(t)+u_H^2(t)} \end{aligned} \tag{1}$$

Where y is synthetic data and u is observed data, the envelope of synthetic y is e_{syn} and e_{obs} is the envelope of the observed data u. "H" is Hilbert transform operator. S is the shot coordinate and R is the receiver coordinate, T is the total recording time. $\mathbf{W}(t)$ is time window and W is its effective window width. Using the adjoint state method and virtual source operator for boundary reflection (Wu and Chen, 2018) the gradient of the MSDEI can be calculated by:

$$\frac{\partial \sigma_W}{\partial v} = \sum_{SRT} \frac{2(\mathbf{e}_0^2(x,z,t))_W}{\mathbf{v}_0(x,z)} \mathrm{G}_e^{W*}\mathrm{r}_W(t) \tag{2}$$

Where $\left(\mathbf{e}_0^2(x,z,t)\right)_W$ is the background window-averaged envelope-field that can be obtained from the background wave-field $\mathbf{y}_0(x,z,t)$. G_e^W is a Green's operator which represents the forward propagation process of the window-averaged energy. G_e^{W*} is the conjugate transformation of G_e^W, it represents the window-averaged energy residual backpropagation.

Signed demodulation

In the signed demodulation,we use the local minima points to divide the envelope into different events. In each event, the sign of the envelope is determined by the dominant energy sign of this event. The signed demodulation workflow is summarized in Table 1.

Table 1 Signed demodulation workflow

(1) Calculate the envelope e *of the seismic data that total recorded time is T.*

(2) Calculate the local minima point coordinates of the envelope $P_k\ (k = 2,3,4....m-1)$, $P_1 = 1$ *and* $P_m = T$ *are the starting point and endpoint of the seismic data, respectively.*

(3) Define $s_k(it) = s(it)$, $e_k(it) = e(it)$, $(it = P_k, P_k+1,...P_{k+1}-1)$. *Define the maximum point coordinates of the absolute value of* s_k *as* Pmax_k .

(4) $e_k^{SD}(it) = sign(s_k(\mathrm{Pmax}_k))e(it), \quad (it = P_k, P_k+1,...P_{k+1}-1)$

(5) Define the signed envelope e^{SD} ,
$$e^{SD}(it) = e_k^{SD}(it) \quad (it = P_k, P_k+1,...P_{k+1}-1, \quad k = 1,2,3......m-1)$$
$$e^{SD}(T) = sign(e^{SD}(T-1))e(T).$$

We utilize this signed demodulation method on one trace seismic data (Figure 1(a)) from the SEG/EAGE salt model. In order to compare the influence of the window function on the signed envelope, we also give the signed envelope with different window width. The spectra of the data in Figure 1(a) are shown in Figure 1(b).

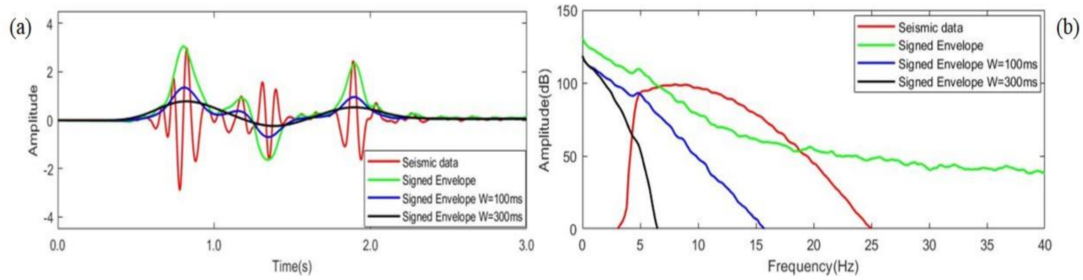

Figure 1 *(a) One trace seismic data from the SEG/EAGE Salt model (red line); signed envelope (green line); signed envelope with window width W=100ms (blue line), W=300ms (black line). (b)The spectra of the seismic data from the SEG/EAGE Salt model (red line), signed envelope (green line), signed envelope with window width W=100ms (blue line), W=300ms (black line).*

Signed multi-scale direct envelope inversion (S-MSDEI)

We introduce the signed demodulation into the multi-scale direct envelope inversion, the misfit function will be

$$\sigma_W^{SD} = \frac{1}{2}\sum_{SRT} r_W^{SD*}(t)\, r_W^{SD}(t) \qquad r_W^{SD}(t) = \frac{1}{W}\int_{-W/2}^{W/2} dt'\,\mathbf{W}(t-t')\left[(e_{syn}^2(t))^{SD} - (e_{obs}^2(t))^{SD}\right] \tag{3}$$

For multi-scale signed envelope inversion, the gradient is:

$$\frac{\partial \sigma_W^{SD}}{\partial v} = \sum_{SRT} \frac{2\left(\mathbf{e}_0^2(x,z,t)\right)_W^{SD}}{\mathbf{v}_0(x,z)} G_{e^{SD}}^{W*} r_W^{SD}(t) \tag{4}$$

Where the note SD is the abbreviation for signed demodulation, $\left(\mathbf{e}_0^2(x,z,t)\right)_W^{SD}$ is the background signed window-averaged envelope-field which can be obtained from the background wave-field $\mathbf{y}_0(x,z,t)$. G_{SD}^W is a propagation operator for the signed envelope. G_{SD}^{W*} is the conjugate operator of G_{SD}^W , it represents the signed window-averaged energy backpropagation. Regarding the residual of the signed window-averaged envelope as one form of waveform data, we use Green's function of the wave equation G to replace the Green's operator of the WAE $G_{e^{SD}}^W$.

Numerical experiments

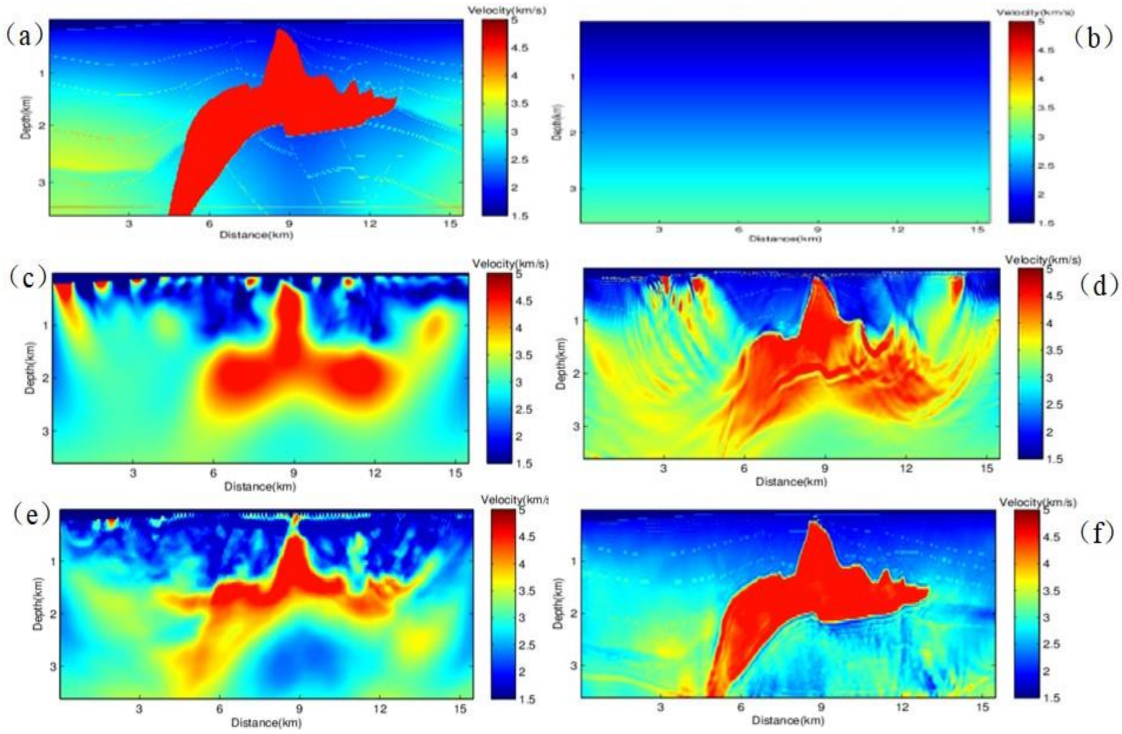

Figure 2. *(a) SEG/EAGE Salt model; (b) Initial model; (c) Inversion result of MSDEI; (d) Inversion result of MSDEI+FWI; (e) Inversion result of S-MSDEI ; (f) Inversion result of S-MSDEI+FWI.*

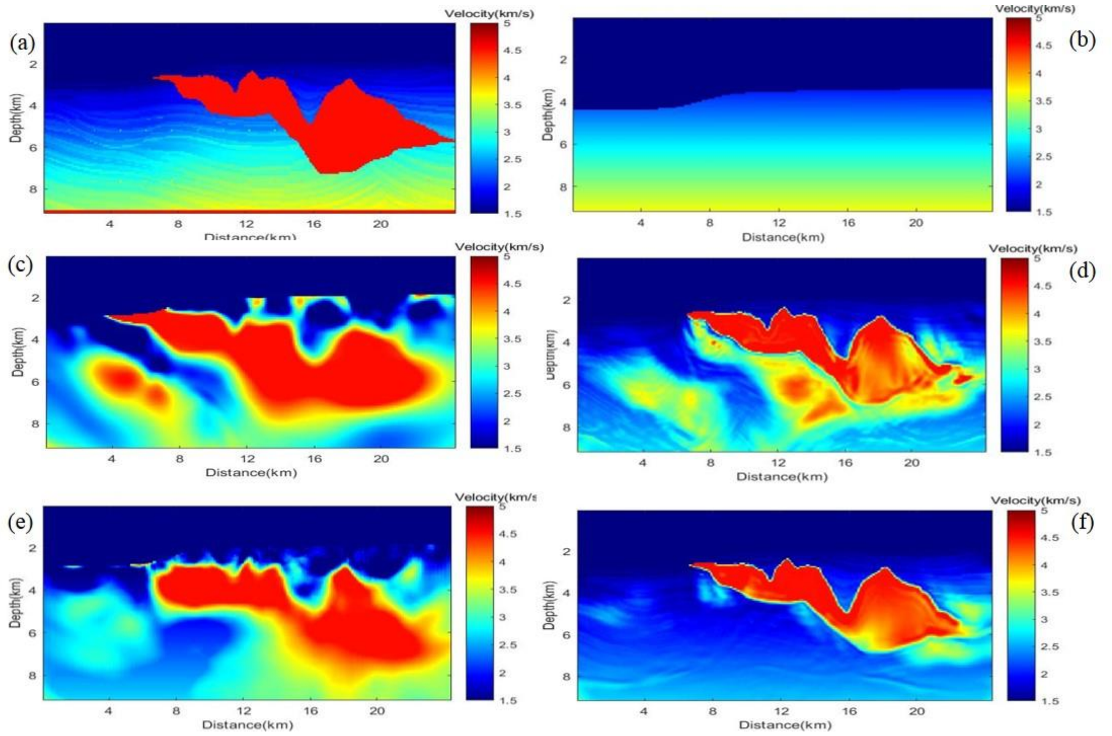

Figure 3. *(a) Sigsbee2A model; (b) Initial model; (c) Inversion result of MSDEI; (d) Inversion result of MSDEI+FWI; (e) Inversion result of S-MSDEI ; (f) Inversion result of S-MSDEI+FWI.*

We use the SEG/EAGE Salt model (Figure 2(a)) to test the inversion effect of the new method on models with strong contrast. Figure 2(b)) is the initial model. We use the Ricker wavelet that dominant frequency is 9 Hz as source in the test (cut from 4Hz below). In the MSDEI, 300ms, 150ms, 50ms are used in succession. Figure 2(c) is the inversion result of MSDEI, Figure 2(d) is the inversion result of

MSDEI+FWI. In the S-MSDEI, we use the same inversion parameters in the MSDEI. Figure 2(e) is the inversion result of the S-MSDEI, due to the amplitude and polarity information are used together, not only the velocity of the salt doom, but also the subsalt structure obtained a good reconstruction. Then we use FWI to invert the fine structure of the model, Figure 2(f) is the inversion result of the S-MSDEI+FWI.

We use the Sigsbee2A model to test the S-MSDEI for larger-scale salt domes. Figure 3(a) and Figure 3(b) are the true model and initial model, respectively. We use the same Ricker wavelet as the last test. In the MSDEI, 500ms, 300ms, 100ms are used in succession. The inversion results of the MSDEI, MSDEI+FWI, S-MSDEI, S-MSDEI+FWI are shown in Figure 3(c), 3(d), 3(e), 3(f), respectively. From the comparison of the inversion results, it can be seen that it is necessary and correct to introduce the polarity information into the envelope.

Conclusion

In this abstract, the polarity information of the envelope are reconstructed by using the signed demodulation method. The signed demodulation can reduce the multi-solution problem of the multi-scale direct envelope inversion, and improve the inversion accuracy. In numerical results, the significant difference between the inversion results of the signed multi-scale direct envelope inversion and the multi-scale direct envelope inversion proves the indispensable role of polarity in the envelope inversion.

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