

Imaging complex near-surface land area with joint traveltime and waveform inversion

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Summary

We image the near-surface seismic velocity structures in complex land area with rugged topography by applying a joint seismic traveltime and waveform inversion method. This method retains the advantages of both traveltime inversion and full waveform inversion (FWI) and overcomes their drawbacks at the same time. The joint method is independent on starting models, has no cycle skipping issues, and converges fast. We apply the method to study complex near-surface land area where shallow overthrust and rugged topography present a significant challenge for using any method alone. We test synthetic data and understand the performance of the joint method, and then apply the method to a 2-D line in Yumen oil field in China. The results and analysis suggest that the joint traveltime and waveform inversion helps to constrain the very shallow velocities and also resolve complex overthrust with large velocity contrasts.

Introduction

The first-arrival traveltime tomography is a robust and standard method for delineating the near-surface structures. However, traveltime inversion assumes a high frequency approximation of the data which results in a suboptimal estimate of subsurface velocity model. In addition, the model resolution of traveltime inversion is less than waveform inversion. (Aki and Richards, 2002; Gauthier et al., 1986). Full waveform inversion can yield highly resolved velocity models because no high frequency assumption is required, and it can also give accurate results in geologically complex areas (Tarantola, 1984; Pratt et al., 1998; Sheng et al., 2006).

For near-surface imaging, it sometimes requires to handle large topography variations in the full waveform inversion. The forward modeling using finite difference approach may produce inaccurate results in this situation. Zhang and Zhang (2011) proposed a variable grid mesh system for acoustic finite-difference modeling to solve this problem. In this study, we adopt this grid mesh system to FWI and the joint inversion method.

PetroChina carried out a multichannel large-offset 2-D seismic survey in northwest China, Yumen Oil Field in September, 2004 (Yilmaz et al., 2005). They analyzed the Yumen large-offset data and derived an image in depth. We apply our joint inversion method to obtain an accurate near-surface velocity model and compare it with conventional FWI results.

Full waveform inversion problem is a nonunique problem. It means that there could be many global minimum and all of them fit data well (Figure 1). The joint traveltime and waveform method minimizes misfit function for both traveltimes and waveform in the inversion process. In this way, the joint inversion method can fit both data with different physical imaging theories (Zhang and Chen, 2014).

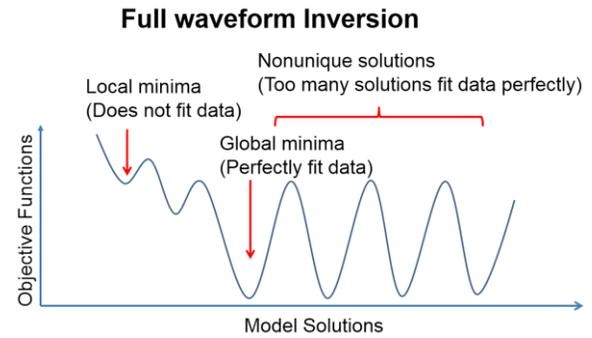


Figure 1: Schematic plot explaining nonunique problem of full waveform inversion.

Joint traveltime and waveform inversion

The objective function of joint traveltime and waveform inversion:

$$\phi(\mathbf{m}) = (1 - \omega) \|\mathbf{P}_o - \mathbf{P}_s(\mathbf{m})\|^2 + \omega \|t_o - t_s(\mathbf{m})\|^2 + \tau \|\mathbf{L}(\mathbf{m} - \mathbf{m}_0)\|^2$$

where \mathbf{P}_o is observed data, \mathbf{P}_s is calculated waveform, t_o is picked traveltime, t_s is synthetic traveltime, \mathbf{m} is the velocity model, \mathbf{m}_0 is a priori model. \mathbf{L} is a Laplacian operator for regularization, ω is a scaling factor between waveform residual and traveltime residual (Zhang and Chen, 2014).

For FWI component, we adopt a variable grid mesh system for time domain acoustic finite-difference modeling to handle large topography variations in FWI. Topography shall be sufficiently sampled with refined boundary conditions in such a system. At the same time, the high velocity area in the deeper part is not oversampled, ensuring efficient computation (Zhang and Zhang 2011).

With the combining traveltime data in the joint inversion, the inverse matrix of traveltime sensitivity could be treated as an effective preconditioner to waveform inversion. Thus, the joint inversion could find solutions quicker than

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performing FWI alone. We can easily access the raypath sensitivity matrix by applying raytracing in traveltimes tomography. In this study, the traveltimes and raypath calculations are based on the algorithm of Zhang and Toksöz (1998).

Conjugate gradient algorithm is applied to solve the joint inversion problem. During the inversion process, selection of a weighting factor ω between waveform misfit and traveltimes misfit is an important issue. If ω is too high, the joint inversion will yield a smoothed and low resolution model close to traveltimes tomogram. If ω is too small, the joint inversion cannot constrain the near-surface velocity well.

Synthetic test

We design a synthetic test which shows that the joint inversion provides an accurate estimate of the near-surface velocity distribution. The result is better than the one estimated from the waveform inversion alone.

In the synthetic example, we carry out the waveform inversion using several frequency bands, starting from a low frequency and gradually moving to a high frequency. The velocity model inverted from the previous frequency range is used as the starting model of the next inversion process. Here, we start from 3 Hz, and gradually increase to 10 Hz. Thus, we are able to retrieve finer velocity structure. The true model is shown in Figure 2a, which is designed according to a geological model of Yumen Oil Field. It includes faults, high-velocity contrasts, and rugged topography. To test the resolving power and reliability of the survey geometry, we choose the same shot and receiver intervals in the synthetic test as in Yumen seismic survey. Figure 2b presents a smoothed model, which is used as an initial model for FWI and the joint inversion. Figure 2c shows the result of waveform inversion after 60 iterations. Figure 2d shows the joint inversion result, it just needs 20 iterations to obtain the final result.

Both FWI and the joint inversion could recover the fault zone successfully. However, in the FWI result, the velocity of the top layer seems too high (marked by the white box). The joint traveltimes and waveform inversion ensures the near-surface velocities to fit the first-arrival traveltimes. At the same time, the joint inversion is more accurate at the right side, where the model presents higher velocity contrast.

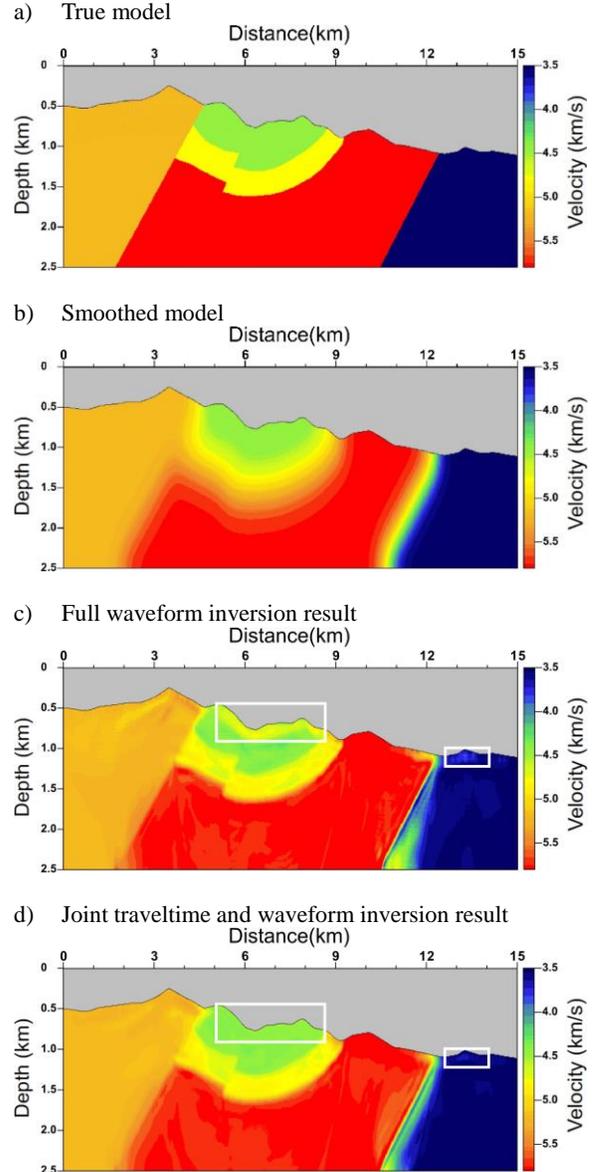


Figure 2: a) True model; b) Initial model for both FWI and the joint inversion (The initial model is a smoothed version of the true model.); c) FWI result; d) Joint traveltimes and waveform inversion result.

Yumen real data example

A 2-D seismic survey was conducted at Yumen Oil Field. This area has significant lateral velocity variations and irregular topography associated with a rugged terrain.

Joint traveltim and waveform inversion

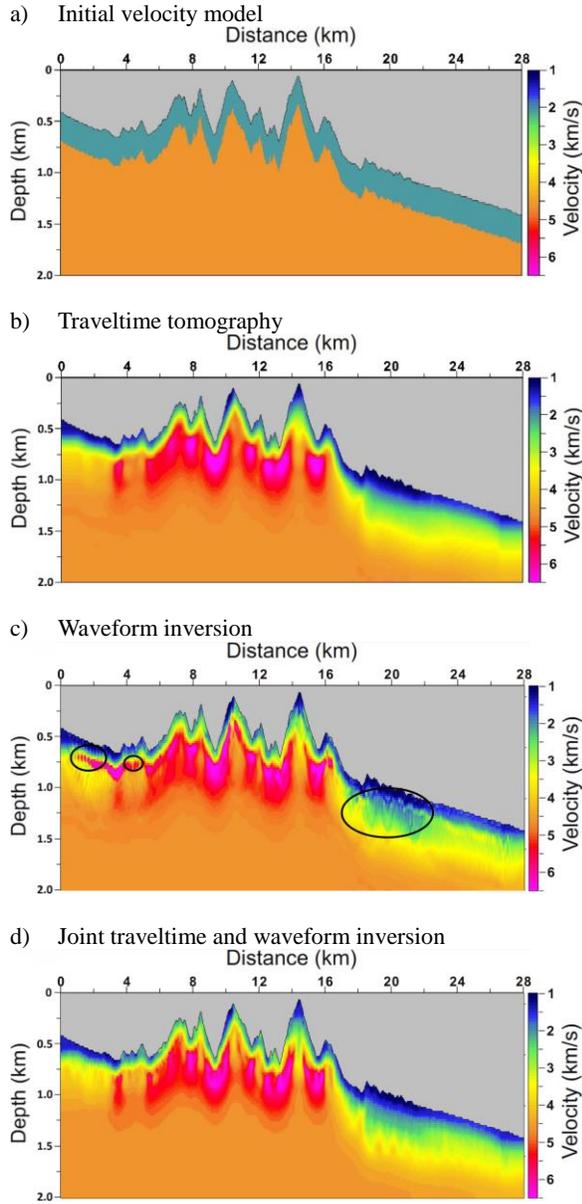


Figure 3: a) Initial velocity model; b) Traveltim tomography result; c) The waveform inversion result; d) The joint inversion solution.

PetroChina conducted the seismic survey to retrieve the complex, imbricate structure associated with the Yumen oil reservoir beneath the high velocity Kulong Shan allochthonous rocks in order to position production wells accurately. The Yumen large-offset survey line is in the SSW-NNE dominant structural dip direction. The northern part of the line is in Gobi Tan (Desert) and the southern

half is over the Kulong Shan (mountains) (Yilmaz et al., 2005). It is a survey line with large topography variations: the altitude difference along the line is larger than 1000 m from south to north.

The geometry consists of 211 shots with a 200 m interval. We choose 137 shot gathers for both FWI and the joint inversion. A total of 1,401 receiver groups is placed along 28 Km line at a 20 m interval. We select 3 Km offset data to image the near-surface velocity structures in this study.

Figure 3a shows a two-layer initial model built by picking refraction turning points from the first arrival traveltims. Figure 3b presents the first-arrival traveltim tomography solution. The traveltim tomography solution is used as the starting model for the waveform inversion and the joint inversion. Figure 3c and 3d show the early-arrival waveform inversion and the joint inversion solutions, respectively. Both waveform inversion and the joint inversion present more velocity details than traveltim tomography alone. The joint inversion result is similar with the waveform inversion result, but fewer artifacts are generated in the near-surface zone in the joint inversion result (marked by black circle).

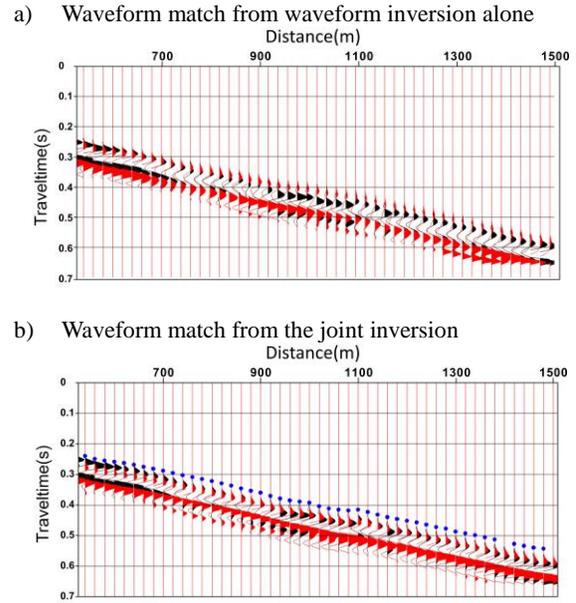


Figure 4: a) Synthetics (red) and observed data (black) after 50 iterations from waveform inversion; b) Synthetics (red) and input data (black) after 12 iterations from the joint inversion (Blue line represents the first arrival picks.).

Figure 4a shows the waveform overlay of a shot gather (black) with synthetic waveform (red) after 50 iterations of waveform inversion. The overall waveform fit is good

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except that some far-offset synthetic waveform does not match the observed data.

Figure 4b displays the waveform overlay of same shot after 12 iterations of the joint inversion. The waveform is matched better than waveform inversion due to the constraints of the traveltimes information.

Conclusions

Numerical experiment confirms that joint traveltimes and waveform inversion produces a reasonable solution for models with large topography variations. Then we apply the joint method to data collected from Yumen Oil field in China. The result shows that the joint inversion can match data better and does not produce shallow artifacts in the velocity model. Nonuniqueness is a fundamental issue in FWI, the joint inversion method cannot solve all of the problems, but in some cases, it helps improve the solution indeed.

Acknowledgment

We appreciate the support from GeoTomo, allowing us to use TomoPlus software package. We thank PetroChina for offering the data from Yumen oil field.