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Application of weighted early-arrival waveform inversion to shallow land data

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ABSTRACT

Seismic imaging of deep land targets is usually difficult since the near-surface velocities are not accurately estimated. Recent studies have shown that inverting traces weighted by the energy of the early-arrivals can improve the accuracy of estimating shallow velocities. In this work, it is explained by showing that the associated misfit gradient function tends to be sensitive to the kinetics of wave propagation and insensitive to the dynamics. A synthetic example verifies the theoretical predictions and shows that the effects of noise and unpredicted amplitude variations in the inversion are reduced using this weighted early arrival waveform inversion (WEWI). We also apply this method to a 2D land data set for estimating the near-surface velocity distribution. The reverse time migration images suggest that, compared to the tomogram inverted directly from the early arrival waveforms, the WEWI tomogram provides a more convincing velocity model and more focused reflections in the deeper part of the image.

1. Introduction

The near-surface velocity distribution is crucial for imaging the deeper parts of the Earth. Complex velocity variations at the near surface are often associated with undulating topography or irregular geology in the near-surface weathered layers (Amorium et al., 1987; Taner et al., 1998). If the near-surface velocity distribution is not accurately estimated, the coherency of the deeper migrated reflections can be strongly degraded (Marsden, 1993; White, 1989). To partly remedy this problem, the near surface velocity model with smooth variations can be estimated by traveltime tomography (Aki and Richards, 2002; Pratt and Goulty, 1991; Zhu and McMechan, 1989) that inverts the first-arrival traveltimes. However, in geologically complex areas, a more highly resolved velocity model is needed for imaging deeper reflectors. In this regard, waveform inversion (Mora, 1987; Tarantola, 1984; Zhou et al., 1995) was developed to invert for more accurate tomograms by finite-frequency seismic wave propagation.

To reduce the computational time and local minima problems (Sirgue and Pratt, 2004), early-arrival waveform inversion (EWI) was proposed by Sheng et al. (2006) in the space–time domain and later applied to marine data (Boonyasiriwat et al., 2010). In this work, we carry out the inversion on land data by following the conventional EWI method but using a recently developed objective misfit function (Shen, 2010), which is more robust and focuses more on matching the phase rather than the amplitude in the data. However, the associated gradient does not have an important energy normalization term which is crucial for optimal imaging. In this work, the gradient associated with this weighted early arrival waveform inversion (WEWI) is properly normalized and shown to significantly improve the accuracy of the final tomogram compared to EWI. Instead of substituting the amplitude spectrum of an observed trace for that of the corresponding predicted trace (Sun and Schuster, 1993), we implement WEWI in the time domain by normalizing both the observed and calculated early arrivals using the L^2 norm of the trace, where this approach avoids the phase wrapping problem in the frequency domain (Shin and Min, 2006). Our synthetic results demonstrate that compared to EWI, WEWI can mitigate the effects of noise and unpredicted amplitude variations in the data and robustly invert for highly resolved near-surface tomogram. Moreover, a land data test illustrates that WEWI produces a more accurate shallow subsurface tomogram where the energy is more focused in the deeper part.

This paper is organized into four sections. The first part is the introduction, and the second part analyzes the misfit function associated with its gradient in our approach. In Section 3, numerical results are shown for inverting data associated with both the Marmousi model and a field experiment in Saudi Arabia. The last section presents the conclusions.

2. Theory

In many field, particularly land data sets, there are strong elastic arrivals such as surface waves that cannot be modeled by the acoustic wave equation. In addition, the amplitudes of some traces are distorted due to unexplained environmental sources that are not explained by geometric spreading. Some elastic effects in the data can be reduced by applying an early arrival window to mute the later arrivals.

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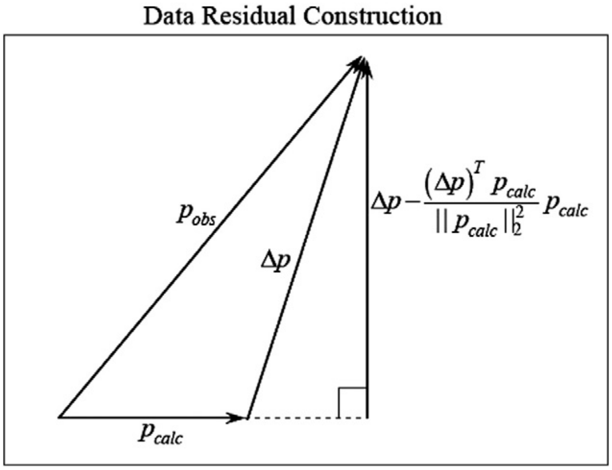

Fig. 1. Construction of data residuals as back propagating sources for EWI and WEWI.

Therefore, the conventional waveform inversion misfit functional E is modified by Shen (2010) and expressed as

$$E=\frac{1}{2}\sum_{s,r}||\Delta p(\mathbf{x}_r,t|\mathbf{x}_s)||_2^2=\frac{1}{2}\sum_{s,r}\left|\left|\frac{p_{calc}(\mathbf{x}_r,t|\mathbf{x}_s)}{||p_{calc}(\mathbf{x}_r,t|\mathbf{x}_s)||_2}-\frac{p_{obs}(\mathbf{x}_r,t|\mathbf{x}_s)}{||p_{obs}(\mathbf{x}_r,t|\mathbf{x}_s)||_2}\right|\right|_2^2, \tag{1}$$

where $p(\mathbf{x}_r, t|\mathbf{x}_s)$ denotes the pressure field trace recorded at the receiver position $\mathbf{x}_r$, with listening time t and a source at $\mathbf{x}_s$; $||p||_2$ denotes the L^2 norm of the N by 1 vector p, namely $\sqrt{p^T p}$, where N is the number of time samples in the trace. Here, p_{obs} represents the recorded trace with windowed early arrivals and p_{calc} represents the synthetic early arrivals. The synthetic data are calculated by solving the constant-density acoustic wave equation,

$$\frac{1}{c^2(\mathbf{x})}\frac{\partial^2 p(\mathbf{x},t|\mathbf{x}_s)}{\partial t^2}-\nabla^2 p(\mathbf{x},t|\mathbf{x}_s)=s(\mathbf{x},t|\mathbf{x}_s), \tag{2}$$

where $c(\mathbf{x})$ represents the velocity model at position $\mathbf{x}$, and $s(\mathbf{x}, t|\mathbf{x}_s)$ is the source term. The solution to Eq. (2) is calculated by a second order in time and eighth order in the space staggered-grid method (Levander, 1988).

Eq. (1) normalizes the observed and the synthetic early arrivals so that their energy can be compared at the same scale, and the waveform inversion in this case is more sensitive to phase differences in the misfit function. To unveil this fact, the Fréchet derivative [$grad(\mathbf{x}) = \partial E/\partial c(\mathbf{x})$] of the functional E with respect to $c(\mathbf{x})$ is calculated by

$$\begin{aligned}grad(\mathbf{x})&=\Delta p^T\frac{\partial(p_{calc}/||p_{calc}||_2)}{\partial c}\\&=\frac{1}{||p_{calc}||_2}\left(\Delta p-\frac{\Delta p^T p_{calc}}{||p_{calc}||_2^2}p_{calc}\right)^T\frac{\partial p_{calc}}{\partial c}.\end{aligned} \tag{3}$$

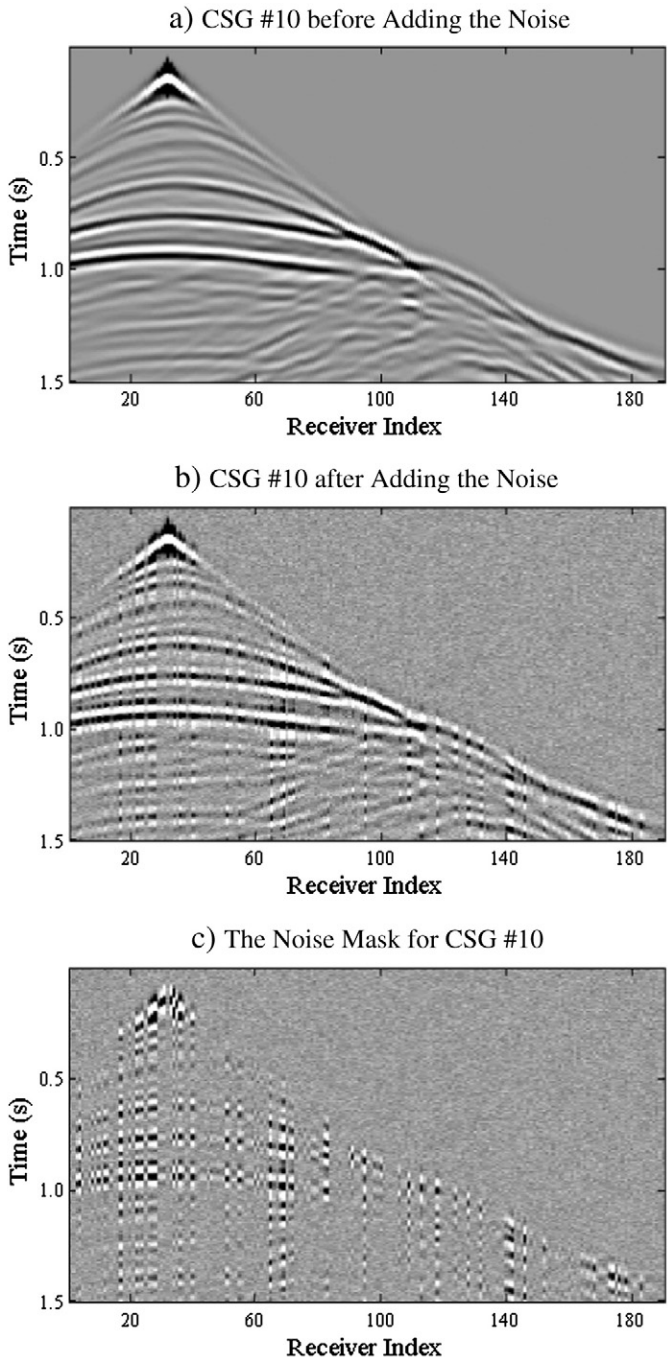

Fig. 3. The CSG #10 generated by the Marmousi model (a) before, (b) after adding the noise, and (c) its noise mask.

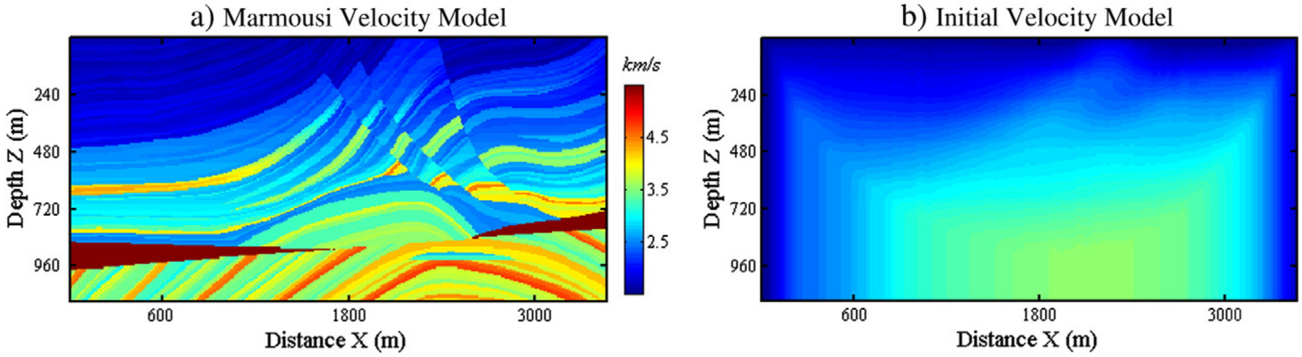

Fig. 2. The Marmousi models with (a) the true velocity distribution and (b) the traveltime velocity model as the initial velocity model for waveform inversion.