

Physical Modeling for Azimuthal AVO Over a Simulated Fractured Medium

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Summary

A seismic physical model experiment has been conducted to acquire multi-offset multi-azimuth P-wave 3D seismic data, and to verify the suitability of physically-modeled data for AVAZ (amplitude variation with azimuth) analysis. Our model consisted of an azimuthally anisotropic layer, phenolic LE™ layer stimulating a vertically fractured medium, overlain by two isotropic layers with the top most layer being water. The amplitudes reflected from the top of the fractured layer have been picked from the primary reflection; acquisition designed to avoid the overlapping of the primary and ghost events. The picked reflection amplitudes required corrections to make them suitable for an AVAZ study. In addition to amplitude corrections used for seismic field data, a directivity correction specific to the physical model transducers was needed. The corrected amplitudes from different azimuths showed a clear azimuthal variation caused by the fractured layer, and agreed with amplitudes predicted theoretically.

Introduction

Seismic modeling has an important role in improving our understanding of seismic wave propagation and in verification of new algorithms. AVAZ analysis, a viable method in studying fractured reservoirs, has been examined by many numerical modeling techniques, including the commonly used finite-difference methods. AVAZ analysis on finite-difference generated data, even for isotropic media, is challenging as the finite grid size causes amplitude variation with azimuth which is independent of the medium properties. An alternative to numerical modeling methods, physical modeling has been attempted by many researchers on the topic of AVAZ in recent years. 3D physically-modeled seismic data have been acquired on stimulated fractured media to detect fracture zone, fracture orientation, and density; Tadeppali (1995), Luo and Evans (2001), and Wang and Li (2003).

Using the University of Calgary seismic physical modeling facility, we have acquired 3D multi-offset, multi-azimuth physical model data over a phenolic LE™ layer, stimulating a fractured layer. We pre-processed the reflected amplitudes from the top of the fractured layer and used them as input to an AVAZ analysis for estimation of the Thomsen anisotropy parameters; the AVAZ inversion is presented elsewhere. Here we describe the acquisition of the P-wave physical model data and reflection amplitude corrections. The amplitudes reflected from the fractured layer have been deterministically corrected to represent the reflectivity; corrected amplitudes agree with the amplitudes predicted by Rüger's equation using the model parameters.

Physical modeling experiment details

In physical modeling, seismic wave propagation and recording experiments are performed on a small-scale earth model. Our model has an area of $50 \times 50 \text{ cm}^2$ and 20 cm thickness. It consists of four layers: an azimuthal anisotropic phenolic LE™ layer stimulating a vertically fractured medium, and three isotropic layers (Figure 1). The x_1 -axis of the model is along the symmetry axis and the x_2 -axis is along the fracture plane of the fractured layer. The scaling factor for our modeling system is 10000, so that a model dimension of 1 mm represents 10 m, and the dominant frequency of 500 kHz represents 50 Hz in

the real world. The system has one source transducer and only one receiver transducer. Vertical stacking of repeated source excitations and the movement of the receiver transducer generate a seismic gather. Our source and receiver transducers are piezopin CA-1136 with piezoelectric crystal 1.27 mm in diameter; as a receiver these transducers simulate vertical component geophones. More details about the laboratory equipment and set-up are as described by Wong et al. (2009). Nine common midpoint (CMP) gathers for the azimuths 0° , 14° , 27° , 37° , 45° , 53° , 63° , 76° , and 90° were acquired; a sample CMP gather is shown in Figure 1. The reflection from the top of the phenolic layer, appearing approximately at 1.2 s, is the target event in this study. The amplitudes from this event for all azimuth profiles were used in the AVAZ analysis.

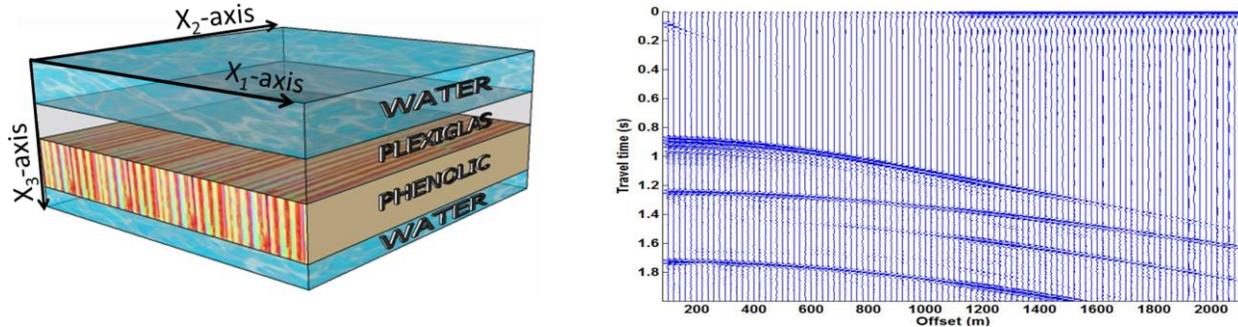


Figure 1: (left) Four-layer earth model. (right) The CMP gather acquired along x_1 -axis profile.

Picking reflection amplitudes was challenging, as the transducers operated near the water surface and both primary and ghost reflections were expected. To avoid the overlapping of primary and ghost reflections which damages the amplitude information required for AVA analysis, preliminary experiment to examine the behaviour of the ghosts was designed. In this new experiment, the source and receiver were kept at a fixed offset of 10 mm, and seismograms were recorded at 0.2 mm depth intervals as both transducers were raised from a depth of 10 mm up to a depth of 0 mm from the water surface. Figure 2 shows a suite of seismograms from this experiment. We see that the reflection event splits into three events, a primary, a ghost, and an asymmetric raypath event reflected between the water surface and main reflectors. The existence of two such asymmetric raypaths makes this event appear strong. Based on the results of this experiment, we decided to acquire our azimuth gathers with the transducers 2 mm beneath the water surface.

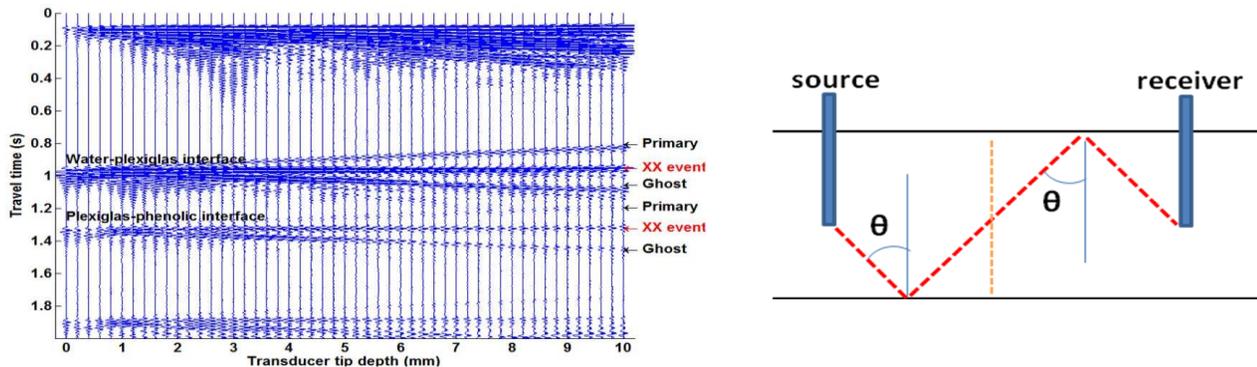


Figure 2: (left) New experiment gather. (right) Asymmetric raypath identified as "xx event" at left.

Amplitude corrections

The primary event amplitudes reflected from the top of the fractured layer, were subjected to a number of corrections to scale them to represent reflectivity. Deterministic amplitude corrections, similar to those used for seismic field data, were applied to the physical model amplitudes. For this study, corrections for geometrical spreading, emergence angle (to correct for total motion), transmission loss, and source-receiver transducer directivity have been applied to the manually picked amplitudes. A very good reference on deterministic amplitude corrections for seismic field data is Spratt et al. (1993). For

the directivity correction, specific to piezoelectric transducers with non-spherical radiation pattern, we used the amplitude response expression by Buddensiek et al. (2009). An illustration of a directional transducer response is shown in Figure 3. For circular disc transducers, the directivity response can be described analytically by the following equations

$$A = 4A_0 \frac{J_1(X)}{X} \sin\left(\frac{\pi D}{8\lambda z}\right), \quad \text{and} \quad X = \frac{\pi D}{\lambda} \sin \gamma, \quad (1)$$

where A_0 is initial amplitude, D is the effective diameter of the piezoelectric crystal, λ is the wavelength, z is the distance to the emitting plane, γ is the angle to the vertical axis, and J_1 is the Bessel function of order 1. The directivity equation as in equation (1) is similar to an array response. The directivity correction for the water/plexiglas reflection amplitudes of 0° and 90° azimuths are calculated using effective diameters of 1.4 mm and 1.6 mm respectively, and with proportional diameter size for azimuths between those angles. For the plexiglas/phenolic reflector (our target) we corrected the picked amplitudes for the 90° azimuth profile by using an effective diameter of 4.5 mm. This value gave a good fit to the spherical-wave Zoeppritz predictions (the 90° azimuth is along the fracture plane, and is considered to be the nearly-isotropic plane for the fractured medium; hence we expect it to follow closely the isotropic spherical Zoeppritz predictions). Between the water/plexiglas and the plexiglas-phenolic reflector, the ratio of best-fit effective diameters for the 90° azimuth is $(4.5/1.6)$ 2.81mm. For all the other azimuths, effective diameters given by $D_1 = 2.81 \times D_0$ are used, where D_0 is the diameter previously determined for the water/plexiglas reflector.

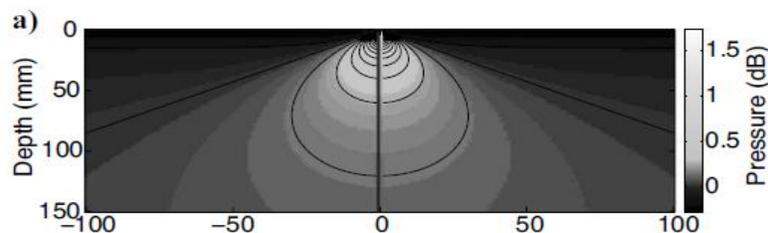


Figure 3: The calculated pressure field for a circular transducer of diameter 12mm as a function of depth and angle for 200 kHz frequency (Figure 4, Buddensiek et al. (2009)).

The directivity correction given in equation 1 is virtually identical to the directivity correction that we have derived numerically. In this numerical method the circular face of a disc transducer is divided up into many small elements. Each element is treated as a source and the Green's function for isotropic and homogeneous acoustic media from all elements are summed at receiver positions at fixed distance R (large compared to the wavelength and transducer diameter) from the center of the disc, but at different polar angles relative to the symmetry axis of the disc.

The reflection amplitudes from the water/plexiglas interface for the 90° azimuth profile are shown (after each correction) versus incident angle in Figure 4 (left). The incident angles are calculated using an isotropic raytracing code. The corrected amplitudes are compared with theoretical values predicted by the spherical-wave and plane-wave Zoeppritz equations (implemented as the JAVA applet Spherical Zoeppritz Explore 3.0 by Ursenbach et al., 2006, and available on the CREWES website). The spherical-wave Zoeppritz predictions are more realistic for our data, since our source and receivers do not produce and detect plane waves. The corrected amplitudes from plexiglas/phenolic reflector for 0° , 45° , and 90° azimuths are shown in Figure 4 (right); the azimuthal amplitude variation, although small, is demonstrated clearly. Note that the AVA variation is small for incident angles less than 30° .

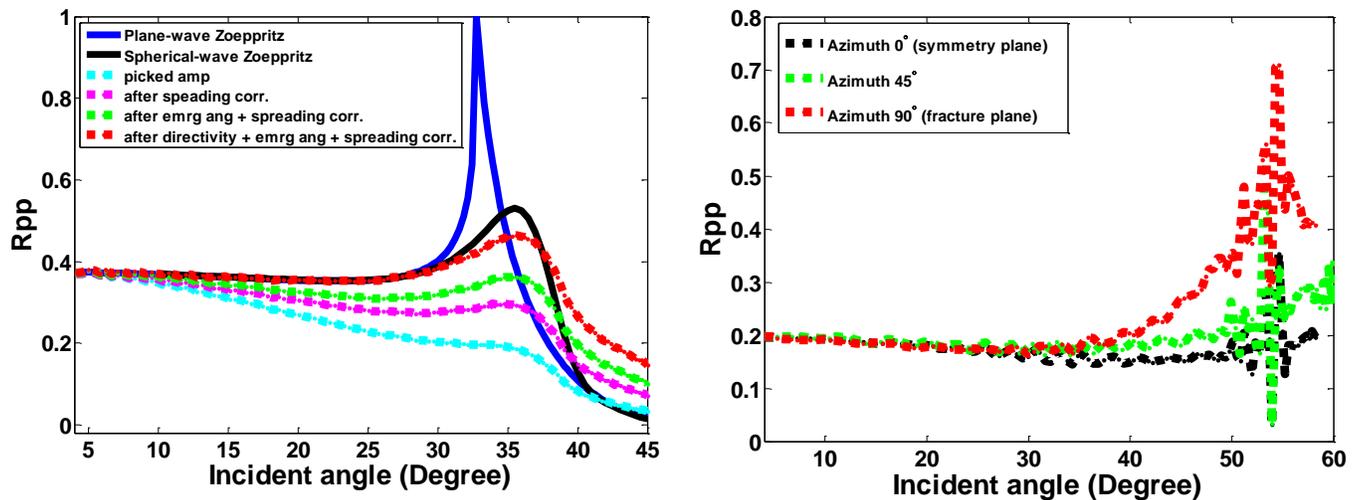


Figure 4: (left) Water/plexiglas reflector amplitudes, for azimuth 90° , corrected for geometrical spreading, emergence angle, and directivity effects. (right) Plexiglas/phenolic corrected amplitude from azimuths 0° , 45° , and 90° .

Conclusions

We successfully collected physical model data that are suitable for quantitative amplitude analysis, a difficult task that is rarely done. The physical modeling is strongly affected by transducer size and performance issues. To reduce the size effect, data were acquired in water, which enabled us to use the smaller size pin transducers. The non-spherical amplitude responses of the pin transducers were mitigated using the directivity correction; this difficulty was overcome by calibrating the target amplitudes to reflections from the water bottom. For the fracture plane (azimuth 90°), corrected amplitudes agreed with theoretical amplitudes predicted by the spherical-wave Zoeppritz equation.

Acknowledgements

We thank the sponsors of CREWES for their financial support. Dr.s P.F. Daley, Chuck Ursenbach, Chad Hogan, David Henley, and Kevin Hall are greatly acknowledged for their help. Faranak Mahmoudian wishes to thank specially David Cho, Mahdi Almutlaq, and Sayeh Moayerian.

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