Elastic prestack reverse-time migration using a staggered-grid finite-difference method

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Summary

We present an elastic prestack reverse-time migration method using a staggered-grid finite-difference scheme, while conventionally reverse-time migration is carried out through the non-staggered grid schemes. The migration method is tested using a point diffractor model and a reduced set of the elastic Marmousi2 model.

Introduction

Finite-difference methods are practiced on numerical grid of nodal points both in space and time. Depending on the choice of the nodal points, the grid scheme can be classified in two broad categories: staggered and non-staggered. Seismologists use both schemes to simulate elastic wave phenomena.

The non-staggered grid scheme is widely employed in both modelling and migration of elastic waves. The early research began with modelling (Alterman and Karal, 1968; Alterman and Rotenberg, 1969; Alford, Kelly, and Boore, 1974; Kelly, Ward, Treitel, and Alford, 1976). This scheme has been widely used in elastic reverse time migration since 1980's (Sun and McMechan, 1986; Chang and McMechan, 1987; Chang and McMechan, 1988; Sun and McMechan, 1988).

The staggered-grid scheme is also popular in the field of modelling. It became well known in modelling wave phenomena from two papers of Virieux (1984; 1986). Since then, the method has been developed from second-order to fourth-order (Levander, 1988) and then higher order, and from 2D to 3D (Ohminato and Chouet, 1997). It was shown that staggered-grid scheme deals with liquid-solid interface without the need for special treatment, which is not the case for non-staggered grid scheme (Virieux, 1986; Levander, 1988; Stephen, 1988). Nevertheless, the staggered-grid scheme is rarely employed in reverse-time migration algorithms.

This paper proposes an elastic prestack reverse time migration using a staggered-grid finite-difference method, in which only particle velocity surface record is needed for the migration. In addition, based on interpreting the causes of imaging artifacts we give practical noise removal methods to improve the image obtained by normalized crosscorrelation imaging condition, which is one of the preferred imaging conditions (Chattopadhyay and McMechan, 2008).

Reverse-time migration

Reverse-time migration involves the processing of forward modelling, reverse-time extrapolation, applying an imaging condition, and image artifacts removal.

Forward modelling

The staggered-grid finite-difference method developed by Virieux (1986) is used to do the forward modelling.

An explosive source was used. Four zero-phase Ricker wavelets were introduced into a staggered-grid model, with displacement directed uniformly about a centre.

The up boundary of the subsurface models is a free surface, which means that the normal stresses must be zero at the surface.

To reduce the artificial reflections that are introduce by the edge of the computational grid, a method combining the absorbing boundary conditions A1 (Clayton and Engquist, 1977) and the nonreflecting boundary condition (Cerjan, Kosloff, Kosloff, and Reshef, 1985) is applied to the sides and bottom of the subsurface model.

To illustrate both modelling and reverse time migration, a subsurface model contains a scatter point in a homogenous medium in $x-z$ plane is designed (Figure 1). The vertical component surface record of this shot is shown on the left in Figure 2.

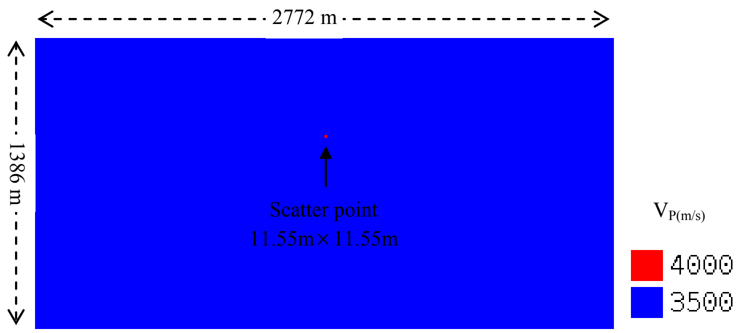

Figure 1: A scatter point in a homogenous medium. This shows the P-wave velocities.

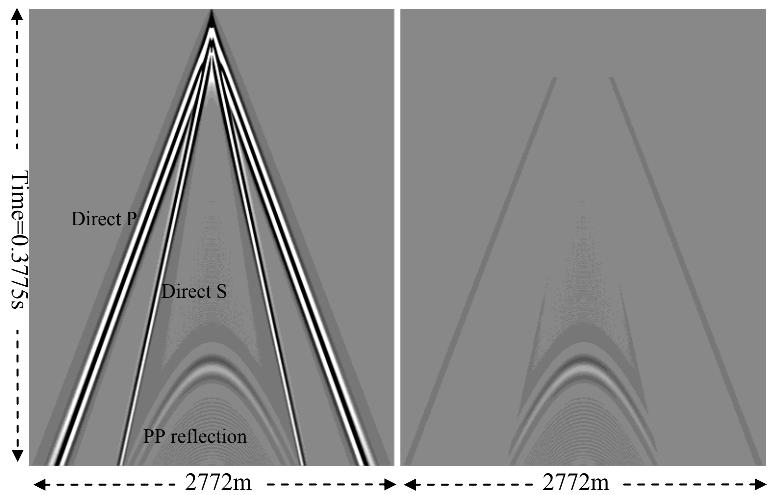

Figure 2: Vertical component of the surface record of centre shot and the record after muting.

Reverse-time extrapolation

Reverse-time extrapolation is mostly the same processing as forward modelling: the same finite-differencing formulas and boundary conditions are used to do reverse-time extrapolation. Nevertheless, during this processing the surface record acts as numerous virtual sources, and the process is reversed in time.

It is necessary to preprocess the surface record before it is used to do reverse-time extrapolation. The purpose of the extrapolation is to retrieve the upgoing (reflected) wave. Direct arrivals in the surface record have nothing to do with the reflected energy, so these should be removed from the surface record before the extrapolation by muting (on the right of Figure 2).

It is assumed that the medium is in equilibrium at the beginning of reverse-time extrapolation, i.e., initially stresses and particle velocities are set to zero everywhere in the medium.

Imaging condition

Normalized crosscorrelation imaging condition is one of the preferred methods for reverse-time migration (Chattopadhyay and McMechan, 2008). Source-normalized crosscorrelation imaging condition (Claerbout, 1971; Whitmore and Lines, 1986; Kaelin and Guitton, 2006; Chattopadhyay and McMechan, 2008) is applied.

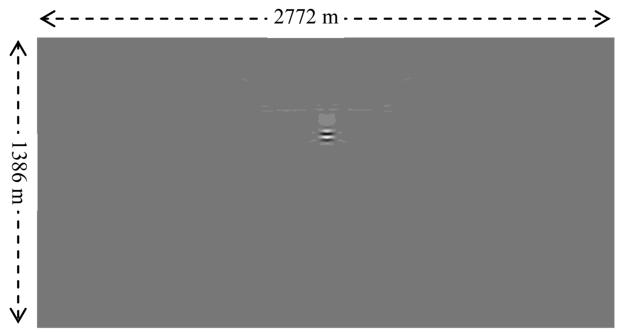

Figure 3: Imaging result by applying the source-normalized crosscorrelation imaging condition on the centre shot for the subsurface model is shown in Figure 1.

Image artifacts removal

The imaging condition provides accurate estimates of reflection coefficients; however, it also leads to some artifacts. In the stacked image, the noise appears as low frequencies, or local DC biases, thus, the signals of reflectivity appear 'riding' on the low frequency artifacts. The low frequency artifacts can be removed by applying a high pass filter. This is shown with a reduced set of elastic Marmousi2 model (Figure 4).

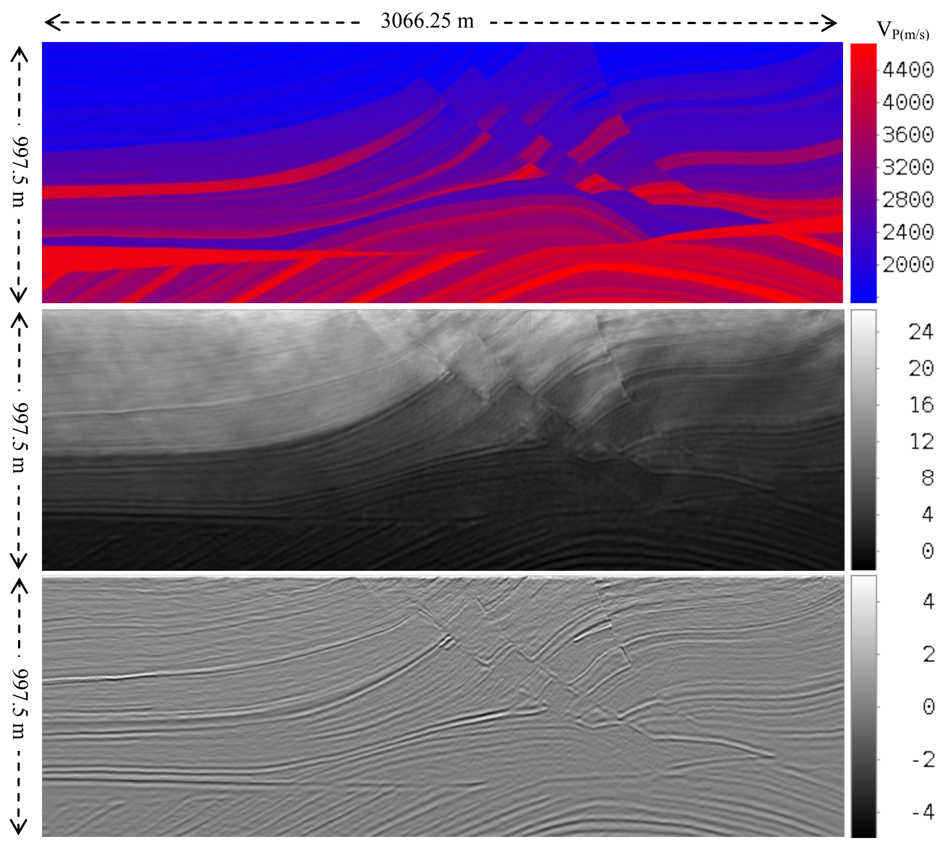

Figure 4: A reduced set of elastic Marmousi2 model (top), the stacked image from 64 shots (middle), and the image after applying a high pass FIR filter (bottom).

Conclusions

We have presented an elastic prestack reverse-time migration method using the staggered-grid scheme. Although the modeling and reverse-time extrapolation involve both particle velocity and pressure data, only the data related to particle velocities are needed to be recorded at the surface.

References

Alterman, Z.S., and Karal, F.C., 1968, Propagation of elastic waves in layered media by finite-difference methods: Bulletin of the Seismological Society of America, 58, 367-398.

Alterman, Z.S., and Rotenberg A., 1969, Seismic wave in a quarter plane, bulletin of the Seismological Society of America, 59, 347-368.

Alford, R.M., Kelly, K.R., and Boore D.M., 1974, Accuracy of finite-difference modeling of the acoustic wave equation, Geophysics, 39, 834-842.

Bancroft, J.C., 2006, A practical understanding of pre- and poststack migration, Society of Exploration Geophysisicsts Course notes publication.

Cerjan, C., Kosloff, D., Kosloff, R., and Reshef, M, 1985, A nonreflecting boundary condition for discrete acoustic and elastic wave equations, Geophysics, 50, 705-708.

Chang, W.F., and McMechan, G.A., 1986, Reverse-time migration of offset vertical seismic profiling data using the excitation-time imaging condition: Geophysics, 51, 67–84.

Chang,W.F., and McMechan, G.A., 1987, Elastic reverse-time migration, Geophysics, 52, 1365-1375.

Chattopadhyay, S., and McMechan, G.A., 2008, Imaging conditions for prestack reverse-timemigration: Geophysics, 73, no. 3, S81–S89.

Claerbout, J. F., 1971, Toward a unified theory of reflector mapping: Geophysics, 36, 467–481.

Clayton, R., and Engquist, B., 1977, Absorbing boundary conditions for acoustic and elastic wave equations, bulletin of the Seismological Society of America, 67, 1529-1540.

Clayton, R., and Engquist, B., 1980, Absorbing boundary conditions for wave-equations migration, Geophysics, 45, 895-904.

Engquist, B. and Majda, A., Absorbing boundary conditions for numerical simulation of waves, Proc. Natl. Acad. Sci. USA, 74, 1765-1766.

Kaelin B., and Guitton A., 2006, Imaging condition for reverse time migration, SEG/New Orleans 2006 annual meeting, 2594-2598.

Kelly, K.R., Ward, R.W., Treitel, S., and Alford, R.M., 1976, Synthetic seismograms: a finite-difference approach, Geophysics, 41, 2-27.

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

Ohminato T. and Chouet, B.A., 1997, A free-surface boundary condition for including 3D topography in the finite-difference method, Bulletin of the Seismological Society of America, 87, 494-515.

Stephen, R.A., 1988, A review of finite difference methods for seismo-acoustic problems at the sea floor: Reviews of Geophysics, 26, 445-458

Sun, R., and McMechan G.A., 1986, Pre-stack reverse-time migration for elastic waves with application to synthetic offset vertical seismic profiles, Proceedings of the IEEE, 74, 457-465.

Sun, R., and McMechan G.A., 1988, nonlinear reverse-time inversion of elastic offset vertical seismic profile data, Geophysics, 53, 1295-1302.

Virieux, J., 1984. SH wave propagation in heterogeneous media: velocity-stress finite-difference method, Geophysics, 49, 1933--1957.

Virieux, J., 1986. P-SV wave propagation in heterogeneous media: velocity-stress finite-difference method, Geophysics, 51, 889--901.

Whitmore, N.D., and Lines, L.R., 1986, Vertical seismic profiling depth migration of a salt dome flank: Geophysics, 51, 1087-1109.