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Elastic Anisotropy Soft Porosity Model for Sands and Shales

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Summary

We have developed an anisotropic elastic rock physics model which models a continuum between sands and shales. The model uses both the joint SCA/DEM model and the Hudson model to add stiff and aligned soft pores in the rock frame. The model adjusts the aspect ratio and quantity of the soft pores to control the anisotropy of the rock. The initial stiffness of the rock is controlled by the biconnected porosity point (used by the SCA/DEM model) of the rock frame allowing both sands and shales to be modelled. The model has been tested against sand and shale data from well logs in the Barents Sea, where an accurate fit between the model and well log data was obtained.
Introduction

Most rocks display some level of elastic anisotropy. In the past, the emphasis has been on conventional reservoir rocks, where anisotropy is low and isotropic rock physics models do well. Recently, more work has been focused on non-conventional rocks, including shales which display varying amounts of anisotropy. Isotropic models in these type of sediment fail to describe the rock fully and can lead to misinterpretation of geophysical data. There are only a few anisotropic rock physics model described in the literature most of which have been tested only on laboratory data and not well log or geophysical data. These models are predominantly inclusion type models and include the Differential effective medium (DEM) model, as formulated by Norris (1985), the Self Consistent, Approximation (SCA), as formulated by Berryman (1980) and the Hudson (1980) crack model. In this project we have developed an anisotropic rock physics model which can model both sands and shales with varying levels of anisotropy. The model has been tested on well log data from the Barents Sea. Well log data was used rather than laboratory data because anisotropy laboratory data is not routinely collected or used for exploration purposes.

Rock physics model

Ruiz and Cheng (2010) proposed a model in which the effective medium has two types of porosity, stiff round pores and soft crack-like pores. This model was initially proposed for tight gas sands. When tested against sand and shale well log data from the Barents Sea this model preforms poorly. We have adapted the model to allow for anisotropy and softer sediments. The Ruiz and Cheng model starts with a solid background calculated using a Hill average for the solid component of the sediment. Into this, stiff inclusions/pores are added (aspect ratio = 1) using the SCA model. Additional inclusions can then be added using the Eshelby-Cheng model (Cheng 1993) for cracks. The model assumes an isotropic background and an idealized ellipsoidal crack shape. It also assumes low crack concentrations but can technically handle all inclusion aspect ratios. The model assumes that the cracks are randomly orientated, while this is acceptable for tight gas sands it is rarely the case for rocks such as shales where strong anisotropy is often observed.

We have improved this model in two principal ways so that the model can be used for both sands and shales (Figure 1). First, by replacing the Eshelby-Cheng model with the Hudson (1980) model for cracks. This allows us to include aligned cracks in different orientations (three orthogonal directions). It further allows more complex anisotropy to be modelled, as different numbers of cracks can be added in different directions. The model is therefore not limited to VTI media but can model an orthorhombic system.

When this initial adaptation was tested against field data we found that the model overestimated the elastic moduli for most shales. In order to correct this, we replaced the SCA model with the joint SCA/DEM model (Hornby, 1990). The SCA/DEM model calculates effective properties of a two-phase medium using the SCA model at a porosity ($\phi_B$) where the medium is biconnected (both phases are interconnected). The DEM model is then used to calculate the effective properties at all other porosities using $\phi_B$ as a starting point. This allows a bi-connected medium to be calculated at all porosities. By changing $\phi_B$ in the model the initial rock stiffness can be adjusted. When using the SCA/DEM model different facies types require different $\phi_B$ (Ellis, 2008). The model has been fitted to the measured data by changing $\phi_B$ for different clay volumes. Detailed analysis of the $\phi_B$ shows three distinct zones. The sands require low $\phi_B$ until approximately 35 % clay volume. After this a transition zone is entered where $\phi_B$ increases with clay volume. At approximately 65 % clay volume a single high $\phi_B$ can be used (Figure 2).
Figure 1 Workflow showing the adapted soft porosity model for soft anisotropic rocks.

Figure 2 Change in $\phi_B$ with clay volume at well 7324/8-1

Data

In order to test the anisotropic model elastic anisotropic data is needed. While this information can be obtained in the laboratory, it is harder to obtain from the field, where different well logging tools and mathematical procedures are necessary. In the well, anisotropy can be estimated from dipole shear data and the Stoneley wave data with the tube wave equation. Assuming a VTI medium, dipole shear data can be used to estimate the C44 and C55 tensors of the elastic stiffness matrix. To estimate the C66 element, the Stoneley wave can be used. The Stoneley wave is sensitive to fractures and formation permeability, and can be used to estimate these two properties. The Stoneley wave can be treated as a tube wave and estimate the C66 tensor of the formation using the following equation (White, 1983):

$$V_T = V_f \left(1 + \frac{K_f}{\mu_f}\right)^{-1/2}$$

where $V_T$ is the Tube velocity (Stoneley wave velocity), $K_f$ is the fluid bulk modulus and $V_f$ is the fluid velocity. When the anisotropy symmetry axis is coincident with the borehole axis, $\mu^{*}(0) = C_{44}(1+2\gamma) = C_{66}$ (White, 1983).

When using this method the following assumptions are made:

- The rocks are weakly anisotropy
- The borehole is vertical
- The earth is VTI
Comparison of model with data

The model was tested against several wells from the Barents Sea, and the results from well 7324/8-1 are shown in Figure 3. We allow the model to fit the measured Vp33, Vs44, Vs55, Vs66 data by adjusting the ratio between the stiff and soft pores, aspect ratio of the cracks and the orientation of the cracks. Using this model we are able match both the measured P-wave and S-wave velocities (Figure 3). There are a few areas where the velocity misfits increase. This mainly occurs in the reservoir where we are unable to fit the data and the model gives lower Vp33 and Vs44 values and higher Vs66 values. This misfit maybe due to how the hydrocarbon has been distributed in the pores in the model. We also get an accurate fit to the Thomsen (1986) and Tsvankin (1997) Gamma parameters (Figure 3). Figure 3 shows how the crack porosities are distributed in the different directions. In the shale facies the crack porosity in the Z direction (horizontal cracks) is high. This is not unexpected as these sediments have strong anisotropy and where Vs66 is larger than Vs44. As we move into the more sand dominated sediments the crack porosity in the Z direction decreases and it increases in the X and Y directions. It should be noted that the model often reaches the maximum allowed crack density (set at 0.2) and the maximum aspect ratio (set at 0.1).

Conclusions

We have developed an anisotropic rock physics model which is able to model both sands and shales. The model uses both stiff and aligned soft pores in the rock frame. The model adjusts the aspect ratio and quantity of the soft pores to control the anisotropy of the rock. The initial stiffness of the rock is controlled by the initial biconnected porosity point (φB) of the rock frame allowing both sands and shales to be modelled. The model has been tested against sand and shale data from well logs in the Barents Sea where an accurate fit between the model and well log data was obtained. Even though the parameters used in the model are fitting parameters and not probable in all situations they represent real rock features, the model is still an accurate tool to estimate the rock elastic tensor as a function of depth. The model can also be used to model different geologic settings away from the well.

References

Figure 3 Comparison of rock physics model and well log data (well 7324/8-1)