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

Naum Marmalyevskyy, Yury Roganov Ukrainian State Geological Prospecting Institute, Alex Kostyukevych*
Tesseral Technologies Inc., Zina Gazarian PetroAlliance

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 in pre-resonant and resonant frequency ranges. The above AVO features cannot be extrapolated on AVO from a TLS with identical physical properties.

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
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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 \( \rho \) 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: \( \alpha_1 = 2177 \text{ m/s}, \beta_1 = 889 \text{ m/s}, \rho_1 = 2160 \text{ kg/m}^3, \sigma_1 = 0.4, \alpha_2 = 1967 \text{ m/s}, \beta_2 = 1311 \text{ m/s}, \rho_2 = 2050 \text{ kg/m}^3, \sigma_2 = 0.1, \) where \( \alpha_1, \beta_1, \rho_1, \sigma_1, \alpha_2, \beta_2, \rho_2, \sigma_2 \) 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 \( h = 10 \text{ m} \) 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 \( \sigma_2 = 0.13, \) 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 \( \sigma_2 = 0.3 \) 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:

\[
\begin{align*}
\alpha_2 &= 2060 \text{ m/s}, \beta_2 = 1050 \text{ m/s}, \rho_2 = 2100 \text{ kg/m}^3, \sigma_2 = -0.05, \\
\delta_2 &= -0.09, \gamma_2 = 0.11, \epsilon_2 = -0.33, \end{align*}
\]

where \( \epsilon_2, \delta_2 \) and \( \gamma_2 \) are Thomsen parameters for a vertical transversely isotropic medium. The \( \epsilon_2=0.33 \) Poisson value does not provide grounds to predict gas presence within the section interval being analyzed.

The \( \sigma_2=0.33 \) value derived from Backus equations does not coincide with what has been computed using the AVO-inversion \( (\sigma_2=0.3) \). 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):

\[
R_{pp} (\theta) = R_{pp}^{\text{iso}} + \frac{1}{2} \Delta \sigma \sin^2 \theta ,
\]

where \( R_{pp}^{\text{iso}} \) is the P-wave reflection coefficient for an isotropic medium, \( \Delta \sigma = \epsilon_2 - \delta_2 \). A negative parameter \( \Delta \sigma \) 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 periodical TLS the following is valid:

- \( \epsilon_2 \) 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 \( \sigma_2 \neq \sigma_1 \), which is also valid for the Yu model.

It is also important to note that the condition \( \epsilon_2 \leq 0 \) 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 $\sigma_2=0.12$, 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 $\sigma_2=0.06$, 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 $\eta$ and Poisson’s coefficient in layers. In this case the conditions $\alpha_1/\rho_1=\alpha_2/\rho_2$ and $\alpha_1/\sigma_1=\alpha_2/\sigma_2$ 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 sandstone. With the 50 Hz wavelet (tuning thickness) for a given TLS, favorable conditions occur for predicting multi-layer hydrocarbon reservoirs (tuning thickness) for a given TLS, favorable conditions occur for predicting multi-layer hydrocarbon reservoirs from AVO-analysis. At the same time, 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.

**Acknowledgements**

We would like to thank Dr. Michael Burianyk of Shell Canada Limited and Dr. Yuriy Tyapkin of Ukrainian State Geological Prospecting Institute for their reviewing our paper and providing us with advice on the matter.

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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

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.
REFERENCES
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