Rock physics modelling in unconsolidated sandstone reservoir based on contact theory method case study: FRR Field, Kutai Basin

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Abstract. The study of rock physics modeling has been successfully carried out in FRR Field, Kutai Basin. This study aims to predict elastic parameters of rock such as \( V_p \), \( V_s \), and density which represent the characteristic of reservoir. The Contact Theory (CT) method was used for conducting rock physics modeling at the unconsolidated reservoir. CT method combines the elastic modulus of Hertz Mindlin at the critical porosity (\( \Phi_c \)) and Hashin Shtrikman Walpole lower bound (HSW-) to interpolate the elastic modulus from the critical porosity to the minerals modulus. Gassman model has been applied to estimate bulk modulus of a fluid-saturated rock with variation water and gas saturation. The data used in this study is log data coming from one well in FRR Field, Kutai Basin. The targeted reservoir was identified as gas sand reservoir that was deposited in the channel complex of turbidity system. Based on the data, the reservoir has the majority of sandstone rock marked by low density and low gamma-ray at the upper part of log data. The results show correlation between elastic properties estimation and log data with the correlation of \( V_p \) was 0.66; \( V_s \) was 0.53; and density was 0.99. This result was indicated that the CT method successfully predicts elastic parameter in unconsolidated sandstone reservoir of the FRR Field, Kutai Basin.

Keywords: Rock physics, contact theory, unconsolidated sandstone reservoir, Gassman model

1. Introduction

Nowadays, hydrocarbon exploration is more challenging, many of hydrocarbon finds in stratigraphic play. It is necessary to characterize the reservoir in a more quantitative subsurface interpretation. Rock physics modelling is one of the methods that could be used to characterize the reservoir quantitatively. When predicting the elastic parameters of a reservoir at least three information are needed; 1) the volume fractions of the various constituents, 2) the elastic moduli of the various constituents, 3) the geometric details of how the phases are arranged relative to each other [1]. The third factor emerges several approaches of rock physics models. There have been many different models of rock physical properties. Each model that has been developed is limited by the type of lithology, porosity range, texture complexity, saturation conditions, and pore fluid dynamics. Rock physics theory provides a link between the elastic properties and the reservoir properties (e.g. porosity, constituent properties, and fluid saturation) [2]. This advantage makes the rock physics as prominent tools for the reservoir characterization.
FRR Field is in the Kutai Basin. Kutai Basin which the most productive of a sedimentary basin in Indonesia. Kutai Basin structurally surrounded by Mangkalihat high in the north, Adang Fault Zone in the south, Sundaland in the west, and Malaka Strait in the east. The targeted reservoir in FRR field is gas sand that was formed by slope deep water channel in Pliocene. The reservoir characterized by elastic parameters of low P-wave velocity and low density that was predicted using rock physic modelling.

2. Methodology

The Contact Theory (CT) is one approach to estimates the rock physics model of reservoir with forward modeling. CT method is used to characterize unconsolidated sandstone reservoirs and at relatively shallow depths [3]. From this method, we can estimate physical behavior of rock such as bulk modulus, shear modulus, and density. The CT method combines the critical porosity ($\Phi_0$) Walton model (1987) [4] and Hashin-Shtrikman-Walpole lower bound (HSW') [5] to interpolate the effective properties of minerals. For fluid-saturated rock (whether gas or water), Gassman model has been applied to estimate bulk modulus with variation water and gas saturation. This research is based on rock physics modelling to characterize the reservoir based on contact theory. Rock physics modelling was conducted by the following steps:

2.1. Hashin-Shtrikman (HS) bounds

The optimal bounds for a perfect elastically isotropic composite are the Hashin-Shtrikman (HS) bounds [4]. Hashin-Shtrikman lower bound (HSW') to interpolate the effective properties of minerals. Hashin-Shtrikman lower bounds given by equation 3.

$$K^{HS} = K1 + \frac{V2}{(K2 - K1)^{-1} + V1(K1 + \frac{4\mu1}{3})^{-1}}$$ (3)

where the bulk modulus $K$ and volume fractions $V$ have indices 1 and 2 that correspond to the stiffest and softest material respectively, i.e. $K1 < K2$ and $\mu1 < \mu2$. 

While the shear modulus for dry rock grains is:

$$\mu^{HM} = \frac{5 - 4\nu s}{10 - 5\nu s} \sqrt{\frac{3C0^2(1 - \Phi 0)^2\mu s^2)Pr}{2\pi^2(1 - \nu s)^2}}$$ (2)

where $\Phi_0$, $\mu$, and $\nu$ are critical porosity, shear modulus and Poisson's ratio of rocks.
2.2. Gassman estimation

Gassman theory often used in approaches to fluid substitution [7]. The Gassman equation relates the saturated bulk modulus of the rock to the porosity, the fluid bulk modulus, the matrix and mineral bulk modulus. This theory can be mathematically written as shown by equation 4.

\[
K_{sat} = K + \frac{1 - \frac{K}{K_0}}{o} + \frac{(1 - o)}{K_0} + \frac{K}{K_0}
\]  

(4)

3. Results and discussion

The log data is a petrophysical log of one well coming from FRR Field as shown in figure 1. This log contains seven types of log from left to the right are, density, gamma-ray, porosity, P wave velocity (Vp), S wave velocity (Vs), volume of shale, and water saturation. Log interval varying from 1970 m until 2400 m, with the most interest zone interval around 2040–2075 m that are indicated by red square. The interesting zone was confirmed as gas sand by the well test data. The reservoir has a low density, and low Vp with the high Vs. The elastic parameter of Vp, Vs, and density would be predicted using the rock physic modeling of the contact theory method.

Based on the log data, the analysis was focused on the interest zone and the overlying shale layer which lies in the depth range of 1970–2075 m. A scatter plot between elastic modulus (Bulk modulus and shear modulus) versus porosity with a color range of shale volume was used to analyze the character of the zone of interest as shown in figure 2. From the scatter plot the shale bulk modulus has a higher value than sand lithology (figure 2a), whereas for shale shear modulus has a relatively the same value as the sand lithology (figure 2b). Furthermore, it can be obtained that the decreasing in porosity made the bulk modulus increased.

![Figure 1. Log Data FRR Field, Kutai Basin, the red square indicates the interest zone.](image-url)
The subsequent analysis is carried out by overlaying the scatter plot with the rocky physical modeling curve as shown in figure 3. There are 11 curves of rock physics elastic modulus modeling which was derived based on CT using quartz and fluid fraction with variations of clay proportion in ranging from 0 % to 100 % with 10 % increment. This method combines critical porosity ($\Phi_c$) Walton model (1987) and Hashin Shtrikman Walpole lower bound (HSW−) to interpolate the effective properties of minerals. The trend correlation between the bulk modulus estimation curve with the distribution of log data is good enough, so, we can develop a model of subsurface rocks that are saturated by the fluid (gas/water) based on the Gassmann equation. The Gassmann equation gives result of bulk modulus with pores already filled fluid. In the research using gas and water saturation with clay composition to derive elastic modulus cube.

Cube elastic modulus resulting from the Gassman equation was shown in figure 4. Cube elastic modulus is a variation of elastic modulus as a function of reservoir parameters consisting of porosity, shale volume, and water saturation. On the X-axis is a porosity parameter that varies from 0–40 %,
the Y-axis is a shale volume varies from 0-100 %, and the Z-axis is a water saturation varies from 0–100 %. Bulk modulus is shown in figure 4a, shear modulus figure 4b and density figure 4c. The range of bulk modulus ranges from the smallest value of 0.0028 GPa and a maximum of 37.9 GPa (quartz bulk modulus). Shear modulus has a range of values from 0 GPa to 44.3 GPa (quartz shear modulus), and for the density range has a variation from 1.5 gr/cc to 2.65 gr/cc. Using the petrophysical data that consists of shale volume, porosity and water saturation, the prediction parameters of Vp, Vs, and density has been done.

The predicted results of the three elastic variables are shown in figure 5. Based on figure 5, we can obtain the correlation coefficient between estimation and log data. The trend shows that the correlation between predicted logs and measured logs have a coefficient correlation of Vp was 0.6552, Vs was, 0.5310, and Density was 0.9892. The log density prediction results give the best results and correlations because the density predictions only account for the fraction of each mineral and fluid that formed the reservoir. This is different from Vp and Vs which require several steps to get the elastic bulk modulus and shear modulus. Furthermore, what can be observed from Figure 6a is the predicted result of Vp in the reservoir was lower compared to the Vp obtained from the measurement, it may be due to the use of bulk modulus gas that is too low. This was caused by there is no information related to the gas bulk modulus in the reservoir of the FRR Field.

Figure 4. 3D cube model of (a) Bulk modulus, (b) Shear modulus, (c) the density with variation of clay, porosity, and gas saturation.
4. Conclusion
Rock physics modelling based on CT method has been successfully conducted to characterize the unconsolidated reservoir in FRR Field, Kutai Basin. This was indicated by the elastic modulus curve with the log data distribution has a strong correlation, although there is still some misfits. Based on the scatter plot the shale bulk modulus has a higher value than sand lithology. This result was influenced by the effect of porosity, where the decreasing in porosity made the bulk modulus increased and the shale has low porosity. The resulted of $V_p$, $V_s$ and density prediction has a good correlation with the coefficient correlation of $V_p$ was 0.6552, $V_s$ was 0.5310, and density was 0.9892. Furthermore, the predicted result of $V_p$ in the reservoir was lower than the measurement, it may be due to the use of bulk modulus gas that is too low, caused by there is no information related to the gas bulk modulus in the reservoir of the FRR Field.

Acknowledgments
This work was financially supported by Universitas Indonesia under research grant PUTI Saintekes with grant contract number NKB-2398/UN2.RST/HKP.05.00/2020.
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