An Applied Geomechanics Study of Pore Pressure and Fracture Gradient Model for Well "BEN-1", Pre-Kujung Formation

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ABSTRACT
An exploration well of BEN-1 was drilled to total depth of 1275 m with main target of Pre-Kujung Formation. There were some problems during the drilling, such as caving and lost circulation. The lack of geomechanics study led the creation of a mud program cannot reach the wellbore stability. This paper discusses about the applied geomechanics study to predict pore pressure and fracture gradient model and evaluate the mud program. Wellbore stability can be achieved as the safe mud window follows the common rule of Pore Pressure < Shear Failure Gradient < Mud Weight < Minimum Horizontal Stress < Fracture Gradient < Maximum Horizontal Stress. Analysis results show the pore pressure and fracture gradient model can be predicted using Eaton's method, minimum horizontal stress using pre-existing failure of Mohr-Coulomb method, maximum horizontal stress with tectonic constant of 0.5 (normal fault), and shear failure gradient using modified Lade criterion. Based on the PPFG model, the stable mud weight recommendations are 10.4 – 11.5 ppg at 0 – 540 m depth (20" casing), 8.33 ppg at 540 – 693 m depth (13⅜" casing) with blind drilling, and 9.6 – 11 ppg at 693 – 1245 m depth (9⅝" casing).

Keyword: Geomechanics, PPFG Model, Wellbore Stability

INTRODUCTION
The Well BEN-1 is an exploration well with main target of sandstone and limestone reservoir of Pre-Kujung Formation. During the drilling, there was a lost circulation problem at a depth of 648 m. This problem occurred due to improper mud weight, thus it is necessary to evaluate to get safe mud weight to prevent the occurrence of these problems.

Safe mud weight can be obtained with an approach focusing on the prediction of PPFG model (pore pressure and fracture gradient) and principal stress (minimum horizontal stress, maximum horizontal stress and shear failure gradient). The safe mud window theory is used to design the mud weight according to the subsurface pressure profile. The safe mud window aims to avoid various drilling problems such as loss circulation, tight holes and also wellbore instability

GEOLOGICAL FINDING AND REVIEW Geologically, the well BEN-1 is located in the North East Java Basin where the Kujung Formation has normal regional faults (Hidartan, 2015) and is dominated by hydrostatic pressure (Sapiie et al., 2015). The lithologies drilled by the BEN-1 well from youngest to oldest respectively are the Kujung Formation, Pre-Kujung Formation, and basement. Figure 1 shows the well BEN-1 location in East Java province.

Figure 1: Well BEN-1 location

This formation consists of clay interbedded with limestone at the top. The bottom of the formation was determined at a depth of 150 m where nummulites intermedius does not exist. The Pre-Kujung Formation is divided into 3 parts, namely: 1) the upper formation has a thickness of 146 m (150 – 296 m) which is dominated by claystone with occasional limestone interbedded; 2) the middle formation drilled from a depth of 296 – 1152 m, consists of claystone containing coal, sandstone, siltstone, and occasionally interbedded with limestone; 3) the lower formation consists of sandstone interbedded with claystone, at a depth of 1152 – 1250 m. The lowest formation is a basement consisting of weakly metamorphosed clay and quartz.

DATA AND METHOD
This research begins with the collection of geological and logging data. Geological data consists of fault types to determine the overpressure mechanism. Logging data consists of sonic log, gamma ray log, density log and resistivity log (Figure 2). Logging data is used to predict the subsurface pressure.

Figure 2: Logging data of well BEN-1

ROCK MECHANICS
Rock mechanical properties must be understood to predict these types of pressures or stresses. The rock mechanical properties consist of Poisson's ratio, Young' modulus, friction angle, and cohesive strength.

P-Wave and S-Wave Velocities
Castagna et al. (1985) generated the ratio of compressional or P-wave to shear or S-wave velocity. The Vp/Vs relationship famous established for mudrock line, water saturated siliciclastic rocks composed primarily of quartz and clay minerals (Castagna et al., 1985).

$$Vs = 0.862\,Vp - 1.172$$

where Vp stands for P-wave velocity (km/s) and Vs is S wave velocity (km/s). The rock mechanical properties determination requires P-wave and S-wave velocity data from the transit time of the sonic log which is then calculated using the equation.

Poisson's ratio

If a solid body is subjected to an axial tension, it contracts laterally, on the other hand, if it is compressed, the material expands sidewise (Waliy et al., 2020). So the definition of Poisson's ratio can be stated as the ratio of transverse strain to axial strain induced by unconfined axial deformation (Kumar, 1976). There are several methods to calculate Poisson's ratio using P-wave and S-wave velocity.

Ludwig (1970) firstly proposed a method to calculate Poisson's ratio. Later it is known as Ludwig's empirical fit, as it shown below:

$$\nu = 0.769 - 0.226Vp + 0.0316Vp^2 - 0.0014Vp^3$$

Brocher (2005) proposed a method to calculate Poisson's ratio with an assumption of 1.5 < Vp < 8.5. The equation can be shown below:

$$\nu = 0.8335 - 0.315Vp + 0.0491Vp^2 - 0.0024Vp^3$$

Zoback's common method is the most precise equation for fracture gradient later. The Zoback (2007) equation that is used can be shown below:

$$\nu = 1/2\frac{(Vp^2-2Vs^2)}{(Vp^2-Vs^2)}$$

Young's Modulus

The Young's modulus was computed from the line resulting from the average of the load-deformation curves obtained during a second test (uniaxial compression test) by the usual stress-strain formula (Heindl & Mong, 1936). Fjær et al. (2008) generated an empirical equation of Poisson's ratio from sonic and density log, as shown below:

$$E = \rho V_p^{\,2}\frac{(3V_p^{\,2} - 4V_s^{\,2})}{(V_p^{\,2} - V_s^{\,2})}$$

Friction Angle

Friction angle is a fracture angle formed from the relationship between normal stress and shear stress in the rock. Several studies explained that shales with high Young's modulus will tend to have a high friction angle value as well. Friction angle can be calculated using Lal's method (1999) based on P-wave and S-wave velocity. The Lal (1999) equation that is used can be shown below:

$$\Phi = \sin^{-1}\frac{Vp-1}{Vp+1}$$

Cohesive Strength

Cohesive strength value was obtained from direct shear strength test or triaxial compression test and empirical calculation using P-wave velocity. Empirical calculation of cohesive strength can be calculated using Lal's method (1999). The Lal (1999) equation that is used can be shown below:

$$CS = 5(V_p - 1)(V_p)^{-1/2}$$

PPFG MODEL

Pore Pressure

Eaton (1975) explained that the majority of subsurface pressures come from the effect of overburden. Eaton (1975) relied on transit time data to obtain the Normal Compaction Trend (NCT). The following is Eaton's (1975) equation in predicting pore pressure:

$$Pp = Po - (Po - P_h)\left[\frac{\Delta t_{normal}}{\Delta t_{observed}}\right]^3$$

$$Pp = Po - (Po - P_h)\left[\frac{R_t}{R_n}\right]^3$$

The method developed by Bowers (1995) basically uses almost the same concept as the Eaton's method. However, the equation proposed by Bowers is better than Eaton's, because the Bowers' (1995) equation considers the unloading factor more. According to Bowers, overpressure due to the loading mechanism is characterized by a curve that tends to follow the virgin curve (Zhang, 2011). Meanwhile, unloading will deviate from the virgin curve and form a new unloading curve. Empirically Bowers formulates the magnitude of the pore pressure as follows (Zhang, 2011):

For Bowers' loading mechanism is:

$$P_p = P_o - \left(\frac{\frac{10^6}{DT} - \frac{10^6}{DT_{ml}}}{A}\right)^{(1/B)}$$

and for Bowers' unloading mechanism is:

$$P_p = P_o - (\sigma_{max})^{(1-u)}\left(\frac{\frac{10^6}{DT} - \frac{10^6}{DT_{ml}}}{A}\right)^{(U/B)}$$

$$\sigma_{max} = \left(\frac{\frac{10^6}{DT_{min}} - \frac{10^6}{DT_{ml}}}{A}\right)^{(1/B)}$$

Miller's (1995) exponential method uses sonic velocity and empirically determined parameters to determine the effective stress, which is then subtracted from the overburden to determine the pore pressure. This method can be applied to predict the pore pressure caused by compaction imbalance. In Miller's method, the input parameter is maximum velocity depth (dmax), controlling whether there is an unloading mechanism or not. If dmax is less than the depth, the unloading mechanism does not occur, then the pore pressure can be obtained from the following equation (Zhang et al., 2008):

$$Pp = Po - \frac{(1/\lambda)\ln\left[\frac{\Delta t}{\Delta t_{ml}}\left(\frac{\Delta t_{ml}-\Delta t_{matrix}}{\Delta t-\Delta t_{matrix}}\right)\right]}{D}$$

If dmax is more than depth, it is assumed that a loading mechanism occurs, then the pore pressure can be predicted by the following equation:

$$P_{unloading} = Po + \frac{(1/\lambda)\ln\left[a\left(1 - \frac{\frac{1}{\Delta t}-\frac{1}{\Delta t_{ml}}}{\frac{1}{\Delta t_{matrix}}-\frac{1}{\Delta t_{ml}}}\right)\right]}{D}$$

Fracture Gradient

Hubert & Willis (1957) assumes that fracture gradient is 1/3 to 1/2 of the maximum vertical compressive stress, so that the minimum pressure in a given borehole must be able to withstand the minimum stress of the principal stress. They concluded that the magnitude of the formation fracturing pressure is influenced by the magnitude of the existing principal stress, the borehole geometry, and the penetration of the drilling fluid. However, this method is not very valid if it penetrates the formation with not so many normal active faults. Hubbert & Willis (1957) formulated a formulation to predict the fracture gradient as follows:

$$G_{rf} =$$

Matthews and Kelly (1967) studied a field on the Gulf Coast and empirically analyzed and predicted fracture stresses in that area. According to Matthews and Kelly (1967) the maximum fracturing pressure value obtained is the same as the overburden pressure. The equation for the prediction of the formation fracture gradient gradient is as follows:

Eaton (1969) published an improved method of the Matthews and Kelly method by introducing the Poisson's ratio parameter. Eaton assumes that the Poisson's ratio and overburden pressure are not constant quantities as depth increases. Determination of the fracture gradient (FG) of the formation can be done with the following equation:

Breckels and van Eekelen (1982) developed an empirical correlation for the estimation of fracture gradient as a function of depth. This relationship is based on hydraulic fracture data from various regions around the world. Prediction of formation fracture gradient can be done using the following equation:

$$P_f = 0.197\ D^{1.145} + 0.46\ (P_p - P_n);\ D \leq 11500$$

$$\text{ft}\ P_f = 1.167\ D - 4.596 + 0.46\ (P_p - P_n);$$

$$D > 11500\ \text{ft}$$

Daines (1982) superimposes horizontal tectonic stresses to Eaton's equation which is written in the following equation (Zhang, 2017):

RESULT AND DISCUSSION

The process of selecting the right pore pressure and fracture gradient method is to compare the prediction method used with the validation data. In predicting the pore pressure, the validation data used are DST data, actual mud and drilling problems. Meanwhile, the fracture gradient was validated using actual mud data and drilling problems. In predicting pore pressure, three methods are used, namely the Bowers' method, Miller's method, and Eaton's method. While the fracture gradient prediction used the Eaton's method, Daines' method, Breckels & van Eekelen's method, and Hubbert & Willis' method.

In the Bowers' method based on figure 3, the mudline sonic values, variable A, and variable B are 156.4 us/ft, 14.8 and 0.74, respectively, with an average pore pressure of 6.2 ppg. These results do not represent the value of pore pressure in the BEN-1 well because at some depths, the pore pressure does not match the value of DST such as at depths of 635 m, 655 m, 1051 m, 1071 m, and 1160 m. so that pore pressure will be predicted using other methods.

Figure 3: Pore pressure prediction using Bowers' method

In the Miller's method based on figure 4, the mudline sonic, matrix sonic, and lambda values are 138 us/ft, 55 us/ft and 0.0002 respectively with an average pore pressure of 8.7 ppg. If you look at the graph as a whole, these results do not represent the value of pore pressure in the BEN-1 well because at some depths, the pore pressure does not match the value of DST such as at depths of 635 m, 655 m, 793 m, 813 m and 1160 m. so that pore pressure will be predicted using other methods.

Figure 4: Pore pressure prediction using Miller's method

In the Eaton's method based on figure 5, the pore pressure is divided into 4 parts, namely at a depth of 0-540 m which is included in the hydrostatic category with an average of 8.45 ppg, a depth of 540-693 m which is included in the underpressure category with an average of 4.089 ppg, a depth of 4,089 ppg. 690-1210 m which is categorized as hydrostatic with an average of 8.23 ppg, and at a depth of 1210-1275 m which begins to show overpressure conditions with an average of 10.02 ppg. If you look at the graph as a whole, these results represent the pore pressure value in the BEN-1 well.

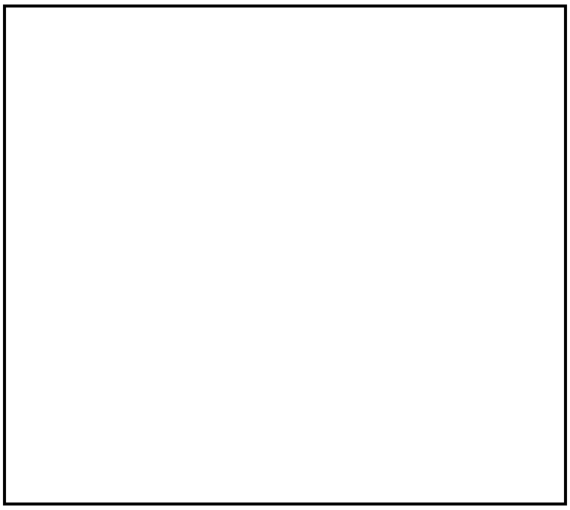

Figure 5: Pore pressure prediction using Eaton’s method

Then pore pressure smoothing was carried out (figure 6), the results obtained were that the pore pressure was divided into 4, namely at a depth of 0-540 m included in the hydrostatic category with an average of 8.48 ppg, a depth of 540-693 m which included underpressure category with an average of 4.00 ppg, a depth of 693-1245 m which is categorized as hydrostatic with an average of 8.17 ppg, and at a depth of 1245-1275 m which begins to show overpressure conditions with an average of 9.92 ppg.

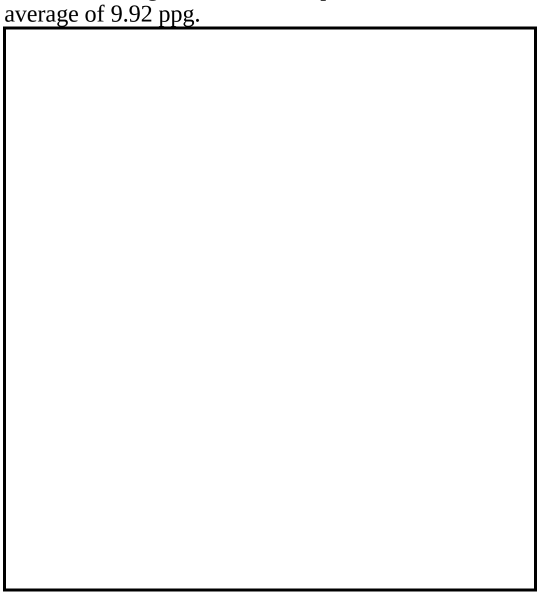

Figure 6: Pore pressure smoothing on software

In subsurface pressure analysis, rock mechanics values such as P-wave velocity, S-wave velocity, Poisson’s ratio, Young’s modulus, friction angle, and cohesive strength are important factors. P-wave velocity, S-wave velocity are used to calculate Poisson’s ratio, Young’s modulus, friction angle, and cohesive strength.

Poisson’s ratio is used to predict fracture gradient, Young’s modulus and friction angle are used to predict minimum horizontal stress, and cohesive strength are used to predict shear failure gradient. In analyzing the BEN-1 well, the Poisson’s ratio was calculated using four methods, namely the Brocher’s method, the Deere & Miller’s method, the Ludwig’s method and the Zoback & Castagna’s method.

Fracture gradient prediction in this case used four methods, namely Eaton’s method, Daines’ method, Breckels & van Eekelen’s method, and Hubbert & Willis’ method. Especially in the Eaton’s method, the Poisson’s ratio value variation is carried out according to the previously calculated. In the final well report of the BEN-1 well, there is no leak off test data which is usually used to validate the fracture gradient prediction results, so the authors validated only based on actual mud weight data and drilling problems that occurred.

Of these several methods, the formula used is almost the same, the difference is the value of the empirical number used by each method. In the Eaton’s method, the value of the empirical number is based on the Poisson’s ratio. Considering the Poisson’s ratio calculation which has several methods, so that the fracture gradient prediction using the Eaton’s method will have several results.

Based on the results of the fracture gradient prediction in figure 7 and figure 8, one that fits the BEN-1 well will be selected. The value of fracture gradient must be greater than the value of the pore pressure and drilling mud. And at a depth of 648 m due to lost circulation problems, at that depth the fracture gradient value should be below the mud density value.

Of these methods, the Eaton’s method with the Ludwig’s and Zoback’s Poisson’s ratios is the criterion. However, the author chose the Eaton’s method with Ludwig's Poisson’s ratio in this paper, because it is compared with the minimum horizontal stress value which will be predicted in the next step.

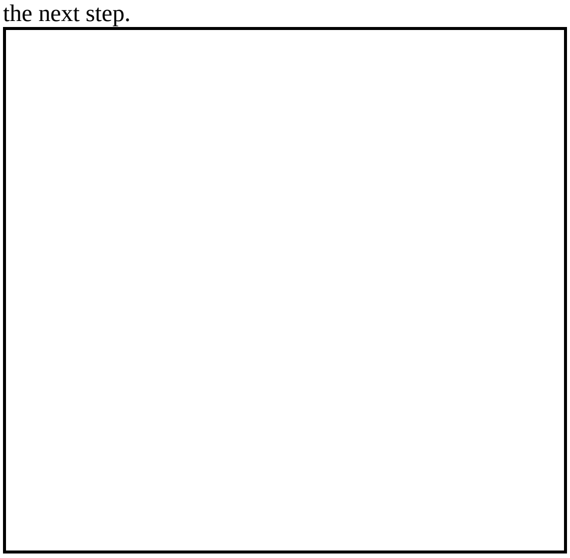

Figure 7: Fracture gradient prediction using some methods of Daines, Breckels & van Eekelen, dan Hubbert & Willis

Figure 8: Fracture gradient prediction using Eaton's methods with some Poisson's ratio method of Brocher, Ludwig, Deere Miller, dan Zoback

After predicting the fracture gradient, the next step is to predict the minimum horizontal stress (Shmin) and maximum horizontal stress (SHmax). The prediction of Shmin requires data of overburden gradient, pore pressure, and friction angle which can be determined by two methods, namely the Mohr-Coulomb pre-existing failure model and the Mohr-Coulomb purely friction failure model.

In the selection, the minimum horizontal stress will be compared with the fracture gradient, where the Shmin value must be smaller than the fracture gradient, but still must consider the drilling mud data and the existence of drilling problems. In figure 9, you can see the Shmin graph and the fracture gradient formed. Fracture gradient prediction using Eaton's method with Ludwig's Poisson's ratio and Shmin prediction using Mohr-Coulomb pre existing failure model, the results represent the BEN-1 well. The final result of predicting the fracture gradient obtained an average value of 13.04 ppg and an average minimum horizontal stress of 12.55 ppg.

Figure 9: Comparison between minimun horizontal stress and fracture gradient

Next is to predict the maximum horizontal stress (SHmax). SHmax can be predicted if Shmin has been predicted. Figure 10 is a comparison of the three insitu stresses, the result is that the overburden pressure (Sv) is greater than the maximum horizontal stress (SHmax) and the minimum horizontal stress (Shmin).

Figure 10: Prediction result of minimum horizontal stress, maximum horizontal stress, and overburden gradient

So, according to the Anderson scheme, the fault regime in the BEN-1 well is a normal fault (Sv > SHmax > Shmin). This is also in accordance with the study presented by Hidartan et al (2015). The final result of the prediction of maximum horizontal stress obtained an average value of 16.375 ppg.

The next step is to predict the value of the shear failure gradient. In predicting the shear failure gradient, data such as friction angle and cohesive strength are needed. In the software there are three methods that can be used to predict the value of shear failure gradient, namely linearized Mohr-Coulomb, Stassi-d'Alia condition and modified Lade criterion. However, the results obtained from the Stassi d'Alia condition method and the modified Lade criterion are exactly the same, while the Mohr-Coulomb method results are almost the same.

Figure 11: Shear failure gradient prediction using modified Lade criterion

In figure 11, the method that is finally used is the modified Lade criterion because this method has several advantages, where in predicting the shear failure gradient this method considers three principal stresses, compared to the Mohr Coulomb method which only considers two principal stresses, namely the maximum and minimum principals. stressed. The final result of the shear failure gradient prediction obtained an average value of 8.37 ppg.

The PPFG model of BEN-1 well can be used to predict the safe mud window. Prediction of the value of the stable mud window aims to maintain stability and avoid drill hole problems. Things that must be considered in determining the value of the stable mud window is how the mud weight is designed so that it meets safe standards. The condition of the stable mud window is as follows: Pore Pressure < Shear Failure Gradient < Mud Weight Recommended < Minimum Horizontal Stress < Fracture Gradient. In determining the minimum mud weight is the shear failure gradient plus 0.5 ppg and the maximum mud weight is the minimum horizontal stress minus 0.5 ppg.

Based on figure 12, the optimal stable mud window range for drilling at a depth of 0-540 m (section 20”) is 10.4-11.5 ppg, a depth of 540-693 m (section 13-3/8”) is 7.6-8.1 ppg, and a depth of 693-1245 m (section 9-5/8”) is 9.6-11 ppg to avoid lost circulation problem. However, on section 13- 3/8” there is something unusual, namely at a depth of 540-693 m including underpressure conditions, causing the formation pressure to tend to be small. To make a mud weight with a density under hydrostatic pressure will be expensive. So that on route B, blind drilling will be carried out, namely drilling with fresh water with a density of 8.33 ppg.

Figure 12: Safe mud window recommendation

CONCLUSIONS

1. PPFG model has been built based on some important validation data, these are DST data, actual mud and lost circulation problem.
2. Pore pressure predicted using Eaton’s method consists of four categories, namely hydrostatic at 0- 540 m depth, underpressure at 540-693 m depth, hydrostatic at 693-1245 m depth, and overpressure at 1245-1275 m depth.
3. Fracture gradient predicted using Eaton’s method and Ludwig’s Poisson’s ratio.
4. Minimum horizontal stress predicted using pre existing failure of Mohr-Coulomb’s method and maximum horizontal stress with dengan tectonic constant of 0.5 (normal fault).
5. Shear failure gradient predicted using modified Lade criterion.
6. Mud weight recommended is range of 10.4-11.5 ppg at 0-540 m depth, 8.33 ppg at 540-693 m depth, and 9.6-11 ppg at 693-1245 m depth.
7. The PPFG model at Pre-Kujung Formation can be used as a reference for plan of development well.

References

Bowers, G. L. (1995). Pore Pressure Estimation From Velocity Data: Accounting for Overpressure Mechanisms Besides Undercompaction. *The 1994 IADC/SPE Drilling Conference. SPE 27488*, pp. 89-95. Dallas: SPE Drilling & Completion.

Breckels, I. M., & van Eekelen, H. A. (1982). Relationship Between Horizontal Stress and Depth in Sedimentary Basins. *Journal of Petroleum Technology, 34*(9), 2191–2199.

Brocher, T. (2005). Empirical Relations between Elastic Wavespeeds and Density in the Earth's Crust. *Bulletin of the Seismological Society of America, 95*(6), 2081-2092.

Buntoro, A., Prasetyadi, C., Wibowo, R. A., Suranto, & Lukmana, A. H. (2018). Validation of Shale Brittleness Index Calculation from Wireline Log of

Well BETRO-001 by Using XRD Test Results and Uniaxial Test as Parameters for Determining Potential of Shale Hydrocarbon - Brown Shale of Pematang Group Formation. *ICEMINE, IOP Conference Series: Earth and Environmental Science, 212*(012069), 1-15.

Castagna, J. P., Batzle, M. L., & Eastwood, R. L. (1985). Relationships between Compressional-Wave and Shear-Wave Velocities in Elastic Silicate Rocks. *Geophysics, 50*(4), 571-581.

Eaton, B. A. (1969). Fracture Gradient Prediction and Its Application in Oilfield Operations. *Journal of Petroleum Technolog*, 1353-1360.

Eaton, B. A. (1975). The Equation for Geopressure Prediction from Well Logs. *The Fall Meeting of the Society of Petroleum Engineers of AIME. SPE 5544*, pp. 1-11. Dallas, Texas: SPE-AIME.

Essien, U. E., Akankpo, A. O., & Igboekwe, M. U. (2014). Poisson's Ratio of Surface Soils and Shallow Sediments Determined from Seismic Compressional and Shear Wave Velocities. *International Journal of Geosciences*, 1540-1546.

Fjær, E., Holt, R., Horsrud, P., Raaen, A. M., & Risnes, R. (2008). *Petroleum Related Rock Mechanics.* Kidlington: Elsevier Science Ltd.

Heindl, R. A., & Mong, L. E. (1936). Young's Modulus of Elasticity, Strength, and Extensibility of Refractories in Tension. *Journal of Research of the National Bureau of Standards, 17*, 463-482.

Hidartan, Ildrem, S., Eko, W., & Suci, S. (2015). Subsurface Interpretation Approach Gravity Method In Hydrocarbon Exploration: Study Subsurface Geology East Java Basin Cepu-Bojonegoro Area for Reference Study in Jambi Basin at South Sumatra. *The 2nd International Conference and The 1st Joint Conference* (pp. 193-204). Sabah: Universiti Malaysia Sabah.

Hubbert, M. K., & Willis, D. G. (1957). Mechanics of Hydraulic Fracturing. *Petroleum Branch Fall Meeting* (pp. 153-163). Los Angeles: Transactions of Society of Petroleum Engineers of AIME.

K.L.Gunsallus, & F.H.Kulhawy. (1984). A Comparative Evaluation of Rock Strength Measures. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, 21*(5), 233-248.

Kahraman, S. (2001). Evaluation of Simple Methods for Assessing the Uniaxial Compressive Strength of Rock. *International Journal of Rock Mechanics and Mining Sciences, 38*(7), 981-994.

Kumar, J. (1976). The Effect of Poisson's Ratio on Rock Properties. *Society of Petroleum Engineers, SPE 6094*, 1-12.

Kurtulus, C., Sertcelik, F., & Sertcelik, I. (2015). Correlating Physico-Mechanical Properties of Intact Rocks with P-Wave Velocity. *Acta Geodaetica et Geophysica*.

Lal, M. (1999). Shale Stability: Drilling Fluid Interaction and Shale Strength. *SPE Asia Pacific Oil and Gas Conference and Exhibition.* Journal of Petroleum Technology.

Ludwig, W. J., Nafe, J. E., & Drake, C. L. (1970). Seismic Refraction. *The Sea, 4*, 53–84.

Lukmana, A. H. (2020). Integrated of Geomechanics Wellbore Stability & Sweet Spot Zone Analysis To Unconventional Well Drilling Optimization. *Jurnal Petro*, 21-29.

Ramdhan, A. M., Goulty, N. R., & Hutasoit, L. M. (2011). The Challenge of Pore Pressure Prediction in Indonesia's Warm Neogene Basins. *Thirty-Fifth Annual Convention & Exhibition. IPA11-G-141*. Proceeding Indonesian Petroleum Association.

Sapiie, B., Danio, H., Priyono, A., Asikin, A. R., Widarto, D. S., Widianto, E., & Tsuji, T. (2015). Geological Characteristic and Fault Stability of the Gundih CCS Pilot Project at Central Java, Indonesia. *Proceedings of the 12th SEGJ International Symposium*, 110-113.

Suryadinata, M. D., Ratnaningsih, D. R., Ariadi, I. K., Waliy, F., & Nugroho, W. A. (2021). Rock Mechanics Effect on Fracture Geometry and Dimensionless Fracture Conductivity of 2D Model KGD (Khristianovic-Geertsma-de Klerk) in Air Benakat Formation, Meruap Field. *International Journal of Petroleum and Gas Exploration Management, 5*(1), 1-14.

Waliy, F., Buntoro, A., Lukmana, A. H., & Rahma, A. A. (2020). The Effect of Poisson's Ratio and Young's Modulus on Fracture Geometry of 2D Model PKN: Case Study of Unconventional Reservoir. *IATMI Simposium Professional Digital Presentasion 2020.* IATMI.

Zhang, J. J. (2011). Pore Pressure Prediction from Well Logs: Methods, Modifications, and New Approaches. *Earth-Science Reviews, 108*(1), 50-63.

Zhang, J., & Yin, S. (2017). Fracture Gradient Prediction: an Overview and an Improved Method. *Petroleum Science, 14*, 720–730.

Zhang, J., Standifird, W., & Lenamond, C. (2008). Casing Ultradeep, Ultralong Salt Sections in Deep Water: A Case Study for Failure Diagnosis and Risk Mitigation in Record-Depth Well. *SPE Annual Technical Conference and Exhibition. SPE 114273*, pp. 1-24. Denver, Colorado: Society of Petroleum Engineers.

Zoback, M. D. (2007). *Reservoir Geomechanics.* Cambridge University Press.