Acoustic Waveform Inversion vs. Elastic data.

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Summary

Full Waveform inversion is a computer intensive process, especially for 3D seismic data. After a tremendous number of synthetic examples, finally real 3D data sets have been undertaken by the industry. As field data is dominated with P waves, one feasible approach is to use the acoustic approximation. The difficulty we face is using an acoustic propagator can make it difficult to accurately predict the amplitudes of real elastic data. In this paper we show how it is possible to make acoustic inversion work on elastic data. The experiment is carried out by using acoustic time-domain inversion on marine synthetic data created by elastic modeling.

Introduction

The aim of waveform inversion is to derive a velocity model that produces the best fit to the seismic data. The geology of a marine environment consists of two different media. One is the water layer that propagates P-waves only. The other is the layered earth underneath that propagates both the P and S-waves. This is why the acquired seismic data behaves in an elastic manner.

Full-waveform inversion, based on the finite difference approach, was originally introduced in the time–space domain (e.g.Tarantola, 1984, Gauthier *et al.,* 1986, Crase *et al.,* 1990, 1992, Pica *et al.,* 1990, Sun & McMechan, 1992). Inversion can also be implemented in the frequency-domain (Pratt *et al.,* 1998, 1999, Ben-Hadj-ali et al., 2008).

The full-waveform inversion described in this paper is solved by an iterative local linearized approach using a gradient method (e.g. Tarantola, 1987). The inversion problem can be addressed in an elastic manner (Shipp and Singh, 2002, Freudenreich *et al.*., 2001) by utilizing the elastic wave equation. Levander (1988) carried this out in the time and space domain. Due to cost considerations, especially in 3D, the elastic solution is not widely used. Since 3D acoustic inversion has been implemented in the time-domain (Vigh and Starr, 2008) and the frequency-domain (Sirgue, 2008, Ben-Hadj-ali et al., 2008, Plessix, 2007), this gives us the opportunity to observe whether the result of the acoustic inversion is reasonable when using elastic seismic data. Elastic effects and anisotropy might limit the use of acoustic inversion when considering the far offsets (Mulder and Plessix, 2008). If early arrivals and reflections are used in the inversion process one should pay attention to the phase validity of the forward modeling (for example, including the phase effect of the source ghost) in order to get the closest match to the data collected, otherwise the phase difference may be translated to an incorrect velocity update.

Data and Inversion Scheme

In our work, a time–domain implementation is used to minimize the misfit function (Tarantola, 1987). If we denote $P(x_r,y_r,z_r,t)$ the pressure data recorded at locations $\mathbf{x}_r$, the velocity is determined by minimizing the misfit function

$$E = \frac{1}{2}\sum_s\sum_r\int dt[P_{cal}(\mathbf{x}_r,t) - P_{obs}(\mathbf{x}_r,t)]^2 , \quad (1)$$

where P_{obs} is the observed data and P_{cal} is the data calculated using the acoustic wave equation.

E is minimized iteratively by calculating the gradient (Tarantola, 1984). When field data is used, P_{obs} is elastic, resulting in a misfit function between acoustic predicted data and elastic acquired data sets.

For this experiment the SMAART Pluto 1.5 model (Stoughton *et al.*, 2001), created with elastic modeling, was used. The model parameters are the following: Vp, Vs, Density, 25 feet cable (receiver) depth and 25 feet shot depth. The grid spacing is 25 feet with depth sampling of 25 feet. The maximum spread length is 27000 feet. The velocity models were generated on a 25 feet x 25 foot grid at a maximum depth of 30000 feet. The model includes both free surface multiples and primary events (Figure 1).

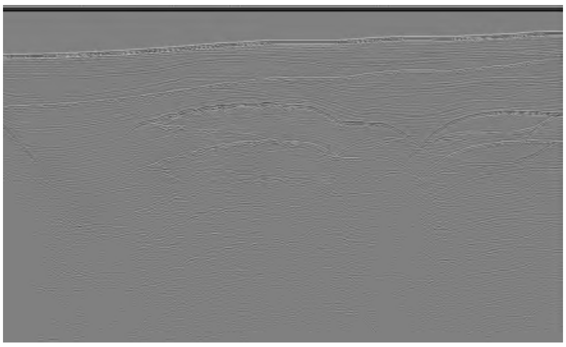


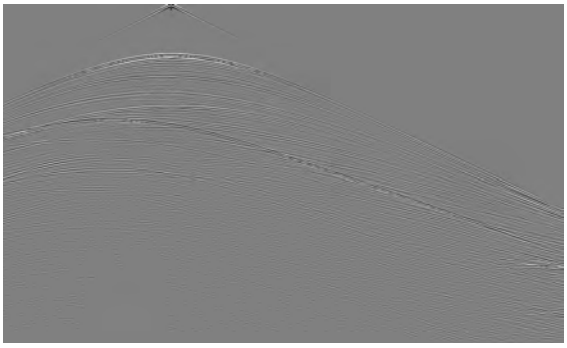
Figure 1. Original elastic common offset showing primary and multiple events.

Acoustic Inversion of Elastic Data

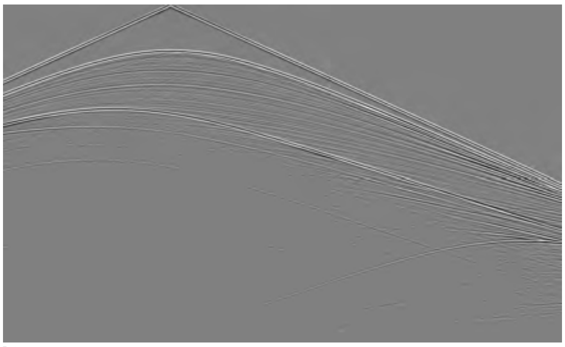
We analyze some of the issues using the above described Pluto 1.5 elastic model as the observed data and invert for the Vp field. The inversion is carried out in the time-domain using the acoustic wave equation:

$$\frac{1}{V^2}\frac{1}{\rho}\frac{\partial^2 P}{\partial t^2} = \left[\frac{\partial}{\partial x}\left(\frac{1}{\rho}\frac{\partial P}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{1}{\rho}\frac{\partial P}{\partial y}\right) + \frac{\partial}{\partial z}\left(\frac{1}{\rho}\frac{\partial P}{\partial z}\right)\right] + S\,, \quad (2)$$

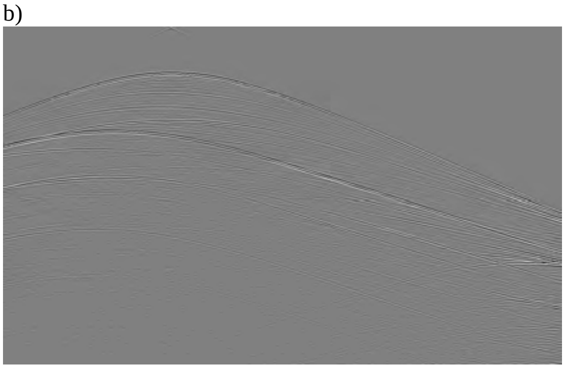
where P(x,y,z,t) is the pressure field, ρ(x,y,z) is the density, V(x,y,z) is the interval velocity and S(x,y,z,t) is the source. Different amplitude and phase characteristics can be observed with the source and receiver ghost by varying the depth of the source and/or receiver combined with using and/or simulating a free surface boundary condition (Figure 2). If the ghost is not taken into account, the phase and amplitude information is going to be different between the observed and calculated data which will lead to a false velocity update. To incorporate the ghosts in the modeling one may use the free surface boundary condition. This option also generates multiples during the modeling process. The other choice is to simulate the source and receiver ghosts only without the free surface multiples (Cunha, 1993). We elected to follow the former path and conduct the Full Waveform Inversion using the ghosts and free surface multiples.



a)



b)



c)

Figure 2. Source and receiver ghosting effects. (a) Original shot record elastic modeling. Source and receiver depth is 25 feet. (b) Acoustic modeling with no free surface boundary condition. Source and receiver are on the surface. (c) Acoustic modeling with free surface. Source and receiver depth is 25 feet.

The inversion proceeded in two scale steps with the inverted velocity output from one step used as input for the next step. The first, low-frequency step ranged from 0 to 13 Hz. The second and final-frequency step ranged from 0 to 18 Hz. Two acoustic inversions were produced. One was with acoustic modeled data without multiples (Figure 3). The other was with the original elastic data (Figure 4) which has some residual multiple in the velocity update. This is due to the fact we are using an acoustic inversion which does not properly model the higher order multiple amplitudes.

The first few acoustic inversion iterations with the elastic data contained the early arrivals and, after a few iterations, the inversion had trouble trying to converge due to the inability to properly model elastic effects at the far offsets. After the initial iterations, the early arrivals were muted to focus on inverting for the reflection data.

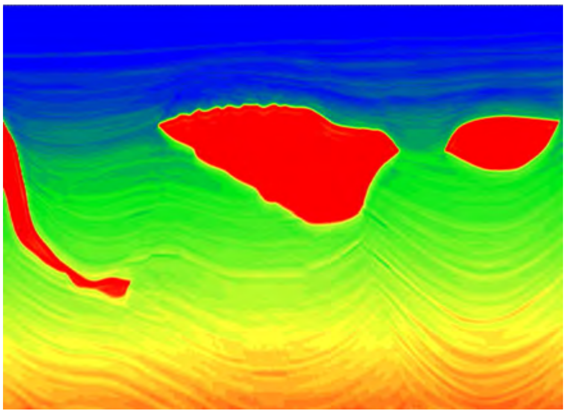


Figure 3. Acoustic inversion with acoustic modeled data without multiples. Multiples were not modeled by placing an absorbing boundary at the surface.

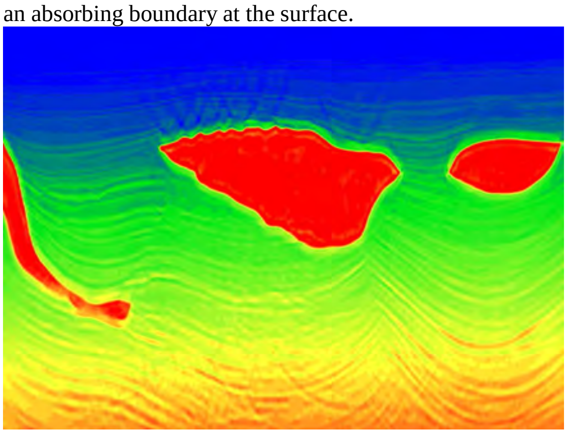


Figure 4. Acoustic inversion with the original elastic data with multiples.

Conclusion

The Full Waveform Inversion described above is acoustic and real data is more accurately described by an elastic model. It is common practice to apply acoustic inversion, especially for 3D data sets because the elastic modeling is prohibitively expensive. Although the long offsets may suffer from elastic effects our experiment shows that the velocity field obtained using acoustic inversion vs. elastic data are reasonable in spite of the difference between the modeling and mother earth.

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EDITED REFERENCES

Note: This reference list is a copy-edited version of the reference list submitted by the author. Reference lists for the 2009 SEG Technical Program Expanded Abstracts have been copy edited so that references provided with the online metadata for each paper will achieve a high degree of linking to cited sources that appear on the Web.

REFERENCES

Ben-Hadj-ali, H., S. Operto, and J. Vireux, 2008, Velocity model building by 3D frequency-domain, full-waveform inversion of wide-aperture seismic data: Geophysics, 73, no. 5, VE101–VE117.

Crase, E., A. Pica, M. Noble, J. McDonalds, and A. Tarantela, 1990, Robust elastic nonlinear waveform inversion: Application to real data: Geophysics, **55**, 527–538.

Crase, E., C. Wideman, M. Noble, and A. Tarantola, 1992, Nonlinear elastic inversion of land seismic reflection data: Journal of Geophysical Research, **97**, 4685–4705.

Cunha, C., 1993, Elastic modeling in discontinuous media: Geophysics, **58**, 1840–1851.

Freudenreich, Y., S. Singh, and P. Barton, 2001, Sub-basalt imaging using a full elastic wavefield inversion scheme: 63rd Conference and Exhibition, EAGE, Extended Abstracts, O-19.

Gauthier, O., J. Virieux, and A. Tarantola, 1986, Two-dimensional nonlinear inversion of seismic waveforms: Numerical results: Geophysics, **51**, 1387–1403.

Levander, A. R., 1988, Fourth-order finite-difference P-SV seismograms: Geophysics, 53, 1425–1436.

Mulder , 2008, W. A., and R. -E. Plessix, 2008, Exploring some issues in acoustic full waveform inversion: Geophysical Prospecting, 56, 827–841.

Pica, A., J. P. Diet, and A. Tarantola, 1990, Nonlinear inversion of seismic reflection data in laterally invariant medium: Geophysics, **55**, 284–292.

Plessix, R.-E., 2007, A Helmholtz iterative solver for 3D seismic-imaging problems: Geophysics, **72**, no. 5, SM185–SM194.

Pratt, R. G., C. Shin, and G. J. Hicks, 1998, Gauss-Newton and full Newton methods in frequency space seismic waveform inversion: Geophysical Journal International, **133**, 341–362.

Pratt, R. G., and R. M. Shipp, 1999, Seismic waveform inversion in the frequency domain, Part 2: Fault delineation in sediments using crosshole data: Geophysics, **64**, 902–914.

Shipp, R. M., and S. C. Singh, 2002, Two-dimension full wavefield inversion of wide-aperture marine seismic streamer data: Geophysical Journal International, **151**, 325–344.

Sirgue, L., J. T. Etgen, and U. Albertin, 2008, 3D frequency domain waveform inversion using time domain finite difference methods: 70th Conference and Exhibition, EAGE, Extended Abstracts, F022.

Stoughton, D., J. Stefani, and S. Michell, 2001, 2D elastic model for wavefield investigations of subsalt objectives, deep water Gulf of Mexico, 1269–1273.

Sun, R., and G. A. McMechan, 1992, 2D full-wavefield inversion for wide-aperture, elastic, seismic data: Geophysical Journal International, **111**, 1–10.

Tarantola, A., 1984, Inversion of seismic reflection data in the acoustic approximation: Geophysics, **49**, 1259–1266

Tarantola, A.,1987, Inverse problem theory: Methods for data fitting and model parameter estimation: Elsevier.

Vigh, D., and E. W. Starr, 2008, 3D prestack plane-wave, full-waveform inversion: Geophysics, **73**, no. 5, VE135–VE144