Quantitative Petrophysical AVO Error Analysis in a Layered Model

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Summary

In order to minimize reservoir prediction error risk from AVO inversion, it is necessary to study the uncertainties of this inversion. By defining an AVO misfit function, we quantitatively measure the AVO inversion errors in a layered rock-physics theoretical model. We especially consider a Class 2 oil sand model, which is often difficult for AVO inversion. In such a case, most of the approximate Zoeppritz equations derived from Aki and Richards (1980) approximation are sufficiently accurate. We emphasize several factors which may affect the quality of inversion for petrophysical parameters but might be ignored in AVO inversion. Such factors include using only the vertical component of reflection amplitude, calculation of incidence angles by using RMS velocities, and utilizing different approximations for Zoeppritz equations. Our analysis shows that these factors could cause errors in petrophysical parameters that might lead to erroneous reservoir prediction. In addition, numerical synthetic waveform modeling shows that uncertainties in attenuation (Q) factors could also lead to uncertainties in reservoir prediction.

Introduction

AVO technique has been widely used in oil and gas industry. Although many of successful applications have been reported, uncertainties in reservoir properties still exist from AVO-based predictions and disturb engineers. Most processing steps affecting seismic amplitudes (Dey Sarkar et al, 1986; Li, et al, 2003) could impact the accuracy of AVO inversion. Along with the quality of true-amplitude processing, the use of approximate Zoeppritz equations and inversion algorithms could lead to inversion errors. Using plane-wave AVO theory to invert spherical-wave data (Haase and Ursenbach, 2007), or using isotropic AVO theory to invert anisotropic media data and vice versa could lead to erroneous results as well. Inversion of the vertical-component reflection amplitudes with disregard of the effects of free-surface reflections and mode conversions, calibration without the S-wave velocity information, etc. could affect the AVO inversion. Thus, it is important to be able to quantitatively measure the errors in AVO inversion and to know to what degree these errors could cause wrong reservoir predictions.

The accuracy of AVO inversion has been studied through the accuracy of the inverted elastic parameters, such as acoustic impedance, velocities, Lambda, Mu, and anisotropic parameters.

However, elastic parameters need to be further inverted for petrophysical parameters, such as permeability, clay content, pressure, porosity and saturation. Petrophysical parameters are more important because they determine the economic viability of hydrocarbon-bearing reservoirs. Errors in elastic parameters could cause uncertainties in petrophysical parameters, such as interpreting a brine reservoir as oil and vice versa. Thus our goal is to evaluate the accuracy of AVO inversion in terms of reservoir prediction and based on a rock physics model (Hilterman, 2001).

Below, based on fluid-substitution model, we define an AVO misfit function and quantitatively analyze several factors which may effect reservoir properties. In particular, we scrutinize the errors caused by the use of several approximations to Zoeppritz equations, use of vertical-component vs. true vector amplitudes, and of the way incidence angles are calculated from the offsets. Finally, in order to simulate the AVO inversion uncertainties in real data, we analyze synthetic seismograms by using the reflectivity method (Fuchs and Müller, 1971) in the same model.

Method

In our fluid substitution model (Table 1), sand content is assumed to be 85%, shale content is 15%, and brine saturation is 100%. P-wave velocity of brine-saturated reservoir is 3470m/s. Tosaya's (1982) velocity-porosity-clay transforms are used to calculate the P- and S-wave velocity in wet sand with varying porosity. Density of brine-saturated sand is obtained from Gardner's (1974) velocity-density transform. The overlying shale parameters are calculated from Castagna's (1985,1993) Vp-to-Vs transform and Vp to shale density relation. Our analysis focuses on layer 6 in the model (Table 1), which represents a Class 2 oil sand.

Layer No.	Depth(m)	Vp (m/s)	Vs (m/s)	Density(g/cm^3)	Sw (%)	φ (%)
1	600.0	2000.0	500.0	2.00		
2	180.0	2410	988.7	2.2		
3	120.0	2088.0 (o)	1117.0 (o)	1.994 (o)	30	35
4	180.0	2410.0	988.7	2.2		
5	100.0	2642.6	1166.8	2.28		
6	**120.0**	**2886.0 (o)**	**1622.0 (o)**	**2.15 (o)**	**30**	**27**
7	100.0	2642.0	1166.8	2.28		
8	100.0	3093.7	1514.8	2.40		
9	120.0	3731.0 (o)	2186.0 (o)	2.22 (o)	30	18
10	100.0	3093.7	1514.8	2.40		

Table 1: Layered Fluid Substitution Model

In order to measure the AVO inversion errors quantitatively, we use the following misfit function (Ma and Morozov, 2007) to compare the plane-wave exact reflectivity with other measures or calculated reflectivity:

$$F(angle) = \sum_{i=angle1}^{angle2} |(R_{Zoeppritz} - R_{compared})|^n \qquad (1)$$

Here, *angle* is the incidence angle, $R_{\text{Zoeppritz}}$ denotes the Zoeppritz solution for P-wave reflection coefficient, and R_{compared} represents some other measure of the P-wave reflection coefficient. R_{compared} may be amplitude of the vertical component of P-wave reflectivity, P-wave reflectivity from an approximation to Zoeppritz equation, or any forms of reflection coefficient. Exponent *n* can be selected as 0.5, 1, 2, etc. Function (1) attains a minimum where the reflectivities match the Zoeppritz solution within the corresponding angular range.

AVO Error Analysis

In AVO analysis, we often we consider the vertical-component amplitude as a measure of reflection coefficient, use approximate formulas for reflection amplitudes, or ignore bending ray paths when converting the offsets to incidence angles in layered models by using the RMS velocity. Figure 1 illustrates the uncertainties caused by such approximations.

We note that in Class 2 cases (Table 1), in which elastic contrast across the boundary is small, both vertical-component and angle errors could lead to large errors at moderate and large angles. By using eq. (1), we analyzed those AVO curves which are the best-fit of the vertical-component reflectivity derived by using the exact reflection coefficient (Figure 2). We note from Figure 2 that only the vertical-component error could lead to wrong brine saturation estimation. The modeled 30% brine saturation is predicted to be 90% (arrows in Figure 2), which means that an oil reservoir could be predicted to be a brine reservoir. The best-fit AVO models from Figure 2 are shown in Figure 1. We can find how these predicted models fit the vertical component of exact reflectivities well. The use of approximate Zoeppritz equation such as Shuey's equation (1985) might also lead to wrong reservoir predictions (Figure 1).

Furthermore, to approach more practical cases in AVO inversion, we produced synthetic seismograms with reflectivity method based on the layered model in Table 1. One of the difficulties in defining a reflectivity model is in unclear relationships between the elastic parameters and quality factors Qp and Qs. Several authors (White, 1965, Winkler and Nur, 1979, Udias, 1999, Frempong, et al, 2007) studied the relationships between 1/Q and seismic velocities. In our model, we simply tested constant and variable quality factors throughout the columns of the model (Table 1). Then seismic amplitudes from top of layer 6 were calibrated and compared to the plane-wave reflection coefficients (Figures 3 and 4). Figure 3 and 4 shows combined factors which affect AVO inversion. As expected, we found that smaller quality factors cause larger AVO inversion errors.

Conclusions

Uncertainty analysis in AVO inversion is very helpful for interpreters for determining the properties of a reservoir. Misfit function is a useful tool to quantitatively analyze errors in AVO inversion. Not only true amplitude processing but also the use of approximate Zoeppritz equation, using the vertical component of reflection coefficient, and determination of the incidence angle deviation could lead to petrophysical parameter inversion errors which might effect evaluation of reservoir. Quantitative error analysis using synthetic seismograms computed using the reflectivity method could be a practical way to understanding the uncertainty of AVO inversion.

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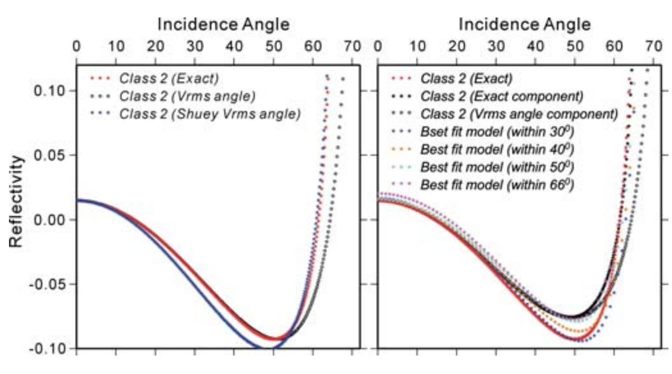

Figure 1

Left: Three types of reflectivities calculated from top of layer 6 (Table 1). *Exact* denotes the reflectivities calculated from Zoeppritz equation with correct incidence angle. *Vrms angle* represents reflectivities calculated from Zoeppritz equation with angle from RMS velocity. *Shuey Vrms angle* represents reflectivities calculated from Shuey's approximation (1985) with angles determined from RMS velocity.

Right: *Exact component* represents the vertical component of reflectivities calculated from Zoeppritz equation with exact angle. *Vrms angle component* is the vertical-component amplitude calculated from Zoeppritz equation with angle from RMS velocity. *Best fit model* shows the reflectivities that are closest to the vertical component of exact reflectivity within the specified angle ranges.

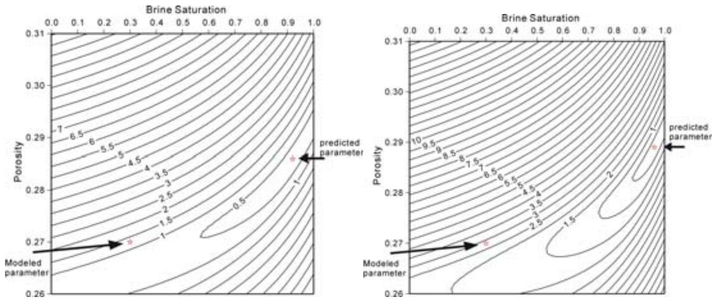

Figure 2: Misfit function calculated between the modeled “vertical- component” and exact reflectivities (Table 1) and predicted models by using eq. (1).

Left: Angles up to 30^0 in eq (1). Note that the modeled reservoir parameters in Table 1 with porosity 27% and 30% brine saturation are predicted to 28.7% porosity and 91% brine saturation (arrows)

Right: Angles range up to 40^0 in eq. (1). Arrows show that the modeled reservoir parameters in Table 1 with porosity 27% and 30% brine saturation are predicted to 29% porosity and 93% brine saturation.

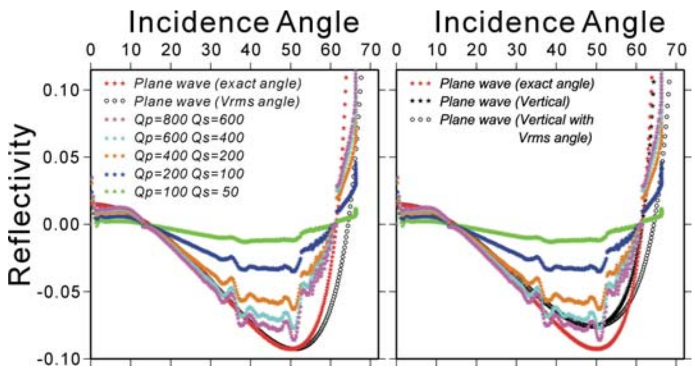

Figure 3: Scaled spherical-wave (numerical) reflection coefficients with constant Qp and Qs for top of layer 6 layers (Table 1). *Plane wave* denotes the same reflectivities calculated from Zoeppritz equation as in Figure 1.

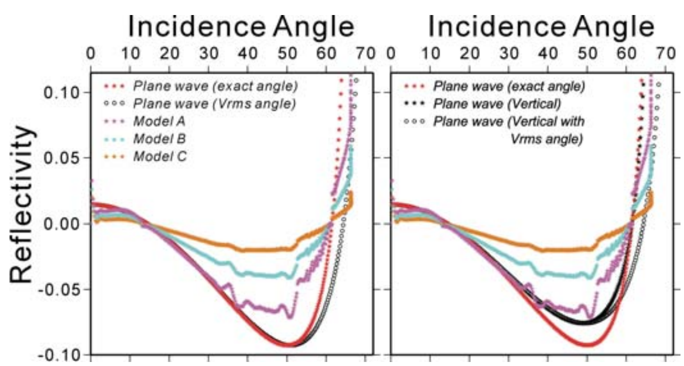

Figure 4: Scaled spherical wave reflection coefficients with varied Qp and Qs for top of layer 6 layers (Table 1). Quality parameters are set as follows: Qp=(Vp/Const.)2, Qs=4Qp/3(Vs/Vp)2 (Udias,1999), where Const equals 200,150 and 101.5 respectively in Models A, B and C. Plane wave denotes the same reflectivities calculated from the Zoeppritz equation as in Figure 1.