Workflow for near-surface velocity automatic estimation: Source-domain full traveltime inversion followed by waveform inversion

Lu Liu*, Aramco Research Center-Beijing, Aramco Asia; Bowen Guo, King Abdullah University of Science and Technology; Tong W. Fei, Yi Luo, EXPEC Advanced Research Center, Saudi Aramco

Summary

This paper presents a workflow for near-surface velocity automatic estimation using the early arrivals of seismic data. This workflow comprises two methods, source-domain full traveltime inversion (FTI) and early-arrival waveform inversion. Source-domain FTI is capable of automatically generating a background velocity that can kinematically match the reconstructed plane-wave sources of early arrivals with true plane-wave sources. This method does not require picking first arrivals for inversion, which is one of the most challenging aspects of ray-based first-arrival tomographic inversion. Moreover, compared with conventional Born-based methods, source-domain FTI can distinguish between slower or faster initial model errors via providing the correct sign of the model gradient. In addition, this method does not need estimation of the source wavelet, which is a requirement for receiver-domain wave-equation velocity inversion. The model derived from source-domain FTI is then used as input to early-arrival waveform inversion to obtain the short-wavelength velocity components. We have tested the workflow on synthetic and field seismic data sets. The results show source-domain FTI can generate reasonable background velocities for early-arrival waveform inversion even when subsurface velocity reversals are present and the workflow can produce a high-resolution near-surface velocity model.

Introduction

Near-surface velocities are critical for subsurface seismic imaging and reservoir delineation. Conventional ray-based first-arrival tomography has been an efficient and robust tool to derive the large-scale near-surface velocities for decades (Zhang and Toksöz, 1998). However, the finite-frequency bandwidth of the seismic data does not meet the high-frequency approximation upon which ray theory is based and this could lead a suboptimal estimation of velocity (Sheng et al., 2006). Besides, ray-based methods involve picking the first arrival traveltimes; although traveltime picking is generally automated, manual intervention and quality control are always required (Keho and Zhu, 2009) and can often be very time-consuming. In addition, when subsurface velocity reversals exist, the first arrivals are shingled, making them very difficult to pick (see below). Thus, the challenges are how to make near-surface velocity estimation automatic and make it work for shingled first arrivals.

To overcome the high-frequency limitation of ray theory and avoid picking, we propose using wave-equation-based source-domain FTI. This method is capable of automatically producing a reasonable background velocity without picking the traveltime even when velocity reversals are present. In particular, the gradient of this method (Luo et al., 2016), assumes that the velocity perturbation only causes traveltime shifts of waveforms. Such theory enables our gradient to distinguish between initial velocities that are slower or faster than the true velocity, which Born-based gradient methods cannot.

Full waveform inversion (FWI) has shown great potential for revealing the high-resolution subsurface velocity details by minimizing the difference between the predicted data and the observed data. However, conventional FWI (Tarantola, 1984) generally fails in field data or the misfit function falls into a local minimum when the initial velocity is not accurate enough or the seismic data do not have the extremely low frequencies, typically less than 2 Hz (Plessix et al., 2010). Therefore, many researchers used refractions or diving waves to implement the inversion for estimating the near-surface velocity as the early-arrival misfit function contains much fewer local minima than when using the entire trace (Shen, 2014; Sheng et al., 2006). To avoid the local minima and relax the requirement for amplitude matching, we use early-arrival waveform inversion with the normalized cross-correlation misfit function (Routh et al., 2011). Moreover, the gradient of the misfit function is calculated using plane-wave data in order to enhance the efficiency.

In this paper, we propose a two-step workflow to obtain a high-resolution near-surface velocity model with a linear velocity as the initial estimation. The workflow first uses source-domain FTI to update the long-wavelength components of the model, followed by early-arrival waveform inversion to update the short-wavelength components. The paper is organized into four sections. First, we introduce the principal of source-domain FTI method. Then, we compared the Born-approximation-based and the FTI-based gradients using a single-flat-layer model. Third, we briefly introduce the theory of early-arrival waveform inversion used in the workflow. Finally, we demonstrate the validity of the proposed workflow using synthetic and field data sets.

Theory

The misfit function of source-domain FTI is defined as,

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$E = \iiint w(x, t - px)^2 d(x, z = 0, t; p)^2 dx dp dt$ (1)
where p is ray parameter quantified by $\sin(\theta_s)/v_0$, θ_s is the surface incident angle, v_0 is the surface velocity and $d(x, z = 0, t; p)$ is the reconstructed plane-wave source which is calculated by backward propagating the plane-wave data to the source location via solving the acoustic equation. $w(\tau)$ is a triangular window with peak value located at the position of the true plane-wave source, which penalizes the energy at non-excitation times. $w(\tau)$ is defined as,

$$w(\tau) = \begin{cases} |\tau - t_0|/\Delta T, & t_0 - \Delta T \leq \tau \leq t_0 + \Delta T \\ 0, & \text{else} \end{cases} \quad (2)$$

where, t_0 is the excitation time of the true plane-wave source and ΔT is the half window length.

The above misfit function was first proposed by Zhang and Wang (2009) to obtain the short-wavelength components of velocity. However, their method is sensitive to the initial velocity. This is because when the velocity has many reflectors, the reconstructed plane-wave source can be very complex and velocity errors could easily lead the misfit function to fall into a local minimum. To avoid this we only use the early arrivals to invert the background velocity.

Figures 1a and 1b show the reconstructed plane-wave sources for slow (10% lower than true velocity) and fast velocities (10% higher than true velocity), respectively. The true velocity is a 1D linear velocity function defined as $v = 1500 + 12.5z$. It shows that the reconstructed source will be earlier than the true source (black line) for slow velocity and later for fast velocity, hence can convey to us information on the sign of the velocity error. By minimizing the misfit function defined in equation 1, we find an optimal background velocity that best focuses the reconstructed plane-wave sources around excitation time t_0 .

FTI-based and Born-based Gradients

FTI theory adds one constraint to the misfit function, that is,

$$d_{pre}(t, v + \Delta v) = d_{pre}(t + \Delta \tau, v). \quad (3)$$

This constraint means velocity perturbation Δv only causes a time shift $\Delta \tau$ of the waveform of predicted data d_{pre} . The gradient of equation 1 is thus calculated as follows,

$$\frac{\partial E}{\partial v} = \frac{\partial E}{\partial d} \frac{\partial d}{\partial t} \frac{\partial \Delta \tau}{\partial v}, \quad (4)$$

where, $\partial \Delta \tau / \partial v$ is derived according to the way in Luo and Schuster (1991). Finally, the FTI-based gradient with respect to velocity $v(y')$ at any location y' for one plane-wave source is written as,

$$\frac{\partial E}{\partial v(y')} = \frac{1}{v_0(x')^3} \iiint r(x', x, t) * \delta r(x, t) dx' dx dt, \quad (5)$$

in which,

$$\delta r(x, t) = d(x, t) \int d(x, \tau)^2 w(x, \tau) \frac{\partial w(x, \tau)}{\partial \tau} d\tau,$$

and,

$$r(x', x, t) = r_1(x', x, t) + r_2(x', x, t),$$

$$r_1(x', x, t) = \frac{\Delta v(x')}{v_0(x')^3} u_r(x', t; x_r) * \dot{G}(y', -t; x') G(y', t; x_s),$$

$$r_2(x', x, t) = \frac{\Delta v(x')}{v_0(x')^3} u_r(y', t; x_r) \dot{G}(x', t; x_s) * G(y', t; x').$$

Here, G is the Green's function of one-way wave equation, $\dot{G} = \partial G / \partial t$, x_r and x_s are the receiver and source locations, respectively, u_r is the receiver-side wavefield, and $\delta r(x, t)$ is the adjoint source which is forward projected along the wavepath defined by $r(x', x, t)$.

Figure 1. Reconstructed plane-wave sources for slow (a) and fast (b) velocities. Black line is the true plane-wave source location.

For comparison, we also derive the Born-based gradient of equation 1, which is similar to equation 5. The only difference is that the adjoint source for the Born-based gradient is $w(x, t - px)^2 d(x, t)$.

To compare the FTI-based and Born-based gradients, we computed them using a 2 by 6 km model which only contains a single flat layer. Forty-five plane-wave shots with a range of surface incident angles $[-30^\circ, 30^\circ]$ are used to compute gradients corresponding to slow and fast velocities shown in Figure 2. Figures 2a and 2b clearly show that the FTI-based gradients have opposite signs, corresponding to the slow and fast velocities, respectively. In contrast, Figures 2c and 2d show the Born-based gradients fail to show whether the background velocity is slower or faster than the true one, and both return the same sign. Therefore, the conventional Born-based algorithm suffers an intrinsic problem in obtaining the correct gradient of the proposed misfit function. In contrast, the FTI-based equation can overcome this sign problem.

In addition to the gradient sign problem, source-domain FTI does not require first arrival picking which could be very time-consuming for ray-based tomography when applied to large field datasets. Moreover, since we aim to focus reconstructed plane-wave sources in the source domain, there is no need to estimate the source wavelet. It is worth mentioning that the one-way Green's function is used here to implement wave propagation. The combination of one-way Green's function and plane-wave data is capable of greatly reducing the computational cost, since the number of plane wave required for our method is much smaller than the number of shots and unlike the two-way Green's function, the plane-wave sources with a one-way Green's function do not need trace padding in the time direction.

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Figure 2. Comparison of the FTI gradient and Born gradient for slow (10% lower than true velocity) and fast (10% higher than true velocity) velocities using a single-flat-layer model. FTI gradient (a) and Born gradient (c) with slow velocity. FTI gradient (b) and Born gradient (d) with fast velocity.

Early-arrival waveform inversion

To further enhance the quality of the near-surface velocity model, we apply early-arrival waveform inversion using the output velocity of source-domain FTI. In order to relax the amplitude sensitivity and improve the efficiency, we use a normalized cross-correlation misfit function with plane-wave data as input. The objective function is written as

$$E = \sum_{p=1}^{n_p} \sum_{x_g=1}^{n_g} \frac{\sum_t d_{obs}(t, x_g, p) d_{pre}(t, x_g, p)}{\|d_{obs}(t, x_g, p)\|_2 \|d_{pre}(t, x_g, p)\|_2}, \quad (3)$$

where, $d_{obs}(t, x_g, p)$ and $d_{pre}(t, x_g, p)$ are the observed and predicted plane-wave data with ray parameter p at the location of receiver x_g , respectively. n_p and n_g are the number of plane-wave data and receivers, respectively.

Numerical Examples

The workflow described above has been applied to the data from a modified BP model (shown in Figure 3a) whose size is 2.4 by 9 km. We use a Ricker wavelet with a peak frequency of 12 Hz to generate 300 shots via 2D finite difference modeling. There are 600 receivers for each shot with spacing of 15 m covering the entire model at the surface. The maximum recording time is 5.0 s, and the time sampling interval is 1 ms. We convert the original 300 shot records to 50 plane-wave source records, covering the surface incident angle ranges $[-80^\circ, -25^\circ]$ and $[25^\circ, 80^\circ]$ with constant p spacing. The initial model is a 1D linear velocity from 1500 m/s to 3750 m/s defined as $v = 1500 + 9.4z$. Figure 3b is the inverted velocity obtained by source-domain FTI. To check the quality of this result, we overlap the true plane-wave source (black-dashed line) for surface incident angle 43° with the initial and inverted reconstructed

plane-wave sources, which are shown in Figures 3c and 3d, respectively. Clearly, the inverted reconstructed plane-wave source is best focused at the true source location. Then, early-arrival waveform inversion is applied using the velocity model from the source-domain FTI. The result is displayed in Figure 3e, which shows the final inverted result is very close to the true one. Finally, time-domain finite-difference forward modeling is implemented using the final inverted model. The predicted data is shown in Figure 3f together with the observed data. It manifests that the predicted data matches the observed data very well.

Figure 3. Results of the workflow using a modified BP model including, (a) the true velocity model, (b) the inverted velocity via source-domain FTI, (c) the initial reconstructed plane-wave source, (d) inverted reconstructed plane-wave source (black-dashed line indicates true plane-wave source), (e) the inverted velocity obtained by early-arrival waveform inversion and (f) a comparison between observed data and predicted data using the final inverted velocity.

Our workflow is also applied to a 2D onshore field data set acquired in Saudi Arabia. The data consists of 801 shots with 6.0 s recording length and 22.8 km maximum offset. The early arrivals of one typical shot are shown in Figure 4a. Shingled first arrivals are clearly seen, which makes both first-arrival auto and manual picking very challenging. Such phenomena arise due to the existence of subsurface low-velocity zones. Starting with a 1D linear velocity defined as $v = 1500 + 9.4z$, we obtain the inverted velocity shown in Figure 4b via source-domain FTI. Figure 4c displays the true plane-wave source for surface incident angle 25° (black-dashed line) together with the corresponding initial and inverted reconstructed plane-wave sources. Results show

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that the inverted source matches the true source well. Finally, early-arrival waveform inversion is applied using the source-domain FTI velocity as input. The result (Figure 4d) clearly indicates the presence of low velocity zones (black arrows).

Figure 4. Field data example showing (a) early arrivals of one typical shot, (b) velocity model estimated by source-domain FTI, (c) initial and inverted reconstructed plane-wave sources (black-dashed line indicates true plane-wave source), and (d) velocity model estimated by early-arrival waveform inversion.

To check the quality of our results, we compare the observed data with the corresponding predicted data shown in Figures 5a and 5b, respectively. The red arrows point to the main events of the observed and predicted early arrivals, and these events are quite consistent with each other. Then migrated images and angle-domain common image gathers (ADCIGs) from selected image points are computed using the initial model, source-domain FTI result and early-arrival waveform inversion result, which are shown in Figures 5c-5h. Figures 5c-5f clearly show that the image is much improved and the ADCIGs are better flattened after applying source-domain FTI. Figures 5e-5h indicate early-arrival waveform inversion further improves the image and flattens ADCIGs, as marked by the red arrows. Some other unflattened events (blue arrows) is probably caused by the multiples. Thus, source-domain FTI can produce good initial velocities for early-arrival waveform inversion and the workflow can be used to estimate a high-resolution near-surface velocity.

Conclusions

We propose a near-surface velocity estimation workflow of source-domain FTI followed by early-arrival waveform

inversion. Source-domain FTI is capable of obtaining a source-domain kinematically accurate velocity. This method contains three advantages. First, it does not require picking the first arrival of the seismic data as input for the inversion. Second, it does not need an estimation of the source wavelet. Third, it can provide the correct gradient sign for the case of slow or fast initial velocities. Numerical tests demonstrate that source-domain FTI is able to provide a good initial model for early-arrival waveform inversion and the workflow we propose can be an effective tool for near-surface velocity estimation.

Figure 5. Field data results showing (a) early arrivals of observed data, (b) the final predicted data, (c) migrated image and (d) corresponding ADCIGs using the initial velocity, (e) migrated image and (f) the corresponding ADCIGs using the velocity generated by source-domain FTI, (g) migrated image and (h) the corresponding ADCIGs using the velocity generated by early-arrival waveform inversion.

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EDITED REFERENCES

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REFERENCES

- Keho, T. H., and W. Zhu, 2009, Revisiting automatic first arrival picking for large 3D land surveys: 79th Annual International Meeting, SEG, Expanded Abstracts, 3198–3202, <http://doi.org/10.1190/1.3255521>.
- Luo, Y., and G. T. Schuster, 1991, Wave-equation travelttime inversion: *Geophysics*, **56**, 645–653, <http://doi.org/10.1190/1.1443081>.
- Luo, Y., Y. Ma, Y. Wu, H. Liu, and L. Cao, 2016, Full-traveltime inversion: *Geophysics*, **81**, no. 5, R261–R274, <http://doi.org/10.1190/geo2015-0353.1>.
- Plessix, R. E., G. Baeten, J. W. de Maag, M. Klaassen, Z. Rujie, and T. Zhifei, 2010, Application of acoustic full waveform inversion to a low-frequency large-offset land data set: 80th Annual International Meeting, SEG, Expanded Abstracts, 930–934, <http://doi.org/10.1190/1.3513930>.
- Routh, P. S., J. R. Krebs, S. Lazaratos, A. I. Baumstein, I. Chikichev, S. Lee, N. Downey, D. Hinkley, and J. E. Anderson, 2011, Full-wavefield inversion of marine streamer data with the encoded simultaneous source method: 73rd Conference and Exhibition, EAGE, Extended Abstracts, F032, <http://doi.org/10.3997/2214-4609.20149730>.
- Shen, X., 2014, Early arrival waveform inversion for near surface velocity estimation: Ph.D. thesis, Stanford University.
- Sheng, J., A. Leeds, M. Buddensiek, and G. T. Schuster, 2006, Early arrival waveform tomography on near-surface refraction data: *Geophysics*, **71**, no. 4, U47–U57, <http://doi.org/10.1190/1.2210969>.
- Tarantola, A., 1984, Inversion of seismic reflection data in the acoustic approximation: *Geophysics*, **49**, 1259–1266, <http://doi.org/10.1190/1.1441754>.
- Zhang, J., and M. N. Toksöz, 1998, Nonlinear refraction travelttime tomography: *Geophysics*, **63**, 1726–1737, <http://doi.org/10.1190/1.1444468>.
- Zhang, Y., and D. Wang, 2009, Travelttime information-based wave-equation inversion: *Geophysics*, **74**, no. 6, WCC27–WCC36, <http://doi.org/10.1190/1.3243073>.