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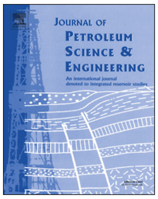

Development of lithology-based static Young's modulus correlations from log data based on data clustering technique

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ABSTRACT

The static Young's modulus is one of the most important geomechanical parameters that are used in the evaluation of the wellbore stability during drilling operations. The static Young's modulus is also important during the design of the hydraulic and acid fracturing operations for conventional and unconventional reservoirs. Static Young's modulus also is important in the evaluation of the in-situ stresses profiles and it can be used to evaluate the reservoir pressures. The existing correlations that determine the static Young's modulus either depend on the dynamic Young's modulus or compressional shear velocity. No previous studies considered the different log parameters to estimate the static Young's modulus. Some of the previous correlations were developed for specific type of lithology and did not consider the lithology variation within the single well.

In this paper and for the first time we developed correlations for the static Young's modulus from the log data based on clustering technique. More than 300 measured static Young's modulus values were correlated to the log parameters such as shear transit time, compressional transit time, and bulk density. Using R-project statistical software the clustering was performed for the measured data along with the corresponding log data. Six clusters were identified based on the shear transit time because it has the highest relative importance to the measured static Young's modulus. Six correlations were developed for the six clusters that can be used to determine the static Young's modulus based on the log data. The developed correlations were tested on three cases from the field given the measured core data for each case.

The developed correlations based on clustering predicted the static Young's modulus perfectly when compared to the measured one for three different cases with different lithology sets. Other correlations did not match the measured static Young's modulus and bad match was obtained in several cases . Log parameters such as shear transit time, compressional transit time, and bulk density showed high relative importance to be included in the correlations that predict the static Young's modulus. Data clustering is a good method to apply to obtain better match between the estimated and measured static Young's modulus.

1. Introduction

Having successful drilling and hydraulic fracturing operations needs a complete description and analysis for the in-situ stresses. In-situ stresses profiles are important to maintain the wellbore integrity either during drilling or stimulation processes to avoid the wellbore stability problems. Petrophysical and mechanical parameters should be assessed and integrated to design a successful drilling and hydraulic fracturing program (Nes et al., 2012). Nes et al. (2012) developed an integrated model that combines several fluid and rock parameters including the rock mechanical parameters. Their model can be used to design and predict drilling problems related to wellbore instability.

Hydraulic fracture modelling and geometry is a strong function on the stress-dependent Young's modulus. Meyer and Jacot (2001) carried out numerical simulation to evaluate the stress-dependent modulus in soft rocks. They found out that as the Young's modulus of the rock increases the fracture net pressure and fracture height increase. The analytical and numerical models carried out by Meyer and Jacot (2001) showed that the stress-dependent Young's

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modulus had major impacts on the fracture geometry and fracture parameters such as fracture propagation and height.

The success of the multi-stage fracturing in horizontal wells in unconventional reservoirs depends on the correct characterization of reservoir petrophysical and geomechanical properties (Sun et al., 2015). Sun et al. (2015) found out that good reservoir description (petrophysical and geomechanical properties) coupled with the optimized completion design gave 30% extra production rate in a well compared to an adjacent well completed with simple geometrical design.

The lack of understanding the geomechanics may lead to ineffective multi-stage fracturing in unconventional shales. Sebastian et al. (2015) developed a toolkit that can handle complex parameters such as stress shadow, fracture rotation, interaction with natural fracture, etc., coupled with 3D unconventional reservoir simulator. They compared the completion design developed by the new toolkit and the standard one and they found that 30% increase obtained in the production rate due to the enhanced completion design. Other methods were used to enhance the completion design efficiency in Eagle Ford shale such as fiber optics (Cadwallader et al., 2015). Fiber optic data provides real time information for the fracturing operations and cementing operations in unconventional shale reservoirs.

Geomechanical parameters such as Young's modulus and Poisson's ration have strong impact of the design of the multi-stage fracturing in unconventional shale gas reservoirs. Wang et al. (2015) developed a coupled model that combines the geomechanics and multi-phase flow in shale. The model can be used to simulate the stresses and fluid flow to help better design and complete the fractures in shale gas reservoirs.

The accuracy of the determination of Young's modulus can greatly impact the results of numerical simulations modelling for the geologic materials. Hammah et al. (2006) investigated the effect of Young's modulus on the stress distribution, rock deformation patterns, and rock failure mechanisms. They concluded that the variation in the Young's modulus led to wide range of behaviors in other mechanical parameters such as stresses. They carried out their model using finite element modelling for several cases.

The damage around the wellbore can be modelled and evaluated in the case that the Young's modulus profile around the wellbore is given. Nawrocki and Dusseault (1996) developed a model to estimate the stresses variation around the borehole given that the Young's modulus varies radially with a specific correlation. The change in Young's modulus in radial direction around the wellbore resulted from the drilling operations due to stress redistribution and other mechanical parameters such as cohesion and friction angle. Their model matched the previously developed model that described the change of the stress regime around the wellbore during the drilling and fracturing operations.

Young's modulus can be determined using several methods; John et al. (1989) used the AVO inversion (Amplitude Variations with Offset) to determine the rock mechanical properties such as Poisson's ratio, bulk modulus, shear modulus, and Young's modulus. The used seismic data and invert it numerically using the AVO inversion technique to determine the rock elastic parameters. Also, they were able to relate the reservoir pressure to the Young's modulus because the Young's modulus is pressure dependent and they developed the following correlations for water and gas saturated sandstone formations:

$$P = 33073 + 46001E_{brine} - 21799E_{brine}^2 + 3577E_{brine}^3 \tag{1}$$

$$P = 11531 + 19147E_{gas} - 10601E_{gas}^2 + 2001E_{gas}^3 \tag{2}$$

where P is the reservoir pressure, kPa; E is the Young's modulus, N/m^2.

Young's modulus can be determined in the laboratory using the uniaxial compression experiments. In these experiments the axial pressure is increased during the confining pressure remains constant. Then Young's modulus can be determined as follows from the stress strain curve:

$$E = \frac{d\sigma}{d\varepsilon} \tag{3}$$

where $d\sigma$ is the change in the stress and $d\varepsilon$ is the change in the strain.

Young's modulus can be determined from the rock acoustics as follows:

$$E_{dynamic} = \frac{\rho V_s^2\left(3V_p^2 - 4V_s^2\right)}{V_p^2 - V_s^2} \tag{4}$$

where ρ is the rock density; V_s is the shear acoustic wave velocity; and V_p is the compressional acoustic wave velocity.

Casper Olsen and Fabricius (2006) carried out laboratory experiments to determine the Young's modulus of North Sea chalk formations. They used two techniques to measure the Young's modulus; the first one was acoustic measurements and the second one was the uniaxial compression test with LVDT and strain gauges. They found out that the uniaxial compression test matched the acoustic measurements when strain gauges were used. They showed that using LVDT in the compression test underestimated the Young's modulus and therefore they are not recommended to be used in these kinds of tests. Acoustic measurements and uniaxial tests measurements using strain gauges are reliable methods to determine static and dynamic Young's modulus.

Banik et al. (2010) estimated the Young's modulus from the inversion of the acoustic impedance obtained from the seismic data. They calculated the Young's modulus from the acoustic impedance only no conversion is needed for the rock density, shear impedance, or Poisson's ratio.

Several models were developed to calculate static Young's modulus. Amon these models is the Gassmann equation, in which the static and dynamic Young's modulus can be calculated as follows (Takahashi and Tanaka, 2012):

$$E = \frac{9KG}{3K + G} \tag{5}$$

where K is the bulk modulus and G is the shear modulus.

Al-Anazi et al. (2011) used the Alternating Conditional Expectation Algorithm (ACE) to predict the Young's modulus of oil and gas reservoirs. They predicted the Young's modulus as a function of depth using the following parameters; laboratory determined porosity, bulk density, overburden stresses, pore pressure, minimum horizontal stress measurements, compressional transit time, and shear transit time. They got high accuracy prediction for the measured and log data they tested.

The Static Young's modulus was correlated to the dynamic one by several correlations. Candy (2011) developed the following correlation that can be used to estimate the static Young's modulus from the dynamic one:

$$E_{static} = \frac{\ln\left(E_{dynamic} + 1\right)\left(E_{dynamic} - 2\right)}{4.5} \tag{6}$$

where E_{static} is static Young's modulus and $E_{dynamic}$ is the dynamic Young's modulus determined from the log data using Eq. (4).

Eq. (6) requires the knowledge of the dynamic Young's modulus first and then the static Young's modulus can be estimated. Several investigators related the static Young's modulus directly to the dynamic Young's modulus such as; Belikov (1970), McCann