Frequency depending AVO for a gas-saturated periodical thin-layered stack

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Summary

AVO modeling for periodic thin-layered stack (TLS) was done. This TLS consists of two-layer elements and simulates a multilayer gas deposit. A sharp change of the Poisson coefficients is a character of this stack. It is shown, that AVO within pre-resonant frequency range of the TLS, which has the bed thickness less than tuning thickness, differs considerably from that in the resonant frequency range. In the resonant case AVO inversion on the basis of the linearized Shuya formula produces an estimate of the effective Poisson coefficient much lower than that of a separate gas-saturated layer. At the same time, in the low-frequency range the effective Poisson coefficient estimate is much higher than in the case of a separate gas-saturated layer. In this frequency range conclusions based on a single thin layer AVO study cannot be extrapolated on AVO from a TLS with identical physical properties. We also have shown the influence of a non-elastic absorption in the layers simulating porous gas-saturated sandstones on AVO from a TLS in pre-resonant and resonant frequency ranges. The above AVO features can not be extended to a TLS in which gas-saturated sandstones are replaced by water-saturated ones with high values of Poisson ratio. The modeling was carried out using a finite-difference solution of the elastic wave equation and a visco-elastic variant of the Haskell-Thompson method.

Introduction

Geological models currently used to aid AVO-analysis are, as a rule, thick-layered. In the actual thin-layered subsurface medium the AVO response has particular qualities, the disregard of which may lead to errors in predicting hydrocarbon reservoirs.

The effects of a thin-layered, elastic stack (TLS) on the AVO response are felt both when the waves travel through such a geological unit, as investigated by Widmair, Shapiro and Hubral (1996), and when the waves are reflected from it. Ursin and Stovas (2002) derived recursive formulas to compute reflection and transmission coefficients for a TLS with visco-elastic parameters of the layers. The same authors (2005) examined transitional frequency zones to find out how various averaging formulas could be applied to them in the case of waves being normally incident on a two-layered periodic stack. Liu and Schmitt (2003) investigated the AVO response from a single thin layer in the case of an appreciable Poisson ratio change.

We have investigated how a periodical TLS, that consists of Yu (Yu, 1985) model elements and characterized by sharply different Poisson ratio values for shale and gas-saturated sandstone would affect the AVO response. We have shown that unlike a gas-saturated TLS AVO of a water-saturated TLS in the pre-resonant and resonant frequency ranges does not differ in practice. We also demonstrate the difference of AVO responses for TLS, single thin bed and thick-layered models with identical physical properties

We used a finite difference solution for the elastic wave equation and the Haskell-Thomson method in its visco-elastic variant to run the investigation.

Method

Our investigation was based on full-wave modeling using a finite-difference solution for the vector wave equation (Kostyukevych et al, 2001). Geophones were located at a depth (50-100 m) not too far from the target interface in order to record AVO-curves unaffected by wave transmission. This permitted recording of both incident and reflected waves, estimations of the slowness vector direction for each of the waves and a numerical computation of the AVO-curve. This method allows due regard for the thin-layering phenomenon, anisotropy, lateral velocity variations on either side of the geological interface and the interface curvature. In this particular case, we only investigated the effects of the thin-layering phenomenon in its elastic variant when appreciable changes in the Poisson ratio values are observed in the layers. Computation of reflection coefficient for a TLS, using Haskell-Thomson method (Aki, Richards, 1978), was utilized to demonstrate how non-elastic absorption in porous gas-saturated sandstones affects AVO. This computation was carried out in two steps. First, we determined scattering matrices for a set of plane waves with different frequencies. Then we selected reflection coefficients from the scattering matrices and convolved them with a Ricker wavelet of a certain frequency. This approach allows the reflection and transmission coefficient vs. plane wave dip angle dependency to be stabilized.

An abrupt change in the Poisson ratio at the top of gas-saturated sandstone overlain by a shale causes, in accordance with the Zoeppritz equations, a remarkable change in the reflection coefficient vs. the angle of incidence. This fact is well illustrated with the linearized formula (Shuey, 1985) for P-wave reflection coefficient, which is valid for a clastic section. This formula also permits estimation of the magnitude of change in the $\Delta\sigma$ effective Poisson ratio, using the least-squares method. We utilize this method to compare the modeling results.

For thin-layered gas-saturated stacks that are much closer to a realistic geology than a thick-layered model, the situation becomes more complex. Within a standard seismic frequency range, such stack may be considered a vertical transversally isotropic (VTI) medium with the average elastic parameters C_{pq} and density ρ defined by Backus equations (Backus, 1962).

Transition from a low-frequency range to a high-frequency range, when the average wave velocity does not differ from the group velocity, is characterized by complex wave-transformations (Rytov, 1952, Stovas and Ursin, 2005). The P-wave-train velocity first becomes slower than the low-frequency one; then, depending on the TLS properties, an imaginary component of the velocity appears, which entail elastic wave attenuation. When the wavelet frequencies are nearing the resonant frequencies of the TLS, the properties of a reflected signal and of AVO have their own specificities. This will be illustrated below with models.

Models

For illustrate the specific AVO response of a TLS, let us consider three models consisting of the same elements. The first model (Model 1) is a two-layer Yu model characterized by the following parameters: α_1 = 2177 m/s, β_1 = 889 m/s, ρ_1 = 2160 kg/m^3, σ_1 = 0.4, α_2 = 1967 m/s, β_2 = 1311 m/s, ρ_2 = 2050 kg/m^3, σ_2 = 0.1, where α_1, β_1, ρ_1, σ_1, α_2, β_2, ρ_2, σ_2 are P- and S-wave velocities, densities and Poisson ratios pertaining to the first (shale) and second (gas-saturated sandstone) layers respectively. To build the second model (Model 2), the above Model 1 parameters were used to create a periodical TLS, which layers of h = 10 m thick. The total unit thickness was supposed to exceed the seismic wave length. The third model (Model 3) is three-layer – a single thin layer of gas-saturated sandstone, 10 m thick, occurring inside a shale section.

Fig. 1 shows AVO-curves for the above models, with a 20 Hz Ricker wavelet. AVO-curves with the given parameter values for the two-layer and three-layer models practically coincide. AVO-inversion on the basis of the least-squares solution of Shuey (1985) equation yields σ_2 = 0.13, which is close to the Poisson ratio value in a gas-saturated sandstone. For Model 2 (a TLS), the AVO response is characterized by a flatter curve which gives σ_2=0.3 after AVO-inversion. So, in the case of a gas-saturated thin layer (Model 3), AVO-analysis would have produced a correct answer: the layer is gas-saturated; whereas in the case of a much more promising prospect – a multi-layer gas reservoir – the answer would have been wrong. Judging by the Poisson ratio value, a wrong conclusion may have been drawn regarding the internal structure of this interval.

It is important to note that wrong prediction may have been drawn not only from the AVO-analysis. A direct determination of P- and S-wave velocities from VSP or surface seismic data would have produced effective parameter values that would satisfy Backus equations (Backus, 1962). For the Model 2 above parameters are:

α_2 = 2060 m/s, β_2 = 1050 m/s, ρ_2 = 2100 kg/m^3, ε_2 = -0.05, δ_2 = -0.09, γ_2 = 0.11, σ_2 = 0.33, (1)

where ε_2, δ_2 and γ_2 are Thomsen parameters for a vertical transversely isotropic medium. The $\sigma_2 \approx 0.33$ Poisson value does not provide grounds to predict gas presence within the section interval being analyzed.

The σ_2=0.33 value derived from Backus equations does not coincide with what has been computed using the AVO-inversion (σ_2=0.3). The explanation is that AVO-curve is dependent on anisotropy (in this particular case on quasi-anisotropy). For the vertical transversely isotropic medium, this dependence is defined as (Banik, 1987):

$$R_{pp}(\theta) = R_{pp}^{iso} + \frac{1}{2}\Delta\delta \sin^2\theta \, ,$$

where R_{pp}^{iso} is the P-wave reflection coefficient for an isotropic medium, $\Delta\delta = \delta_2 - \delta_1$. A negative parameter $\Delta\delta$ modifies the AVO-curve in the same direction as a negative abrupt change of the Poisson ratio characteristic of the Yu model does, and which influences the $\Delta\sigma$ determination.

As can be seen from the preceding discussion, it is practically impossible in this particular case to correctly predict the internal structure of a TLS from AVO attributes. At the same time, analysis of some additional effective parameters is helpful in making the prediction more accurate. Thus, on the basis of Backus equations for a periodic TLS the following is valid:

- ε_2 may become negative (see (1)) if $\alpha_2 < \alpha_1$ only when $\beta_2 > \beta_1$, i.e. the Yu model conditions are met inside a geological unit
- $\delta_2 \neq 0$ only when $\sigma_1 \neq \sigma_2$, which is also valid for the Yu model.

It is also important to note that the condition $\delta_2 < 0$ would cause the interval velocity to decrease (by 10% in this particular case) inside the gas-saturated stack (Thomsen, 1986).

Estimation of the above parameters from seismic data is a separate and not a simple issue; it is, however, a right way to a correct prediction of the TLS internal structure.

Transition to a high frequency seismic range changes the AVO response of a TLS. Fig. 2 shows comparison of AVO-curves obtained for Model 2 with a 20, 30, 40 and 50 Hz Ricker wavelet. As can be seen from Fig. 2, the AVO-curve varies remarkably with the change of frequency. At a frequency of about 35-40 Hz, AVO-inversion produces the Poisson ratio estimate of $\sigma_2 \approx 0.12$, which corresponds to the gas-saturated sandstone. With the 50 Hz wavelet (at the first resonant frequency of the TLS), a super AVO-effect is observed. As a result of AVO-inversion, the estimate is $\sigma_2 \approx 0.06$, i.e. less than for the gas-saturated sandstone. Note that if the thickness of layers had been h = 5 m, the above super AVO-effect would have been observed at 100 Hz, while the low frequency seismic range would have been much broader.

In case of a water-saturated TLS with parameters of layers: $\alpha_1 = 2177$ m/s, $\beta_1 = 889$ m/s, $\rho_1 = 2160$ kg/m^3 $\alpha_2 = 2133$ m/s, $\beta_2 = 870$ m/s, $\rho_2 = 2100$ kg/m^3, AVO practically does not depend on the offset and the frequency range of a wavelet. AVO depends on three major factors: interferences, impedance ratio $\alpha\rho$ and Poisson's coefficient in layers. In this case the conditions $\alpha_1\rho_1 \approx \alpha_2\rho_2$ and $\sigma_1 \approx \sigma_2$ influences much more the AVO response than interference does. A similar result was obtained for a single thin bed by Liu and Schmitt (2003).

Although the Yu model is such that was actually observed in practice, yet it is unrealistic in that any gas-saturated sandstone with a significant porosity should be inelastically absorptive. Let us introduce inelastic absorption into gas-saturated layers, leaving shale layers elastic. Two cases with different Q-factors for P-waves were simulated: the first with $Q_p=10$, the second with $Q_p=4$. The latter characterizes a highly porous gas-saturated sandstone. In order to determine Q-factor for S-waves, we use a formula applicable to high-porosity rocks (White, 1983): $\alpha_p / \alpha_s = \gamma = V_s / V_p$, where α_s, V_s, α_p and V_p are the absorption coefficients and velocities of S- and P-waves, respectively. Hence, $Q_p = Q_s$.

As can be seen from Fig. 3, Q=10 would lead to decreased absolute values of reflection coefficient, whereas the curve slopes decrease insignificantly. At the same time, when Q=4, the AVO-curve slopes, for both frequencies, 20 and 50 Hz, decrease appreciably and in the standard range of AVO-analysis (0-20°) are nearing the slopes which are characteristic of a water-saturated section. Taking into account the low Q-factor value, this instance should be viewed as an extreme case.

Attention should be paid to AVO-curves for the 50 Hz wavelet (tuning thickness) without due account of absorption. The curves were obtained from the full-wave modeling based on the finite-difference solution (Fig. 2) and by utilizing the Haskell-Thomson method (Fig. 3). In the latter case, with the curve slopes close enough, the absolute values of the reflection coefficient are much higher. The explanation for this is that when modeling at the resonant frequency is based on finite-difference method, the signal gets distributed in time because of a very sharp amplitude-frequency characteristic of the TLS.

Conclusions

Disregard of the thin-layering phenomenon while running AVO-analysis within a standard seismic frequency range may give rise to gross errors, even unable to detect a promising multi-layer gas deposit. This conclusion equally applies to predicting hydrocarbon presence from direct measurements of P- and S-wave velocities in both VSP and surface seismic surveys. In a low-frequency range the AVO response of a single thin bed differs from that of a TLS.

Within a frequency range close to the resonant frequency (tuning thickness) for a given TLS, favorable conditions occur for predicting multi-layer hydrocarbon reservoirs from AVO-analysis. At the same time, disregard of absorption may lead to interpretation errors.

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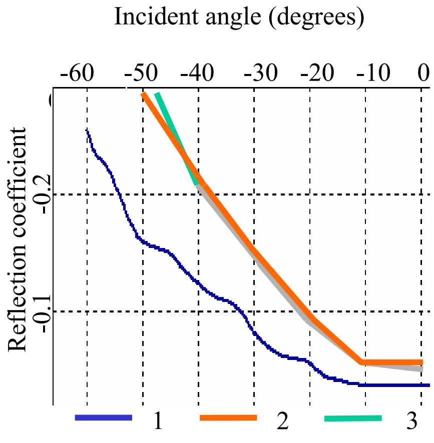

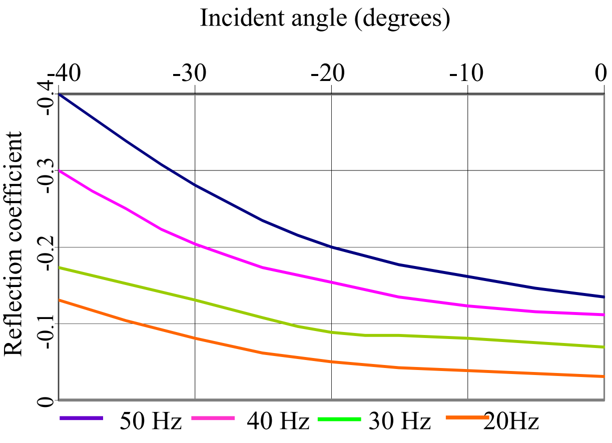

Figure 1. Comparison of AVO-curve from multi-layer (1), two-layer (2) and three-layer (3) Models with a 20 Hz Ricker wavelet

Figure 2. Comparison of AVO-curves produced from different frequency ranges for a thin-layered model

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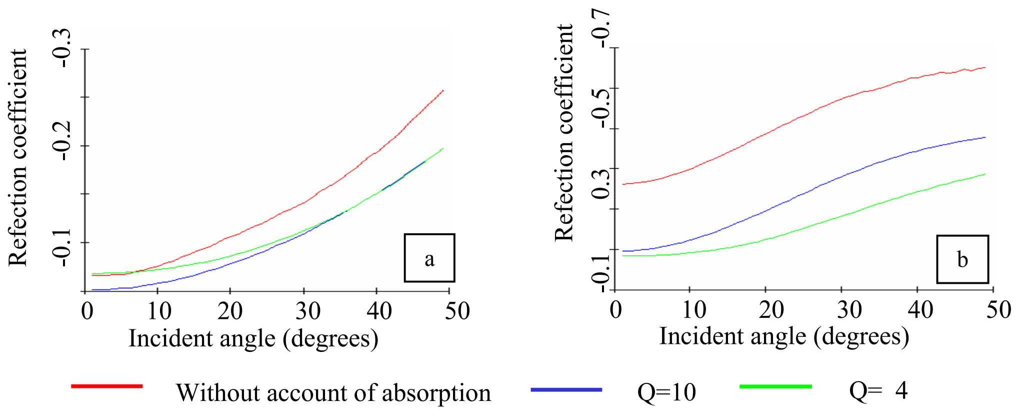

Figure 3.Comparison of AVO-curves from a thin-layered inelastically absorptive gas-saturated model: (a) a 20 Hz Ricker wavelet, (b) 50 Hz Ricker wavelet.

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