Validity of Acoustic Early-Arrival Waveform Tomography for Near-Surface Imaging

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Summary

Time domain early-arrival waveform tomography is an advanced approach to image the near-surface velocity structures. For the reason of computation efficiency, we solve an acoustic wave equation problem instead of elastic wave equation for forward modeling. Since we are fitting the amplitude and phase of the early arrivals, but the waveform includes converted waves, we should understand the validity of such acoustic waveform tomography for imaging the near-surface velocity structures in reality. We design numerical experiments to compute the waveforms by applying elastic wave equation modeling and then apply acoustic early-arrival waveform tomography to study the liability of the imaging solutions. The results suggest that the imaging solutions is sensitive to the window size. It should be reliable as long as the time window of the early arrivals is properly selected. Testing the foothill velocity model with elastic waveform input produces a reasonable near-surface solution, but does require more sophisticated processing to remove elastic effects.

Introduction

Time domain early-arrival waveform tomography is a new approach for imaging the near-surface velocity structures from the surface down to about 1 km in depth with standard recording geometry (3km offset) (Sheng et al., 2006; Boonyasiriwat et al, 2008; Zhang and Zhang, 2011). With geometry offset increasing, it may be applied to image much deeper subsurface. The early arrivals are the events within a small time window right following the first arrivals, and they are supposed to be associated with the near-surface velocity structures. The imaging method solves a visco acoustic wave equation for the forward simulation with proper handling on the surface boundary condition and side boundary condition (Zhang and Zhang, 2011). Since we assume an acoustic wave propagation problem, we need to mute the surface waves in the input data. However, selected early arrivals may still include elastic effects such as the interference of converted waves. Therefore, we should study the validity of the acoustic assumption for the need of near-surface imaging. As opposed to traveltime tomography, the process of waveform fitting could produce a much higher resolution image but at the same time potentially introducing more uncertainty in the solution.

Although waveform tomography is also presented with frequency domain approaches and the frequency domain approaches should be a lot more efficient (Song and Williamson, 1995; Brossier et al., 2008; Erlangga and Herrmann, 2008), it may not be proper for imaging the near-surface velocity structures. Frequency domain approach cannot deal with events within a variable time window easily, or applying any processing function to the calculated synthetics. Frequency domain approach is good for inverting the whole data trace for the deep subsurface model building.

Near-Surface Elastic Wave Propagation

For a simple one layer over half a space velocity model, we can simulate elastic wave propagation and observe the elastic effects in the waveform. Figure 1 shows a snap shot of the simulation for a 1D velocity model with v_1=1000 m/s, h_1=300 m, v_2 = 3000 m/s.

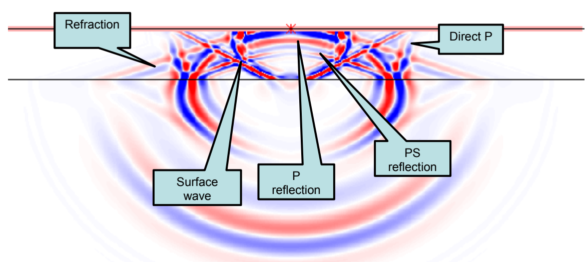

Figure 1: a snap shot of elastic wave propagation in a model with one layer over half a space.

Among various events, surface wave and PS reflection seem to be the major ones. The following Figure 2 shows the synthetic seismogram (vertical component).

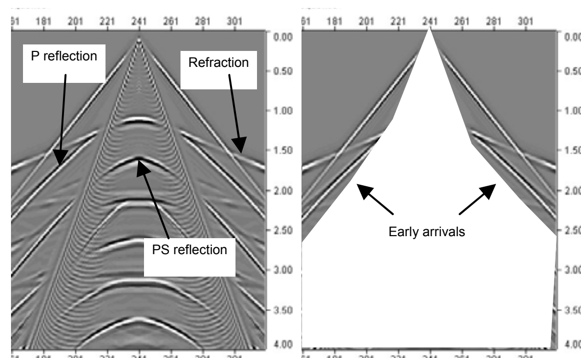

Figure 2: Elastic wave on the vertical component which shows surface waves and PS reflection. Inside muting is applied.

It appears for a layer with 300 m thickness, PS reflection is delayed enough (at least 50 ms in near offset) to be out of the time window of early arrivals. Of course there may be other converted waves as well. We hope that their amplitudes are small and insignificant.

The early arrivals primarily include direct waves, refractions, refraction multiples, and shallow wide-angle reflections. These events can be approximated by acoustic equation modeling. But it is a matter of the values of amplitude and phase. We shall test them quantitatively.

Elastic Waveform of Foothill Velocity Model

The following is the near-surface area in foothill velocity model:

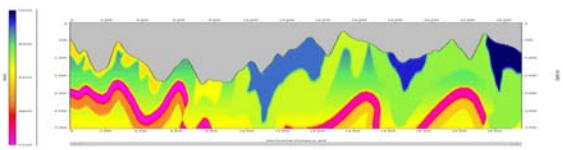

Figure 3: Near-surface velocity structure in foothill model

We calculated both acoustic and elastic waveforms using foothill velocity model, and the following shows one of the shot gathers.

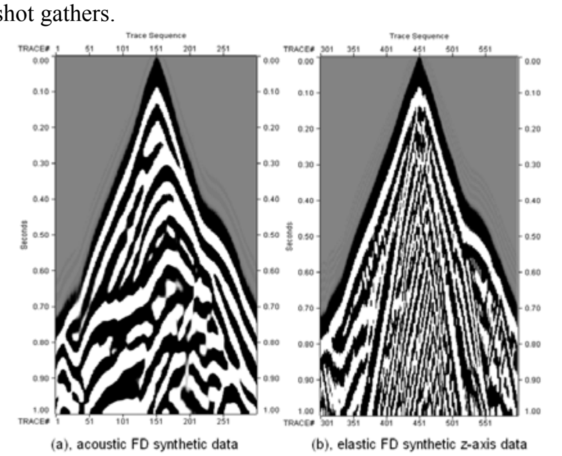

Figure 4: Calculated shot gather with acoustic and elastic modeling method.

The results between the two modeling are generally consistent in the first arrivals and within a small time window after the first arrivals. We shall mute the surface waves and use a time window about 300 ms following the first arrivals to select the early arrivals. The elastic modeling that we apply in this study does not include attenuation, which is another factor influencing the results when we process real data.

Acoustic Waveform Inversion with Elastic Input

We assume that the calculated elastic waveforms are the input data, and we follow a standard procedure of applying acoustic early-arrival waveform inversion. That includes processing input data and selecting early arrivals, extracting source wavelet, deriving an initial model from traveltimes. The following figures show comparison between inversion results with acoustic input waveform and elastic input waveform, but both inversions are performed with acoustic method.

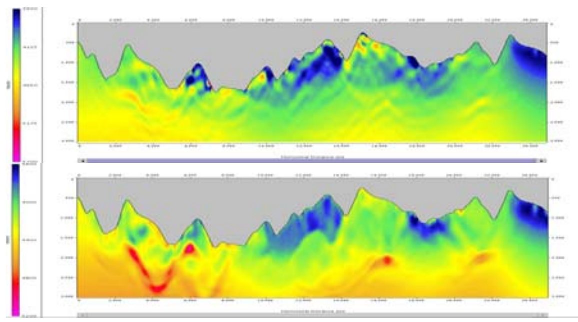

Figure 5: Acoustic waveform inversion with 17 shots only, (a) Top panel, elastic waveform input, acoustic inversion; (b) Bottom panel, acoustic waveform input, acoustic inversion.

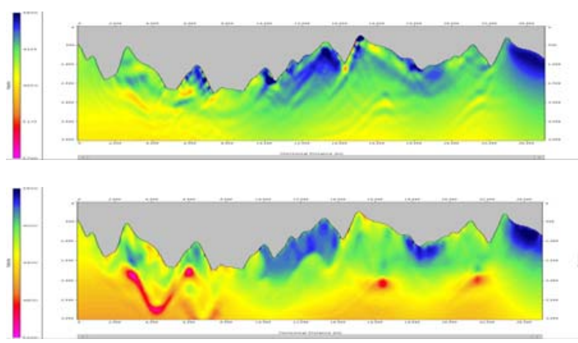

Figure 6: Acoustic waveform inversion with 84 shots only, (a) Top panel, elastic waveform input, acoustic inversion; (b) Bottom panel, acoustic waveform input, acoustic inversion.

With the same parameters for inversions, both results are similar in many ways. However, acoustic input always produces better results. The impact of elastic response in the waveform does make some differences. Continued efforts to remove these elastic responses in the waveform input data during processing phase seem important to achieve better results.

Since the amplitude of the input data cannot be simulated in the absolute sense, we actually apply shot amplitude balancing to both data and synthetics before inversion.

That approach requires a good starting model. And balancing elastic waveform and acoustic waveform may present an issue when the starting model is not good enough.

Obviously the selection of mute window size is critical too. It determines what data are included in inversion. This is also subjective.

The following figures show the comparison between elastic input data (black) and calculated synthetics (red) before and after inversions over 60 iterations for a shot gather:

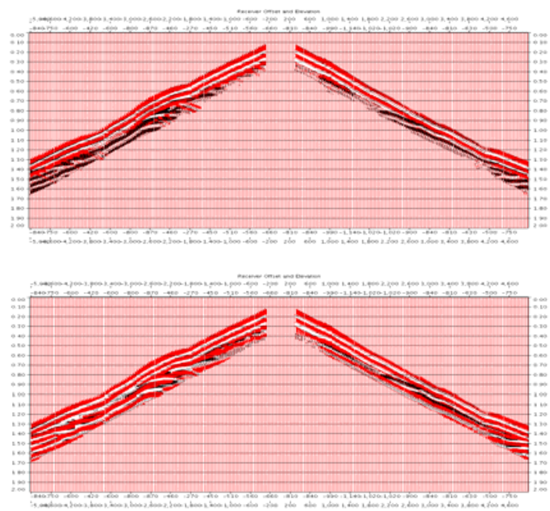

Figure 7: (a) Top panel: acoustic synthetics (red) from initial model overlays elastic input data (black) ; (b) bottom panel: acoustic synthetics (red) from final model overlays elastic input data (black).

Inversion process indeed helps to fit data better in the window of early arrivals. Therefore, what is in the fitting window from elastic data is critical to the results.

Conclusions

We analyzed elastic wave propagation in the near surface area, and tried to understand if the early arrivals from elastic media are valid for acoustic waveform inversion. In principle, early arrivals should be less affected by the elastic responses than the reflections where processing must be applied to remove surface waves and others. Nevertheless, synthetic tests using foothill velocity model suggest that elastic responses in the window of early arrivals still play some roles in the waveforms and make them different from acoustic responses, although the influence is not significant. But further research on removing such elastic effects is necessary in order to improve resolution on imaging with real data.

Another effort is to apply elastic early-arrival waveform tomography for near-surface imaging. With such an approach, it should not be sensitive to the window selection for acoustic responses. The tradeoff is that it requires much more computation time.

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EDITED REFERENCES

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