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A New Approximation of Water Saturation Estimation Based on Vertical Seismic Profiling Data

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ABSTRACT
Water saturation is the ratio between the volumes of fluid in the rock pores. Water saturation is one of the important reservoir parameters to be known in the exploration or exploitation of oil and gas. I have developed a new technique to estimate the distribution of water saturation values based on the seismic wave attenuation analysis, frequency and porosity from the equation of Biot-Turgut-Yamamoto-Sismanto. It is applied to the real data using the vertical seismic profiling (VSP) data in Pasir Cantang well, West Java for some layers.
The obtained values of water saturation have not been calibrated to the known value of the well. This step needs to be done, so that the results that have been corrected can be performed to estimate the area around the well Pasir Cantang guided by seismic section. Regardless of the calibration factor, the method of the water saturation estimation on VSP data can technically be well done but still needs necessary calibration for the accuracy.
Keywords - Water saturation estimation, Biot-Turgut-Yamamoto-Sismanto, Pasir Cantang.

I. INTRODUCTION

The application of seismic methods in the oil and gas industry today is not only limited to the determination of the subsurface geological structures for prospective sites but has also been operated for development of the field, estimated reserves and production, reservoir characterization such as volume, pressure, temperature, porosity, permeability, and fluid saturation [1]. Various studies have been conducted to determine the relationship between seismic waves with reservoir parameters. One is a study by Sismanto [2] who studied the relationship between the attenuation of seismic waves on the reservoir properties of sedimentary rocks such as permeability and water saturation. Ertanti [3] has made estimates of water saturation by calculation that is theoretically based on the analysis of the attenuation of the equation Biot-Yamamoto-Turgut. The theoretical results are calibrated against log data to estimate the water saturation in the same layer in the same field based on information porosity logs through Cross plot method.

Sony [4] has conducted some tests to estimate the water saturation using the formulation of synthetic seismic data based on the equation-Turgut Biot-Yamamoto-Sismanto. The test results offer an optimism that the techniques developed can be used to estimate water saturation on real data. In this research, I apply the method of estimation of water saturation on seismic data vertical profiles or VSP (vertical seismic profiling) using the analysis of seismic wave attenuation, frequency and porosity of the equation-Turgut Biot-Yamamoto-Sismanto.

The nature of a rock depends on a number of parameters affecting the dynamic response such as porosity, permeability, fluid type contained in the rocks and the interaction between the solid skeleton with fluid. The equation proposed by Timur in [5] indicates that the porosity is proportional to the water saturation obtained from the laboratory test samples.

Sony [4] and Sismanto [6] has discussed the relationship between the water saturation obtained from the linear-frequency relaxation by generating 1D synthetic seismograms with the water saturation obtained from the relaxation frequency. The results can be summarized such as;

1. The relationship between water saturation with porosity indicates that water saturation is sensitive to porosity. When the porosity is high, the water saturation will also increase. This occurs because the medium has a great porosity; in this case of wide pore space, the probability of the fluid filling the pores will increase.
2. The medium containing fluid will be able to reduce the amplitude of seismic waves, the higher water saturation on the medium, and the higher the attenuation of the waves. The attenuation is inversely proportional to the quality factor of the wave, so that if the water saturation increases, the quality factor of the seismic waves will tend to decrease.
3. The seismic wave frequency will be smaller when the high water content of medium or the rising water saturation decreases the frequency of seismic waves.

4. Water saturation is more sensitive to changes in porosity, while that of frequency and attenuation is still very difficult to observe.

II. THE CONCEPT OF WATER SATURATION ESTIMATION EQUATION

Biot [7],[8] provides a mechanism for the concept of the wave equation in the elastic, porous, and fluid saturated rock. The rock is assumed to be homogeneous isotropic. Turgut and Yamamoto [9] solve the equation for unconsolidated rocks such as marine sediments, sandstone, limestone, and porous rock in general that have a high quality factor. From these equations, it was derived the attenuation-frequency relationships. In the experiments, Turgut - Yamamoto uses ultrasonic wave source, so that it is difficult enough to implement in low-frequency, due to the seismic wave having less than 200 Hz [2]. For practical purposes, Sismanto [2] modify and develop the equation to be transformed into a linear form that it is more operational. According to the approximation for marine sedimentary and unconsolidated rocks, Turgut and Yamamoto [9] obtained the attenuation Q^{-1} relationship with frequency ω as a quadratic function of,

$$\boldsymbol{Q}^{-1} \approx \frac{\dfrac{\boldsymbol{V}_\infty^2}{\boldsymbol{V}_0^2} - 1}{\dfrac{\tilde{\boldsymbol{q}}_i}{\boldsymbol{A}} + \dfrac{\boldsymbol{A}}{\tilde{\boldsymbol{q}}_i} \cdot \dfrac{\boldsymbol{V}_\infty^2}{\boldsymbol{V}_0^2}} \quad (1)$$

where $\tilde{q}_i$ $(=\eta/k_p\omega)$ is the imaginary part of $\tilde{\boldsymbol{q}}$ and, $\boldsymbol{A} = (\boldsymbol{\rho m} - \boldsymbol{\rho}_f^2)/\boldsymbol{\rho}$, ω is angular frequency $(= 2\pi f)$, and

$$\boldsymbol{V}_o^2 = \overline{\boldsymbol{H}}/\boldsymbol{\rho} \quad \text{for} \quad \omega \to 0, \quad (2)$$

$$\boldsymbol{V}_\infty^2 = (\overline{\boldsymbol{H}}\boldsymbol{m} + \boldsymbol{M\rho} - 2\boldsymbol{C\rho}_f)/(\boldsymbol{\rho m} - \boldsymbol{\rho}_f^2) \quad (3)$$

for $\omega \to \infty$.

From equation (1), when the attenuation Q^{-1} is plotted to the frequencies, it can be obtained the dominant frequency which is called the relaxation frequency and the magnitude is,

$$\boldsymbol{f}_r = \left[\frac{\boldsymbol{\rho\eta}}{2\pi(\boldsymbol{\rho m} - \boldsymbol{\rho}_f^2) \cdot \boldsymbol{k}_p}\right] \frac{\boldsymbol{V}_0}{\boldsymbol{V}_\infty} \quad (4)$$

By using the relaxation frequency, the permeability can be calculated, if the other parameters are known. This method is referred to as Turgut-Yamamoto method or the relaxation frequency method.

In the low frequency region, the curve of equation (1) is a straight line; therefore, to obtain the linear equations, equation (1) is extended through the Taylor series in frequency and in the linear order such as [2]:

$$\boldsymbol{Q}^{-1} \approx \frac{2\pi \boldsymbol{k}_p}{\boldsymbol{\eta}} \left(\frac{\boldsymbol{\rho m} - \boldsymbol{\rho}_f^2}{\boldsymbol{\rho}}\right) \left(\frac{\boldsymbol{V}_\infty^2}{\boldsymbol{V}_0^2} - 1\right) \boldsymbol{f} \quad (5)$$

Thus, if the attenuation Q^{-1} is plotted to the frequency, it can be obtained the slope of straight line (called *slop*) in the curve such as

$$\boldsymbol{slop} \approx \frac{2\pi \boldsymbol{k}_p}{\boldsymbol{\eta}} \left(\frac{\boldsymbol{\rho m} - \boldsymbol{\rho}_f^2}{\boldsymbol{\rho}}\right) \left(\frac{\boldsymbol{V}_\infty^2}{\boldsymbol{V}_0^2} - 1\right)$$

$$\textbf{or} \;\; \boldsymbol{\rho} = 4 \frac{\dfrac{2\pi \boldsymbol{k}_p}{\boldsymbol{\eta}} \left(\dfrac{\boldsymbol{V}_\infty^2}{\boldsymbol{V}_0^2} - 1\right) . \boldsymbol{\rho}_f^2}{-4.\boldsymbol{slop} + 5.\dfrac{2\pi \boldsymbol{k}_p}{\boldsymbol{\eta}} \left(\dfrac{\boldsymbol{V}_\infty^2}{\boldsymbol{V}_0^2} - 1\right)} \quad (6)$$

Substituting $\boldsymbol{\rho} = (1-\Phi).\boldsymbol{\rho}_m + \Phi\left[\boldsymbol{S}_w.\boldsymbol{\rho}_w + (1-\boldsymbol{S}_w).\boldsymbol{\rho}_g\right]$ into equation (6), it can be calculated the water saturation by

$$\boldsymbol{S}_w = \frac{\boldsymbol{\rho} - (1-\Phi).\boldsymbol{\rho}_m - \Phi.\boldsymbol{\rho}_g}{\Phi(\boldsymbol{\rho}_f - \boldsymbol{\rho}_g)}, \quad (7)$$

If there is no gas, $\rho_g = 0$ and the water saturation is,

$$\boldsymbol{S}_w = \frac{\boldsymbol{\rho} - (1-\Phi).\boldsymbol{\rho}_m}{\Phi\boldsymbol{\rho}_f} \quad (8)$$

Substituting equation (6) to equation (8), will result in

$$\boldsymbol{S}_w = \frac{4\dfrac{\dfrac{2\pi \boldsymbol{k}_p}{\boldsymbol{\eta}} \left(\dfrac{\boldsymbol{V}_\infty^2}{\boldsymbol{V}_0^2} - 1\right) . \boldsymbol{\rho}_f^2}{-4.\boldsymbol{slop} + 5.\dfrac{2\pi \boldsymbol{k}_p}{\boldsymbol{\eta}} \left(\dfrac{\boldsymbol{V}_\infty^2}{\boldsymbol{V}_0^2} - 1\right)} - (1-\Phi).\boldsymbol{\rho}_m}{\Phi\boldsymbol{\rho}_f} \quad (9)$$

Thus, if we know the numerical values of the permeability k_p, the viscosity η, the porosity Φ, the slope of the curve, the velocity at low frequency, and the velocity at high frequencies, then the water saturation can be determined by using equation (9).

Meanwhile, if we make a substitution $\boldsymbol{\rho} = (1-\Phi).\boldsymbol{\rho}_m + \Phi\left[\boldsymbol{S}_w.\boldsymbol{\rho}_f + (1-\boldsymbol{S}_w).\boldsymbol{\rho}_g\right]$ for gas density is zero into equation (5) without any plotting curves (Q^{-1} - f), then the water saturation Sw will be in equation (10).

However, if the water saturation equation is derived directly from equation (1), the theoretical Sw can also be obtained by combining the equations with gas content formulated by equation (11),

$$Sw=\frac{1}{2}\left(\frac{-\Phi+\frac{2\pi k_p}{\eta}\left(\frac{V_\infty^2}{V_0^2}-1\right).f.Q.m.\Phi\pm\sqrt{\begin{matrix}\Phi^2-2\frac{2\pi k_p}{\eta}\left(\frac{V_\infty^2}{V_0^2}-1\right)f.Q.m.\Phi^2+\left(\frac{2\pi k_p}{\eta}\right)^2\left(\frac{V_\infty^2}{V_0^2}-1\right)^2.f^2Q^2m^2\Phi^2\\-4\frac{2\pi k_p}{\eta}\left(\frac{V_\infty^2}{V_0^2}-1\right)f.Q.\rho_m+4\frac{2\pi k_p}{\eta}\left(\frac{V_\infty^2}{V_0^2}-1\right)f.Q.\rho_m.\Phi\\+4\left(\frac{2\pi k_p}{\eta}\right)^2\left(\frac{V_\infty^2}{V_0^2}-1\right)^2f^2.Q^2.m.\rho_m-4\left(\frac{2\pi k_p}{\eta}\right)^2\left(\frac{V_\infty^2}{V_0^2}-1\right)^2f^2.Q^2.m.\rho_m.\Phi\end{matrix}}}{\frac{2\pi k_p}{\eta}\left(\frac{V_\infty^2}{V_0^2}-1\right)f.Q.\rho_f}\right) \tag{10}$$

$$Sw=\frac{2\pi k_p m f\rho_m\left(V_\infty^2-V_0^2-\phi V_\infty^2+\phi V_0^2+\frac{\phi\rho_g V_\infty^2-\phi\rho_g V_0^2}{\rho_m}\right)+2\pi k_p\rho_f^2 f\left(V_0^2-V_\infty^2\right)-Q^{-1}\eta V_0^2\rho_m\left(1-\phi+\frac{\phi\rho_g}{\rho_m}\right)}{\left\{Q^{-1}\eta V_0^2\phi\left(\rho_w-\rho_g\right)-\phi 2\pi k_p m f\left(\rho_w-\rho_g\right)\left(V_\infty^2-V_0^2\right)\right\}} \tag{11}$$

Saturation is a ratio of the fluid volume to the total porosity volume. By using equation (10) or (11) it can also be calculated and plotted the water saturation as a function of attenuation, frequency, and porosity when the other parameters have been computed or known [6] and [9].

Permeability is the ease of fluid flow through the rock formations. The greater the permeability of the reservoir rock, the greater the amount of fluid that can be flow in the reservoir. Geerstma and Smit [10] examine the Biot's equations from low to medium frequencies to find the velocity - frequency relationships in the fluid saturated rocks, and they obtained that the permeability depends on the frequency and velocity in the saturated rock as,

$$k_p=\frac{\phi\eta}{2\pi\rho f}\frac{1}{\sqrt{\frac{V_\infty^4-V_p^2V_\infty^2}{V_p^2V_0^2-V_0^4}}}\ . \tag{12}$$

Seismic wave attenuation Q^{-1} can be defined as a function of the energy absorption by Johnston and Toksöz [11] such as,

$$\frac{1}{Q}=\frac{\alpha V}{\pi.f} \tag{13}$$

Numerical analysis results have been obtained from the study conducted by Sismanto [6] which is based the equations (10) and (11). The curve of the water saturation Sw to the porosity, frequency and wave attenuation was obtained by equation (10). In general it can be concluded that, when the porosity is high, the water saturation increases, and the medium with high water content will be able to absorb the seismic waves strongly or rising water saturation increase the attenuation, and the medium with high water content, the frequency of seismic wave that through will be smaller. Water saturation is more sensitive to changes in porosity, while the change in frequency and attenuation is insignificant.

III. EXPERIMENT AND DISCUSSION

The steps of calculation can be formulated as follows;

1. VSP data that have been processed is taken from well Pasir Cantang [12]. The geophone intervals of 15m, which shows the layer system, are 3 layers or 4 layers (with a small layer on the second layer). The data of each layer is read for every interval of 15m for the first layer, and the second layer is 45m and 30m for the third layer.
2. The VSP data are read and then the attenuation Q^{-1} is re-calculated, then we determine the dominant frequency and the permeability. Finally those three values (Q^{-1}, f, and k) are used to calculate the water saturation through equation (10).
3. Due to lack of the real water saturation information of the Pasir Cantang, the estimated water saturation has not been calibrated. The equation should be used after calibration with the standard water saturation in the survey area.

The first layer of VSP data at Pasir Cantang was read at a depth of 650m with an interval of 15m by 12 trace (geophones). The estimation of water saturation on VSP data of Pasir Cantang in the first layer (Cisubuh Formation) is 5.5% (the calibration has not been performed). Cisubuh Formations are consisting of limestone, sandstone, siltstone and batuserpih.

For the second layer, there are two layers that are at a depth of 965m-1370m called layer 2a (Parigi Formation) and at a depth of 1415m-1505m as layer 2b (Zone 16). Each has different velocity i.e, 3440 m/s and 2100 m/s. The geophone interval is 45m; there are 12 traces (9 geophones in layer 2a and 3 geophones in layer 2b). The estimation of water saturations are 4.9% and 0.37%. Those values are not calibrated. The Parigi Formation and Zone 16 consist of limestone, sandstones and clay.

For the third layer (Baturaja Formation) in the VSP data of Pasir Cantang at a depth of 1685m-2135m has the velocity of 4820 m/s. The geophone interval is 30m by 9 trace. The estimated water saturation is 8.54%. The calibration has not been performed. The rocks of Baturaja Formation are limestone, sandstones and clay. The summarized results are shown in table 1.

Table 1. The estimation of permeability and water saturation.

Layers	*Vp* (m/s)	*f* (Hz)	*Q* (λ/dB)	depth (m)	k_p(m^2) x10^{-13}	*Sw (%)*
fisrt	2070	18	19	650-830	0.11	5.5
2a	3440	19	11	965-1370	9.7	4.9
2b	2100	18	43	1415-1505	9.1	0.37
third	4820	17	10	1685-2135	46	8.54

IV. Conclusion

We have developed a new technique to estimate the distribution of water saturation values based on the analysis of seismic wave attenuation, frequency and porosity of the equation Biot - Turgut - Yamamoto - Sismanto. We have obtained the results of the test of the method for estimating water saturation using real seismic data in vertical profiles of well Pasir Cantang, West Java. The water saturation obtained has not been calibrated to the real water saturation in the well. It is necessary to ensure that the results have been corrected and then it can be used to estimate the area around the well of Pasir Cantang.

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