Experiments on elastic wave modelling in isotropic and anisotropic media

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Summary

Recent advances in seismic data processing with multi-component land and ocean-bottom-node (OBN) data have shown some contributions from share waves, converted waves as well as anisotropy. To get better understanding of the elastic wave propagation in isotropic and anisotropic media, we compared the wavefields in acoustic and elastic media with and without anisotropy. The preliminary experiments on three synthetic models, i.e., wave/solid interface, free surface with topography, and near-surface low velocity layer, demonstrate the complicated wave propagations in elastic media.

Introduction

Recent advances in seismic data processing with multi-component land and ocean-bottom-node (OBN) data have shown some contributions from share waves, converted waves as well as anisotropy. Proper treatment on elastic waves can avoid misinterpretation of shear waves and converted waves as artifacts and provide complimentary information over acoustic waves. It is crucially important to understand and exploit elastic wave propagation in complex media. Finite-difference scheme has been considered as the most popular implementation to model the wave propagation in elastic media. Kelly et al. (1976) described a simple finite-difference approximation to the elastic wave equation to model P- and SV-waves in isotropic homogeneous media. Virieux (1986) proposed an approach that updates stress and particle velocity on a staggered grid that overcomes the accuracy and stability problems of the non-centered standard finite-difference approximation for P-SV wave equation. Kosloff et al. (1984) introduced a pseudo-spectral method to solve the isotropic elastic wave equation. Transformation of the spatial derivatives into wavenumber domain by Fourier transform provides more accurate simulation than finite-difference. However, the pseudo-spectral method requires much more memory and is more computationally expensive in 3D anisotropic elastic media.

Free surface with topography, shear wave triplications, and water/solid interface are among the major issues of elastic wave modeling in isotropic and anisotropic media. Levander (1988) proposed an image method for free surface calculation in the velocity-stress staggered-grid finite-difference method. An alternative method is called vacuum formulation proposed by Boore (1972). This method assumes P- and S-wave velocities to zero but keeps constant density above the free surface. The vacuum method is easy to implement with the same finite difference equation used for the interior model (Hayashi et al., 2001). Shear wave triplications are commonly observed in crust. In anisotropic media, elastic wave modeling shows the nature of shear wave triplication (Thomsen and Dellinger, 2003). In exploration seismology, shear wave triplications are usually treated as artifacts and need to be specially handled in pre-stack depth migration.

In this paper, several experiments on the elastic wave modeling in isotropic and anisotropic media demonstrate the effect of wave propagation with the water/solid interface for marine data, in the presence of topographic free surface and the low velocity layer near surface for land data. The different wave types will also be addressed and discussed.

Numerical examples

In the following examples, a higher-order staggered grid finite-difference scheme is implemented for the simulation of wave propagation.

Experiment I: Wave propagation with a single dipping interface between water and solid

Assume the first layer is water with velocity of 1500m/s and the second layer is a solid with P-wave velocity of 3000m/s and S-wave velocity of 1732 m/s. TTI parameters in the solid are assigned as ε=0.23, δ=0.12, and the dip angle is 20°. The source is located in the center at surface. To correctly simulate the wave propagation in liquid, shear module needs to set as zero if the finite-difference grid is located at liquid and solid boundary. Figure 1(a), (b) and (c) are the snapshots in isotropic, VTI and TTI acoustic media. Figure 1(d), (e) and (f) are the snapshots of the vertical particle velocity in isotropic, VTI and TTI elastic media. Figure 1(g), (h) and (i) are the snapshots for the horizontal particle velocity in isotropic, VTI and TTI elastic media. The snapshots of acoustic and elastic waves show identical P-wave wavefronts in water layer. As expected, S-waves are present in the elastic solid layer. In anisotropic TTI media, the wavefront is tilted by the TTI dip angle. We also notice that the S-wave is generally stronger on the horizontal component than that of the vertical component.

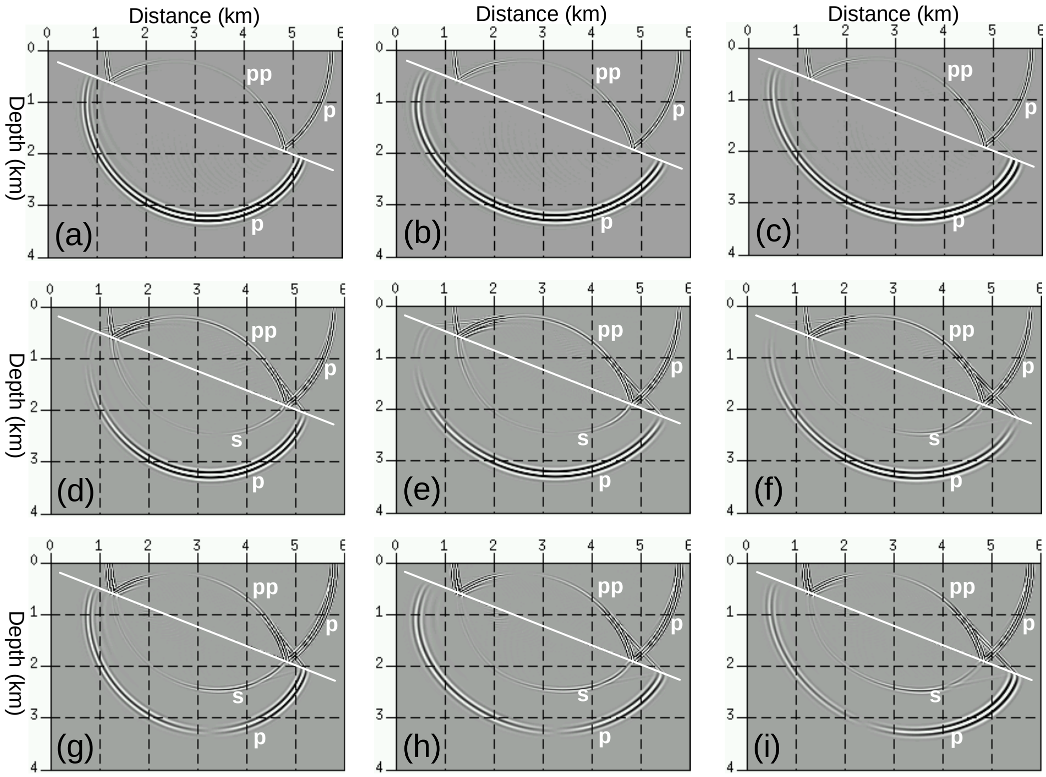


Figure 1: Comparisons of the snapshots with a single interface between water and solid layer. (a), (b) and (c) are snapshots in isotropic, VTI, and TTI acoustic media; (d), (e) and (f) are snapshots of the vertical component in isotropic, VTI and TTI elastic media; (g), (h) and (i) are snapshots of the horizontal component in isotropic, VTI and TTI elastic media.

Experiment II: Wave propagation with a topographic free surface

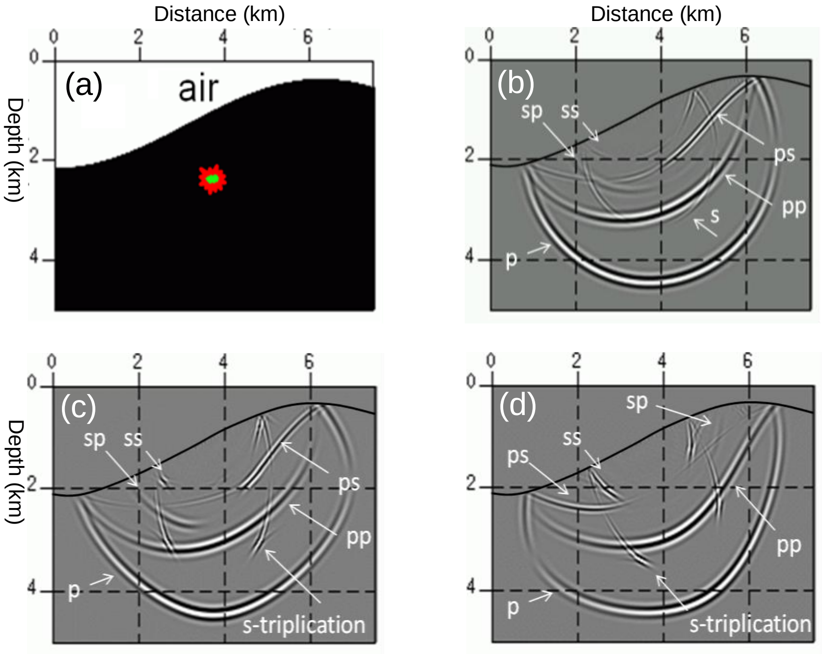
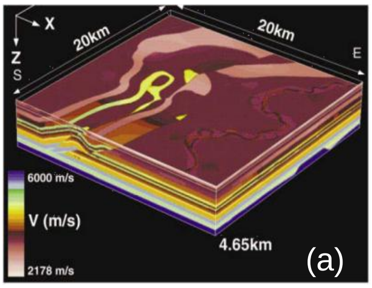


Figure 2: Comparisons of the snapshots with the presence of topographic free surface. (a) Topographic free surface model; (b), (c) and (d) are snapshots in isotropic, VTI and TTI elastic media. In this model, Vp=2000m/s,Vs=1000m/s, ε=0.2, δ=-0.1. TTI dip angle is 30° in (d).

Topographic free surface can make wave propagation more complicated especially for land data. To test the effect of free surface with topography, we generate a half surface model with constant anisotropic elastic parameters. In the model, P- and S-wave velocities are 2000m/s and 1000m/s, respectively. ε=0.2 and δ=-0.1. The TTI tilted dip angle is 30°. An explosive source is shown in Figure 2(a). A vacuum method is applied to address the variation of topography. In Figure 2(b), (c) and (d) are the snapshots of the vertical component in isotropic, VTI and TTI elastic media. The converted wave S to P and P to S are generated by free surface. In anisotropic elastic media, S-wave triplications exist after S-waves are reflected from the free surface.

Experiment III: Modified 3D SEG overthrust model with near-surface low velocity layer

To simulate the near-surface wave propagation, a 3D SEG overthrust model was modified by adding a low velocity layer with random density variation on top of the model as shown in Figure 3. The P-wave velocity in the layer is 1229m/s. S-wave velocity was set as half of the P-wave velocity. The near-surface low velocity layer disturbs the wave propagation and generates complicated wave modes such as Rayleigh wave. The (x,y) grid spacing is 25m by 25m. The depth interval is 12.5m. Ricker wavelet with dominant frequency of 12.5Hz was used in the numerical simulation. Figure 4(a), (b) and (c) are the snapshots of acoustic waves, vertical component of elastic waves, and horizontal component of elastic waves. The wave modes on the elastic horizontal component are very different from the elastic vertical component. Figure 4(d), (e) and (f) are the corresponding shot gathers of acoustic waves, vertical component of elastic waves and horizontal component of elastic waves. Due to a near-surface low velocity layer, Rayleigh wave has strong dispersions near surface as shown in Figure 4(e) and (f). The amplitude of Rayleigh wave decreases exponentially with the increasing propagation time.



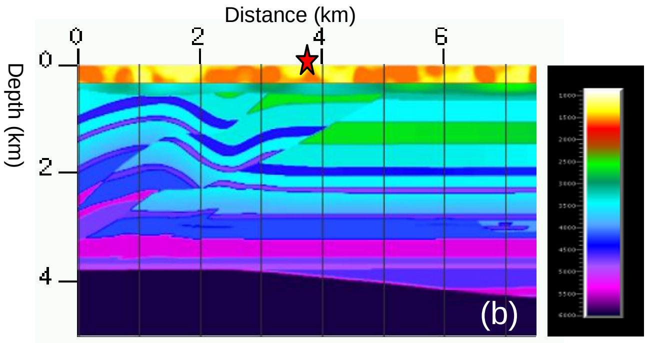


Figure 3: A modified 3D SEG overthrust model with a near-surface low velocity layer with random density variation. (a) Velocity model of the 3D SEG overthrust model; (b) A cross section with random density variation in the low velocity layer. (Courtesy of Christof Stork).

Conclusions

Wave propagation in elastic media generates more wave modes than that in acoustic media. The wavefronts of P- and S-waves in TTI media are tilted by the TTI dip angle. S-wave triplications are present on the modeling result in anisotropic elastic media. Free surface reflections make the wave propagation more complicated. Near-surface low velocity layer generates Rayleigh waves with strong dispersion.

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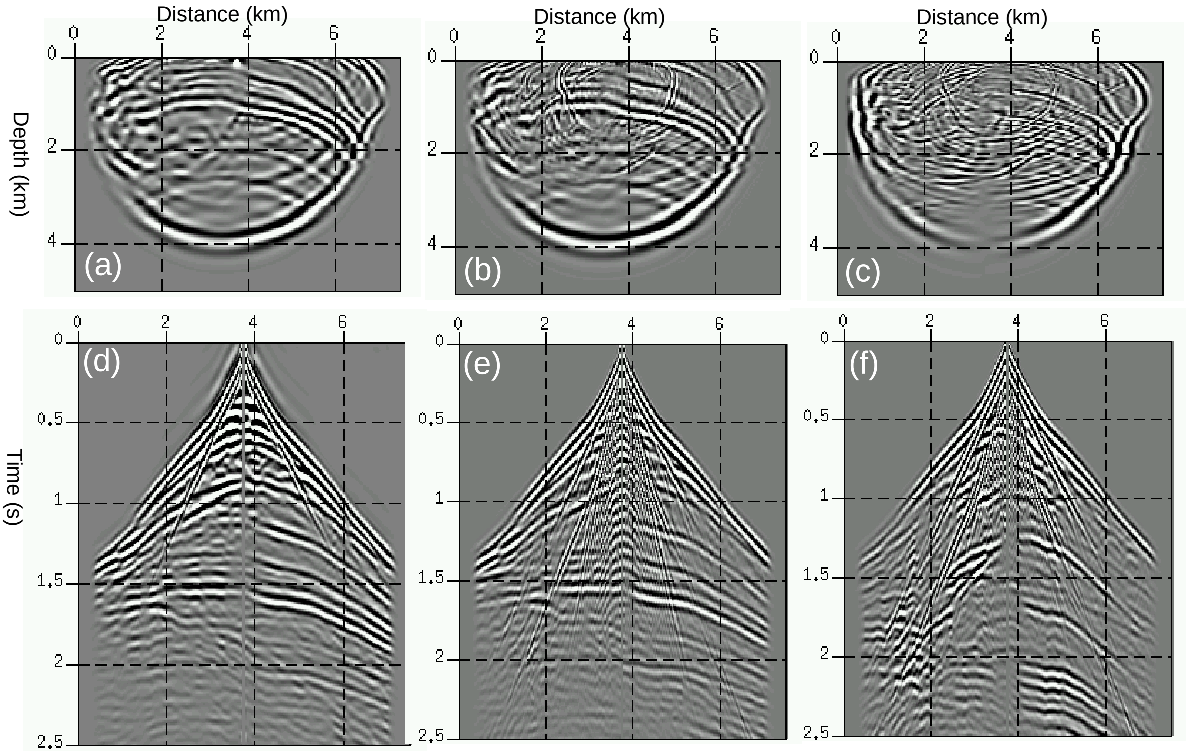

Figure 4: Comparisons of acoustic and elastic wavefields in a modified 3D overthrust model with a near-surface low velocity layer. (a), (b) and (c) are snapshots for acoustic waves, vertical and horizontal components of elastic waves; (d), (e) and (f) are shot gathers for acoustic waves, vertical and horizontal components of elastic waves.

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