Vp-Vs ratio versus effective pressure and rock consolidation – a comparison between rock models and time-lapse AVO studies

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Summary

The Vp to Vs ratio is a key parameter in seismic AVO analysis, and especially for lithology and fluid prediction methods this parameter plays a key role. For pressure prediction methods, the key parameter is Vp, since an overpressure often results in a drop in the P-wave velocity. However, for AVO-based pore pressure prediction methods, one must expect that the Vp to Vs ratio also is a key parameter for pressure prediction. The Hertz-Mindlin geomechanical model predicts a constant Vp-Vs ratio as the effective pressure changes. Ultrasonic rock physics measurements show increased Vp-Vs ratio as the effective pressure decreases, especially for unconsolidated sands. It is therefore likely to assume that in addition to pore pressure variation, the Vp to Vs ratio is also related to the degree of rock consolidation. By combining the Hertz-Mindlin model with the Gassmann model we show that it is possible to obtain a simple rock physics framework containing both the effective pressure and the degree of rock consolidation. We use the number of contact points per grain material to represent the rock consolidation. For two field examples, we calibrate this consolidation parameter for the in situ stress conditions, and then compare the predicted Vp to Vs ratios for the over-pressured reservoir conditions with the observed changes in time-lapse AVO. The correspondence between modeled and AVO-estimated Vp to Vs ratios is good within the assumed accuracy of the observed time-lapse AVO-changes. In both cases we observe AVO-changes that indicate a slight increase in Vp-Vs ratio as the effective pressure is decreasing. In the first case, a pore pressure increase of 5-7 MPa was measured, while the other case shows a pore pressure increase up to 10 MPa. The first reservoir represents a low to medium consolidated sandstone reservoir of 33 % porosity, while the second reservoir has slightly more consolidated sands with similar porosities (35%).

Introduction

From various rock physics studies (Huffman and Castagna, 2001; Prasad, 2002) it has been shown that the Vp-Vs ratio is increasing with decreasing effective pressure (or net pressure). Siggins and Dewhurst (2003) find a distinct difference between ultrasonic measurements on dry and oil saturated core samples: The Vp to Vs ratio increases with decreasing differential pressure in the oil saturated case, while a decrease is observed for the dry core material. The last observation is in contrast to the core data that will be used in this paper, where a slight increase in Vp to Vs ratio is observed for dry core samples. Huffman and Castagna (2001) show that the Vp to Vs ratio variation with effective pressure is strongly dependent on the clay content of the rock sample, the increase is weaker for increased shale content. The main effect leading to the strong increase in Vp-Vs ratio for low effective pressures is that the shear wave velocity (Vs) is approaching zero. Prasad (2002) measures S-wave velocities in the order of 300 m/s, and a corresponding P-wave velocity of 1750 m/s. Other measurements (Capello and Batzle, 1997) show a flat response for the Vp-Vs ratio as a function of effective pressure. The degree of cementation of the rock might be one explanation for these variations in observed behavior. Damage of the core sample due to unloading and reloading is another issue that might explain such differences. It is reasonable to assume that this effect is more pronounced at small effective pressures, than for higher effective pressures. Therefore, it might be useful to compare ultrasonic core measurements with other types of measurements, as for instance 4D seismic. Time-lapse seismic surveys might be a complementary tool to study how the Vp-Vs ratio varies as a function of effective pressure, and this is the focus in this paper. In a specific segment at the Gullfaks Field (North Sea), a significant pore pressure increase (caused by water injection) was measured. The measured pore pressure (RFT measurement in the well) increased from approximately 32 to 39 MPa between the base and monitor survey, corresponding to an assumed drop in effective pressure of about 7 MPa. An example on how time lapse AVO analysis can be used to discriminate between pressure and fluid changes in this segment is discussed by Landrø, 2001. Another example demonstrating how time shift analysis can be used to interpret pressure variations with depth is shown in Landrø et al., 2001. In a second field example from the Statfjord Field (Rognø et al. 1997), pore pressure increases up to 12 MPa are measured, and observed on the time lapse seismic data. By studying changes in AVO over production time, we will use these two field examples to study how the Vp-Vs ratio varies when the pore pressure increases.

The combined Hertz-Mindlin and Gassmann model

Various contact models have been proposed to estimate effective modulus of a rock. Some of these models are presented by Mavko, Mukerji and Dvorkin in their rock physics handbook, 1998. The Hertz-Mindlin model (Mindlin, 1949) can be used to describe the properties of pre-compacted granular rocks. The effective bulk (K_{eff}) and shear modulus (G_{eff}) of a dry random identical sphere packing are given by

$$K_{eff} = \left\{ \frac{C_p^2 (1-\varphi)^2 G^2 P}{18\pi^2 (1-\nu)^2} \right\}^{\frac{1}{3}} \quad ;$$

$$G_{eff} = \left\{ \frac{3C_p^2 (1-\varphi)^2 G^2 P}{2\pi^2 (1-\nu)^2} \right\}^{\frac{1}{3}} \frac{5-4\nu}{5(2-\nu)} , \qquad (1)$$

where ν and G are the Poisson's ratio and shear modulus of the solid grains, respectively, φ is the porosity, C_p is the average number of contacts per grain and P is the effective or net pressure (that is $P=P_{eff}$). The P and S wave velocities are given as

$$V_P = \sqrt{\frac{K_{eff} + \frac{4}{3} G_{eff}}{\rho}} \quad ,$$

$$V_S = \sqrt{\frac{G_{eff}}{\rho}} \quad , \qquad (2)$$

where V_P and V_S are P-wave velocity and S-wave velocity, respectively, ρ is the sandstone density. Inserting equations (1) into equations (2) yields that the Vp-Vs ratio is equal to 1.4 (square root of 2). This means that according to the simplest granular model (Hertz-Mindlin), the Vp-Vs ratio should be constant as a function of effective pressure. In the limit where the effective pressure approaches zero, the P-wave velocity should at least equal the water velocity. Therefore, a simple way to obtain more realistic Vp/Vs-ratios for low effective pressures is to combine the Hertz-Mindlin (dry rock) model with the Gassmann (1951) model to account for the effect of fluid saturation.

Calibration of the combined rock physics model

The Vp to Vs ratio for a typical oil saturated sand at Gullfaks is approximately 1.9 for initial stress condition (Figure 1). The first step in the calibration procedure is to fix the solid rock shear modulus G, and we used a value of 44 GPa. Furthermore, we assume that the grain material is quartz sand, and therefore a Poisson ratio of 0.07 was used in equation (1). Figure 2 shows how the Vp-Vs ratio varies with respect to the degree of rock consolidation (represented by the number of contact points per grain, C_p) and effective pressure. For the Cook reservoir at Gullfaks, the initial effective pressure is estimated to be around 6 MPa. Based on calibration (Figure 2) we found that C_p=6 matched this observation. According to the ultrasonic core measurements (dry cores) the Vp to Vs ratio for the two samples representing the Cook Formation is equal to 1.7 at 6 MPa effective pressure and 1.9 at 2 MPa effective pressure. The measured pore pressure increase is around 6 MPa, which means that the effective pressure at the time of the monitor survey is likely to be close to zero. According to the calibrated rock physics model, this should correspond to a Vp-Vs ratio around 2.5.

Comparison between two-layer Zoeppritz modeling and time lapse AVO

To compare the predicted Vp to Vs ratios with observed AVO changes, a simple two-layer Zoeppritz-modeling was used, based on well data, see Table 1. The shale sequence shown in Figure 1, represents the shale above the Cook reservoir, and therefore a Vp-Vs ratio of approximately 2.6 was chosen for layer 1 for the AVO modeling. In addition to the baseline situation, three monitor situations were modeled: One representing no change in Vp to Vs ratio (Vp/Vs = 1.9), another representing Vp/Vs = 2.8 (Figure 2) and a third one representing Vp/Vs = 10. All modeling results are summarized in Figure 3, where also the observed amplitude changes from the real time-lapse seismic data are shown (stars). RMS-amplitudes were computed for 46 traces, derived within a 60 ms window around the top reservoir interface. Standard deviations were calculated, and the vertical bars indicate ± one standard deviation. A global scalar (derived from well-tie) of 0.000017 was applied to the real data. Based on comparison between real and modeled AVO behavior, it is likely to assume that the Vp-Vs ratio is above 3, caused by the over-pressure. According to the calibrated rock physics model (Figure 2) a Vp-Vs ratio around 3 is expected, while the seismic observations suggest a slightly higher Vp/Vs-ratio.

Discussion and conclusions

A lot of uncertainties need to be addressed when comparing time-lapse AVO data with two-layer Zoeppritz-modeling: First of all there is an uncertainty coupled to the properties of both sand and shale. Furthermore, the individual scaling of the near, mid and far offset stacks is uncertain. Although we corrected for the dip angle of the top reservoir interface, there might still be some uncertainties related to the estimation of the incidence angles for the offset stacks. Using the number of contact points per grain (C_p) as a calibration parameter in the Hertz-Mindlin model and coupling the Hertz-Mindlin model to the Gassmann model is a straightforward way to obtain a model that can be used to link seismic and rock parameters. Based on the dry rock core measurements we have observed that the Hertz-Mindlin model predicts the Vp-Vs ratio more accurate than for instance the Vp or Vs velocity. For the Gullfaks case, we estimate C_p=6, which is indicating a loosely consolidated sand. The combined rock physics model has been tested for two North Sea fields, close to injector wells showing significant pore pressure increases.

Based on comparison between a calibrated rock physics model and time-lapse AVO data, we conclude that the Vp-Vs ratio increases significantly as the reservoir pressure increases. This effect is more pronounced for low effective pressures.

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Table 1: Seismic parameters used in the two-layer modeling, Gullfaks. P-wave velocity and density values (pre-production) were taken from the well logs, while the S-wave velocity was computed based on a Vp-Vs ratio from another well. (No S-wave logs were available within the actual segment). The monitor P-wave velocity decrease caused by the pore pressure increase was assumed to be 15% in this example.

	Vp(m/s)	Vs(m/s)	Density (kg/m^3)	Vp/Vs-ratio
Layer 1	2600	1000	2300	2.6
Layer 2 (baseline)	2500	1315	2100	1.9
Layer 2 (monitor 1)	2125	1118	2100	1.9
Layer 2 (monitor 2)	2125	850	2100	2.5
Layer 3 (monitor 3)	2125	212	2100	10

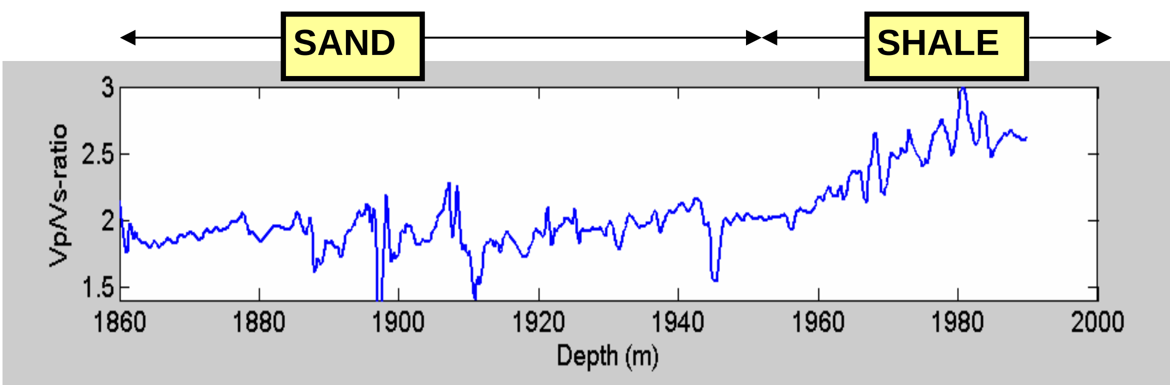

Figure 1: Vp-Vs ratio versus depth for oil saturated rock at in-situ pressure conditions. Notice that the top Cook sand is not logged in this well (top Cook is at approximately 2050 m).

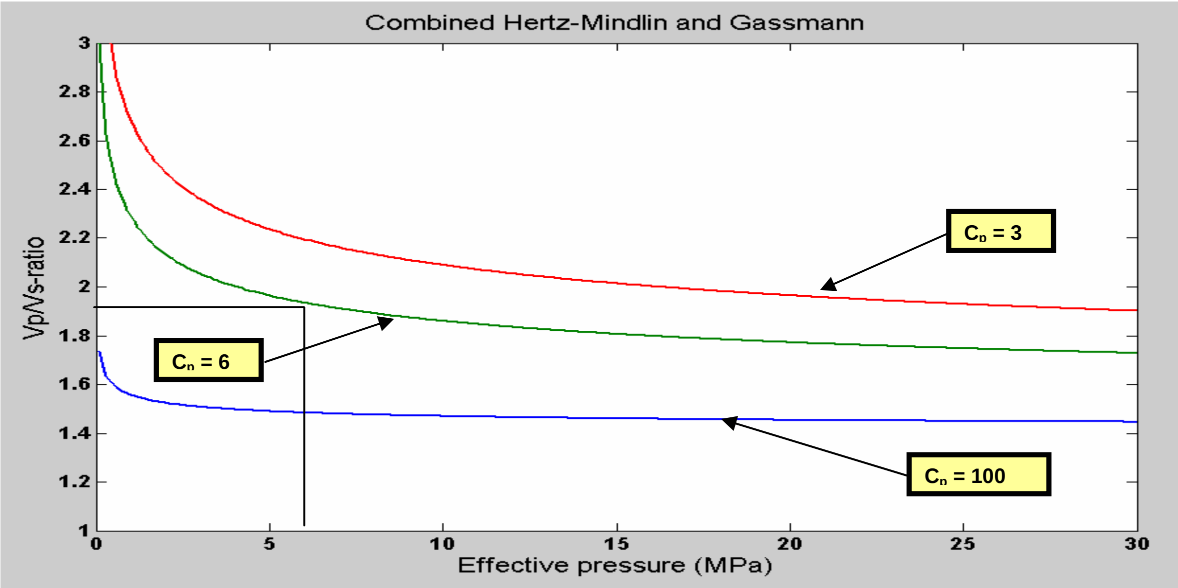

Figure 2: Combined Hertz-Mindlin and Gassmann modeling of Vp-Vs ratio for various values of rock consolidation (C_p) levels.

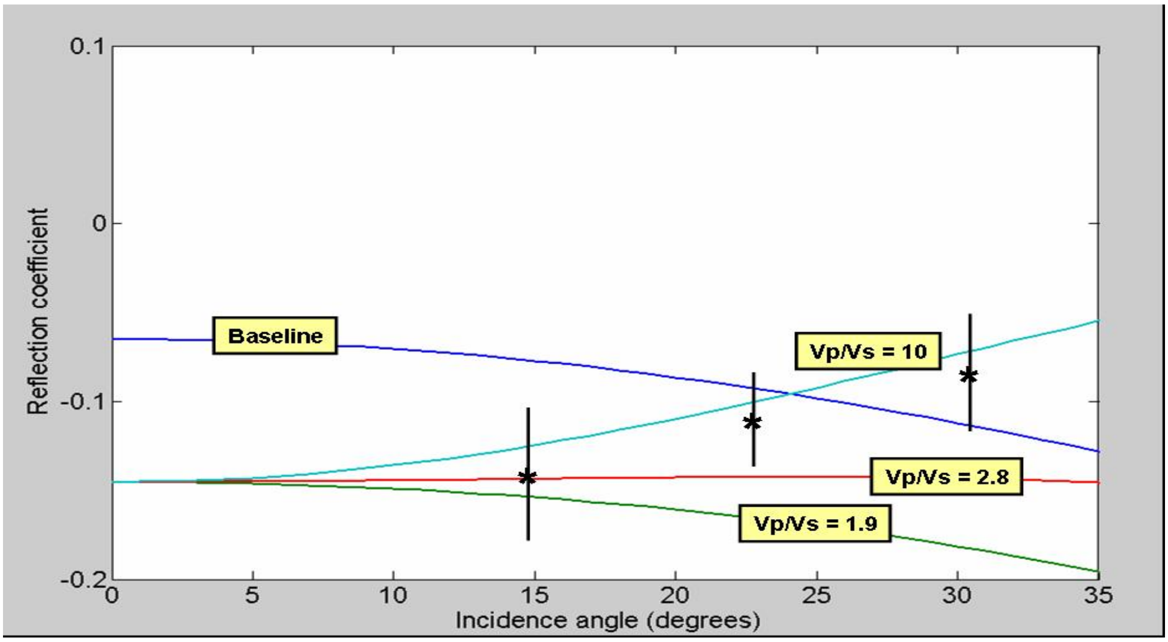

Figure 3: Comparison between two-layer Zoeppritz-modeling and time-lapse AVO data from the Gullfaks Field, assuming various Vp/Vs-ratios for the monitor. Stars denote average RMS-values, and solid bars represent +/- one standard deviation. The solid green line shows the monitor survey assuming a 15% drop in P-wave velocity (see Table 1).