AVOaz response of a fractured medium: Laboratory measurements versus numerical simulations

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Summary

Azimuthal variation of the AVO response (AVOaz response) of fractured reservoirs is usually modeled using equations for reflection coefficients obtained for plane waves. However, the plane wave approximation can break down at long offsets where incidence angle approaches the critical angle. Since azimuthal variation of AVO response is often more noticeable at large offsets (and can be rather weak), spherical wave effects must be carefully analysed and taken into account.

In order to analyse these effects quantitatively we performed AVOaz laboratory experiment under fully controlled conditions, and numerically simulating this experiment. The AVOaz response is studied by physical modelling in the laboratory with a finely layered Plexiglas model simulating vertical fractures. Transmission measurements are performed to construct the elasticity tensor for the HTI model. This elasticity tensor is used as an input into numerical simulations which are performed using an anisotropic full-wave reflectivity algorithm.

The comparison of the experimental data with simulations shows very good match for isotropic case and good qualitative agreement for azimuthal variations. The agreement is especially good for critical angles extracted by picking inflection points on AVO curves for each azimuth. This shows that (1) reflection measurements are consistent with the transmission measurements; (2) anisotropic numerical simulation algorithm is capable of simulating subtle azimuthal variations with excellent accuracy; (3) the methodology of picking critical angles on seismograms using the inflection point is robust, even in the presence of random and/or systematic noise.

Introduction

In recent years variations of the AVO response with azimuth (AVOaz response) have been increasingly used for characterisation of fractured reservoirs. However up until now in many cases the interpretation of such multi-azimuth data has been qualitative, and focused on estimating fracture and/or stress direction. With novel processing methods which enable preservation of the long offset data quantitative interpretation becomes feasible. Quantitative interpretation requires good understanding of AVOaz response as a function of medium parameters.

Behaviour of plane-wave reflection coefficients in anisotropic media and their azimuthal variations can be analysed using an extension of Zoeppritz equations to anisotropic media (Musgrave, 1970; Schoenberg and Potazio, 1992), and is well understood. More recently, Tsvankin (1996) and Rüger (1997) have derived concise and robust approximate relationships for reflection coefficients, which extend to anisotropy the well-know isotropic AVO approximations.

While the theory has been derived for plane waves it is known that seismic surveys utilise localised sources which produce spherical, rather than plane waves. Nevertheless, the plane wave approximation for reflection coefficients is assumed to be quite accurate for typical hydrocarbon exploration target depths and is routinely used in isotropic AVO analysis and inversion. However it is well known that plane wave approximation can break down at long offsets where incidence angle approaches the critical angle. Since azimuthal variation of AVO response is often more noticeable at large offsets (and can be rather weak), spherical wave effects must be carefully analysed and taken into account. This can be done either by full-wave numerical simulations (Karrenbach et al., 1997; Urdaneta, 1997; Landro and Tsvankin, 2007) or physical modelling in the laboratory (Fatkhan et al., 2001; Luo and Evans, 2004; Doruelo et al., 2006).

In this paper we combine these two approaches by conducting an AVOaz laboratory experiment under fully controlled conditions, and numerically simulating this experiment. The AVOaz response is studied by physical modelling in the laboratory with a layered model simulating vertical fractures. Transmission measurements are performed to construct the elasticity tensor for the HTI model. This elasticity tensor is used as an input into numerical simulations which are performed using an anisotropic full-wave reflectivity algorithm. The comparison shows a very good agreement between experiment and simulations.

Experiment

Seismic wave propagation and partitioning of energy at an interface can be effectively studied by using physical modeling, whereby models are constructed in such a way that they resemble real geological structures taking into account the scale factor. Hence, by using scaled models in a controlled environment, it can be assumed that the response from the models is the same as it would have been obtained from real earth materials.

An advantage of laboratory experiments is that real waves propagate through models with no approximations made to the propagation process. Laboratory experiments are conducted using the Curtin University Physical Modeling Laboratory equipment (Luo and Evans, 2004). The crux of the system is a set of computer controlled ultrasonic piezoelectric transducers, operating as seismic source and receivers. Movement of transducers is controlled in three-dimensions by high-precision step motors. A Lab View data acquisition program enables versatile source-receiver configurations, from transmission measurements to 2D, 3D and VSP surveys.

Physical properties of model materials need to be considered carefully to ensure successfully built physical models. For solid media this includes P and S-wave velocities and density. Plexiglas is often a material of choice as is intrinsically isotropic but at the same time can be cast in very fine layers which can be pressed together to simulate a fractured (anisotropic) medium. Plexiglas has P-wave velocity of about 2700 m/s which provides good velocity contrast with a water column. Its density of 1.2 g/cc allows the material to be positioned deep into the water tank.

The objective of this laboratory experiment was to analyze the variations of P-wave reflectivity with incidence angle and azimuth caused by a set of vertical fractures embedded into an otherwise isotropic medium. Thin Plexiglas plates (2mm thickness) were used to simulate vertical fractures. The surfaces of the Plexiglas sheets were roughened to establish asperities. Then the plates were pressed together under water to make sure that no air bubbles were trapped inside. With a scaling factor of 1:10000, the model simulates a 500 m thick fractured medium, with 20 m fracture separation, over an area of 1500 × 1200 m. A solid block of Plexiglas of the same dimensions was used for calibration.

The first step after designing the presumably HTI model is to check that it shows expected anisotropy (Urosevic, 1985). Transmission measurements were first performed in order to construct the stiffness matrix of such HTI medium by inverting the group velocity measurements. The results are shown in Table 1.

Solid model	V_p	V_s	ρ	Water	V_p	ρ
	2.724	1.384	1.2		1.484	1
Fractured model	$Vp(0)$	$Vp(45)$	$Vp(90)$	$Vs(fast)$	$Vs(slow)$	ρ
	2.704	2.660	2.709	1.382	1.320	1.2
Anisotropic parameters	ε^v	γ^v	δ^v			
	-0.0011	-0.044	-0.068			

Table 1. Elastic parameters of the solid (isotropic) and fractured (anisotropic) Plexiglas models. Velocities are in km/s and densities in g/cc.

The first reflection experiment was done for water/solid Plexiglas interface. Recorded AVO response was used for calibration and to examine and compare the radiation pattern of transducers to numerical modeling.

The solid block of Plexiglas was submerged in a water tank. Omni-directional P-wave transducers with a 220 kHz dominant frequency were also submerged in water and positioned 24 cm (2.4 km, scaled) above the model. Common mid-point (CMP) shooting was employed for data acquisition. The minimum offset was 2 cm and source and receivers were moved apart at an increment of 1 mm in the opposite directions. A total of 270 CMP gathers were recorded over the model. At each position, 20 CMP traces were repeated and vertically stacked to increase the signal-to-noise ratio. With a scaling factor of 1:10000 this model simulates 20 m trace spacing, and a source wavelet of 22 Hz dominant frequency reflecting from an interface at the depth of 2.4 km. The acquisition parameters and the resulting CMP gather are shown in Figure 1a,b.

For AVOaz reflection experiment, all acquisition parameters were kept the same as in the previous experiment over the isotropic model, but instead of recording a single 2D CMP line, a total of seven 2D lines were recorded along different azimuths with the middle CMP being at the centre of the fractured model. The azimuths were measured with respect to the symmetry axis direction, starting from zero azimuth (perpendicular to fractures) up to 90 degrees azimuth (parallel to fractures) with increment of 15 degrees. For every 2D CMP line, the model was rotated 15 degrees with respect to the symmetry axis. Figure 2 illustrates three azimuthal recordings at 0, 45 and 90 degrees. The black dotted line is the symmetry axis and the red lines are the 2D CMP lines corresponding to three azimuth directions.

Experimental results

The AVOaz experiement described above produces seven seismograms (one for each shooting azimuth) similar to the one shown in Figure 1b. Rpp amplitudes for water/HTI interface are picked, calibrated and plotted against angle and azimuth as shown in Figure 3. The following features can be observed in this figure:

- Fracture induced anisotropy has a negligible effect on amplitudes for incidence angles up to 25 degrees. This focused our analysis to large angle/offset reflection coefficients close to the critical angle.
- The reflection amplitude peak (close to the critical angle) shifts towards larger incidence angles from azimuths 0º to 45º, and then reverts back to its original position for azimuths 45º to 90º.

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Numerical simulations

The elastic parameters extracted from transmission measurements were used as an input to numerical simulation algorithms. The first idea was to compute plane-wave reflection coefficients for the water/solid Plexiglas interface using the anisotropic Zoeppritz equations (Schoenberg and Potazio, 1992). However it is clear from analysis of Figures 3 and 4 that the azimuthal variation can only be observed at offsets where the match of the measured reflection coefficients with theoretical plane-wave solutuon is poor. This discrepancy is most likely caused by spherical wave effects (Doruelo et al., 2006).

In order to make a precise quantitative comparison between experiment and theory, we employed full-wave reflectivity algorithm to simulate both isotropic AVO and anisotropic AVOaz responses numerically using the same elastic properties and acquisition geometry. The simulations were performed for the point source with a spherically symmetric radiation pattern. As a result we obtained a series of CMP seismograms for each shooting azimuth. Then, the amplitudes were picked on the seismic traces in the same manner as on the experimental traces. The resulting reflection coefficients are shown in Figures 4 and 5.

Comparison of experiments and simulations

The AVO response obtained from simulations for an isotropic Plexiglas block is shown in Figure 4 (along with experimental response and plane wave reflection coefficients). The AVOaz Rpp amplitudes for different azimuths are plotted against angles in Figure 5.

There is an excellent agreement between laboratory measured AVO response for the water/solid Plexiglas interface and isotropic AVO numerical simulations. This shows that spherical approximation of the radiation pattern of the transducers is appropriate.

Now we compare the two sets of AVOaz curves as shown in Figures 3 and 5. The two data sets show good agreement for azimuths 90º, 75º, 60º, 45º and 30 º degrees. On the other hand, for azimuths close to the symmetry axis, (15º and 0º), the physical modeling data show higher amplitude (by up to 7.5%), especially for large incidence angles. Possible reasons for the discrepancy are as follows.

- Finite fracture separation (violation of the effective medium approximation).
- Possible spatial heterogeneity of the model caused by the fact that the stress exerted by brackets used to hold Plexiglas sheets together is not uniform.
- Deviation of the radiation pattern of the cylindrical transducers from spherical in the transverse direction
- Effect of the edges of the rectangular Plexiglas model.

One way to mitigate the effect of amplitude distortions is to analyze the azimuthal variation of the critical angle (Karrenbach et al., 1997, Landro and Tsvankin, 2007). Landro and Tsvankin (2007) suggested that a robust method of picking a critical angle from the AVOaz curves is to pick the point of the fastest amplitude increase of the reflection coefficient. Critical angles calculated from laboratory experiment and numerical simulations using this technique are shown in Figure 6. Also shown is plane-wave critical angles computed from the equation:

$$\frac{\sin\theta_{cr}}{V_{p1}} = \frac{1}{V_{p2}(\phi)} \quad (1)$$

where θ_{cr} is the critical angle, V_{p1} is the velocity of the up medium (water), and $V_{p2}(\phi)$ is the phase velocity as a function of azimuth which can be calculated in terms of anisotropic parameters:

$$V_{p2}(\phi) \approx \alpha(1 + \delta \sin^2\phi \cos^2\phi + \varepsilon \sin^4\phi) \quad (2)$$

(Mavko, 1998), where α is P-wave velocity along the symmetry axis, ε and δ are anisotropic parameters extracted from transmission measurements. All curves are symmetric about 45º azimuth, which is expected for a liquid-filled fractured medium with very small ε (Rüger and Tsvankin, 1997). An excellent agreement is observed between three different data sets at the critical angle.

Conclusions

In this paper we performed laboratory measurements and full-waveform numerical simulations of the azimuthal variation of AVO response for a fractured Plexiglas medium. The comparison of the experimental data with simulations shows that (1) Reflection measurements are consistent with the transmission measurements (which are used as input into numerical simulations); (2) anisotropic numerical simulation algorithm is capable of simulating subtle azimuthal variations with excellent accuracy; (3) the methodology of picking critical angles on seismograms using the inflection point is robust, even in the presence of random and/or systematic noise.

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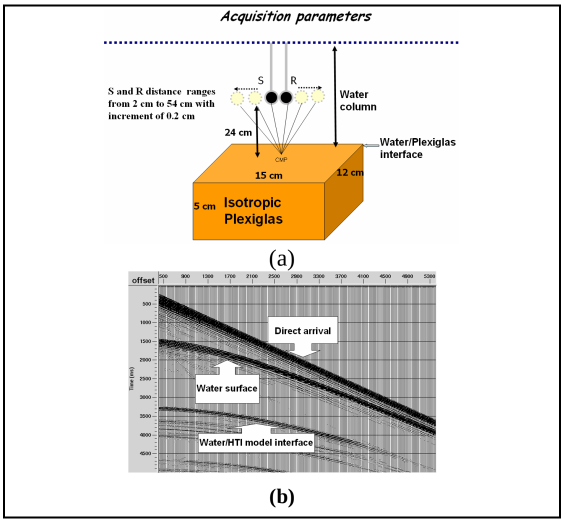

Figure 1. (a) Acquisition parameters used to perform reflection measurement out of water/ isotropic Plexiglas interface producing CMP gathers (b) with three seismic events indicated by arrows.

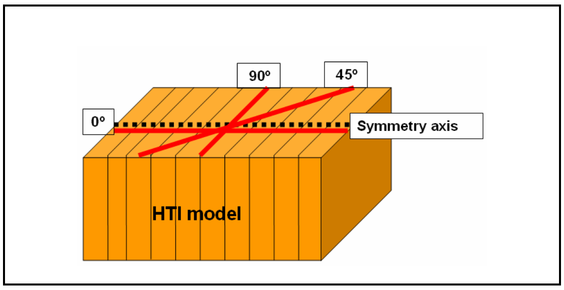

Figure 2. Azimuthal recordings at 0º, 45º and 90º. The black dotted line is the symmetry axis and the red one is the 2D CMP line azimuth direction.

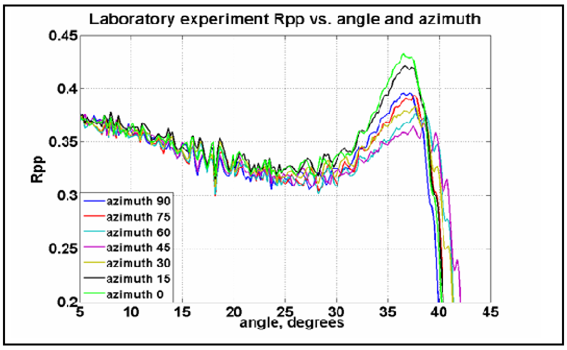

Figure 3. Laboratory experiment Rpp amplitudes for water/HTI interface, plotted against angle and azimuths.

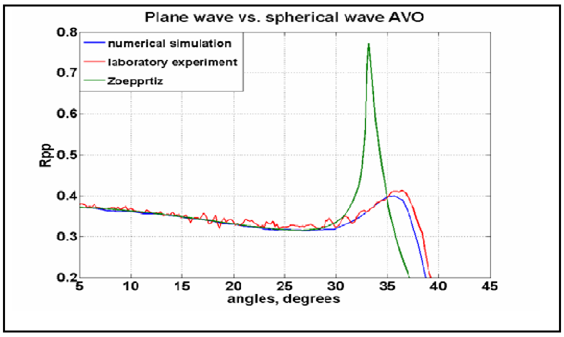

Figure 4. Rpp reflection amplitudes with applied geometrical spreading for water/isotropic model interface are plotted against angle of incidents using Zoeppritz equation (green curve). Laboratory and numerical simulation AVO responses are also shown (red and blue curves respectively).

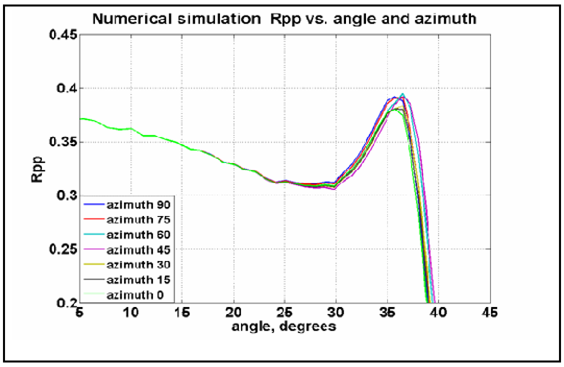

Figure 5. Numerical simulation Rpp amplitudes for water/HTI interface, plotted against incident angles of incidence and azimuths.

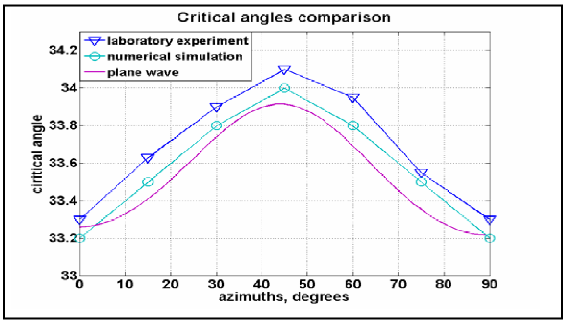

Figure 6. Comparison between critical angles computed from laboratory experiment, numerical simulations, and Snell's law at different azimuths.