A modified Nur Model for microporous carbonate rocks

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Abstract

The forecasting of fluid saturation changes within the reservoirs is one of the main issues of rock physics, which is often done using Biot-Gassmann theory. However, this theory demands the known of dry rock elastic moduli. Nur (Critical porosity) model is one of the theories to evaluate those dry rock properties from porosity and the mineral elastic properties of rock constituents. In this paper, a modification to Nur model is proposed based on the observations of the misfits of the model to the observed data. Such modified Nur model includes the effect of pressure upon the rock and provides more accurate results.

Introduction

Carbonate reservoirs are extremely important in the international petroleum and gas business once 60% of worldwide reserves of oil and 40% of the world's reserves of gas are associated to such type of reservoirs.

In Brazil, the public interest about the physical properties of this kind of rock has increased since the announcement of the pre-salt huge reservoirs at Santos Basin in 2005. Those rocks are characterized to be heterogeneous, fractured and to present a great textural variation, which leads to complex relationships between the rock physical properties and geophysical data (Vanorio et al., 2008). Nevertheless, the mapping of fluid distribution inside carbonates reservoirs through the seismic data is one of the main issues for reservoir management. Rock physics models can be used to forecast fluid saturation changes inside reservoirs through the analysis of the effect of those variations in the seismic properties such as velocities or elastic moduli. Biot-Gassmann (BG) theory is the most used method to relate fluid saturation changes and seismic properties, although its efficiency to carbonate rocks is sometimes questioned (Rasolofosaon et al., 2008; de Paula et al., 2010). However, the success of Biot-Gassmann theory depends on the accurate characterization of the dry rock bulk modulus. There are several theories described in the literature that aim to evaluate the dry rock bulk modulus from mineralogy and porosity info, as Geertsma (1961), Krief et al. (1990) and Nur et al. (1995). The latter is also known as a critical porosity model and is based on the concept of a limit porosity in which the consolidated rock turns into a suspension of grains in a fluid load-bearing domain.

Fournier and Borgomano (2009) studied core samples of microporous carbonate rocks obtained at two wells in southern France and verified that Nur model could describe efficiently the dry bulk modulus.

In this work, Fournier and Borgomano data were re-analyzed and resulted in the observation that the misfit between the measured and the modeled data using Nur theory followed a trend line, which could be used to perform an adjustment of the Nur model results. This modified Nur model includes the sensibility to effective pressure and proved to be more accurate than the original model for the studied rocks.

Nur model

Nur et al. (1995) reported the idea that there is a trend of P and S wave velocities between the velocities of mineral grains in low porosity rocks and the values for a mineral-pore-fluid suspension for high porosity rocks. This idea is based on the concept of a critical porosity, ϕ_c, which sets a limit between two distinct domains. For porosities lower than ϕ_c, mineral grains are load-bearing and for porosities greater than ϕ_c, the rock becomes a suspension of grains and the fluid phase is responsible for load-bearing. Eq. 1 and 2 can express bulk (K_{dry}) and shear (G_{dry}) moduli for dry rocks.

$$K_{dry\_Nur} = K_{ma}\left(1 - \frac{\phi}{\phi_c}\right) \quad (1)$$

$$G_{dry\_Nur} = G_{ma}\left(1 - \frac{\phi}{\phi_c}\right) \quad (2)$$

Where:

K_{ma}=bulk modulus of the mineral part;

G_{ma}=shear modulus of the mineral part;

ϕ=porosity.

Mavko et al. (2009) listed typical values of critical porosity as 60% for limestones and 40% for dolomites.

The dataset

In this work, part of the database reported by Fournier and Borgomano (2009) was used, which consists of measurements of the physical properties of microporous mixed carbonate-siliciclastic rocks obtained at two wells located within the South Provence Basin, in France. Those wells were drilled down to 150 m and were named as La-Ciotat 1 and La-Ciotat 2. The authors performed ultrasonic measurements to estimate P and S wave velocities, porosity measurements, X-ray diffraction (XRD), thin section and SEM image analysis for rock characterization.

The ultrasonic experiments were carried out at five effective pressures, ranging from 5 to 70 MPa, on dry core plugs, using 700 KHz ultrasonic transducers. Density and porosity were evaluated using dry and saturated weights. Mineralogy was determined from XRD results according to Rietveld approach. Thin section and SEM analysis allowed estimating the micritic volume fraction.

From the seven petrographic classes contained in Fournier and Borgomano database, we choose only five, which consists of the limestones described as follows:

1. Limestone with grainstone texture (quartz<5%);
2. Limestone with wackestone-packstone texture (quartz<5%);
3. Quartz-rich limestone with sparitic/microsparitic intergranular space (grainstone texture) (quartz 5%-50%);
4. Quartz-rich limestone with micritic intergranular space (wackestone-packstone texture) (quartz 5%-50%);
5. Slightly argillaceous quartz-rich limestones with wackestone-packstone texture (quartz 5%-50% clay 2%-5%).

This selection corresponds to 28 core samples data, with porosity ranging from 0.18% to 8.61%. The authors also identified that the pore volume located within the micritic fraction, in the intercrystalline space, played a major role for total porosity. After analyzing plots of dry bulk modulus of the micritic fraction versus micrite porosity and modeling the trend using Nur model, they estimate a critical porosity value of 18%.

Method

Dry bulk and shear moduli were estimated from the velocities using Equations 3 and 4.

$$K_{dry} = \rho_b \left(V_p^2 - \frac{4}{3} V_s^2 \right) \quad (3)$$

$$G_{dry} = \rho_b V_s^2 \quad (4)$$

Where:

V_p=P-wave velocity;

V_s=S-wave velocity;

ρ_b=Bulk density.

Figure 1 shows a comparison between the dry bulk modulus estimated from the observed velocities at each effective pressure and the counterparts provided by the Nur model (Eq. 1). Differently from the approach of Fournier and Borgomano (2009), instead of using the micrite porosity, we used the total porosity, once it is more usual to be found in other databases, either core plug results or well log info. A reference line, where both values should be expected to coincide is plotted as a solid black line. It is possible to note that most of the points that fall on that line are related to samples with high values of dry bulk modulus and there is clearly a trend that deviates from the expected line as the dry bulk modulus decrease. Using the entire dataset, i.e., including all the measurements at all pressures, it was possible to perform a linear regression that resulted in the trend line shown as a dashed black line.

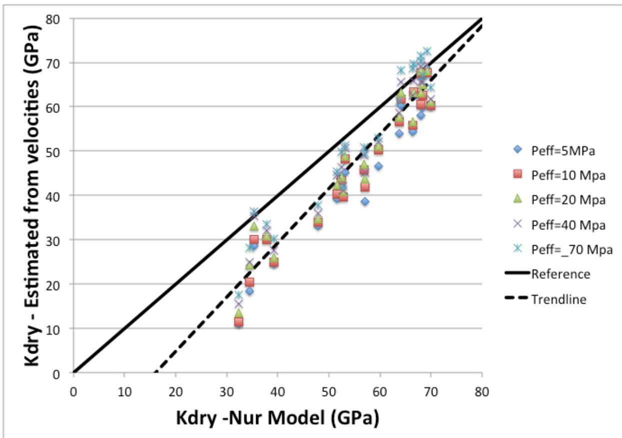

Figure 1 - Comparison of the dry bulk modulus estimated from observed velocities and from Nur model. The solid line is a reference where both values should be the same. The dashed line is a trend provided by a linear regression of the entire data set.

The best fit using this entire dataset is shown in Equation 5 and its determination coefficient (R^2) was 0.909.

$$K_{dry} = 1.2251 K_{dry\_Nur} - 19.681 \quad (5)$$

Another approach is to analyze how this relationship (y=ax-b) varies for each value of effective pressure, which is shown in Figures 2a, 2b, 2c, 2d and 2e. In each of these figures, a linear regression analysis was performed to estimate the best fit. The variation of the linear relation and the determination coefficients as a function of the effective pressure were plotted as shown in Figures 3a, 3b, and 3c. As can be seen, either coefficient a as the determination coefficient is practically constant. However, coefficient b varies with effective pressure. The best fit for such pressure dependence comes as a second order polynomial. This way, a relationship to correct the Nur model estimates can be proposed as follows:

$$K_{dry\_Nur\_mod} = aK_{dry\_Nur} - b \quad (6)$$

Where:

$a = 1.2251$

$b = 0.0024 \left(P_{eff} \right)^2 - 0.2596 P_{eff} + 23.851$

K_{dry_Nur} = Original Nur model estimate for dry bulk modulus

$K_{dry\_Nur\_mod}$ = Modified Nur model estimate for dry bulk modulus

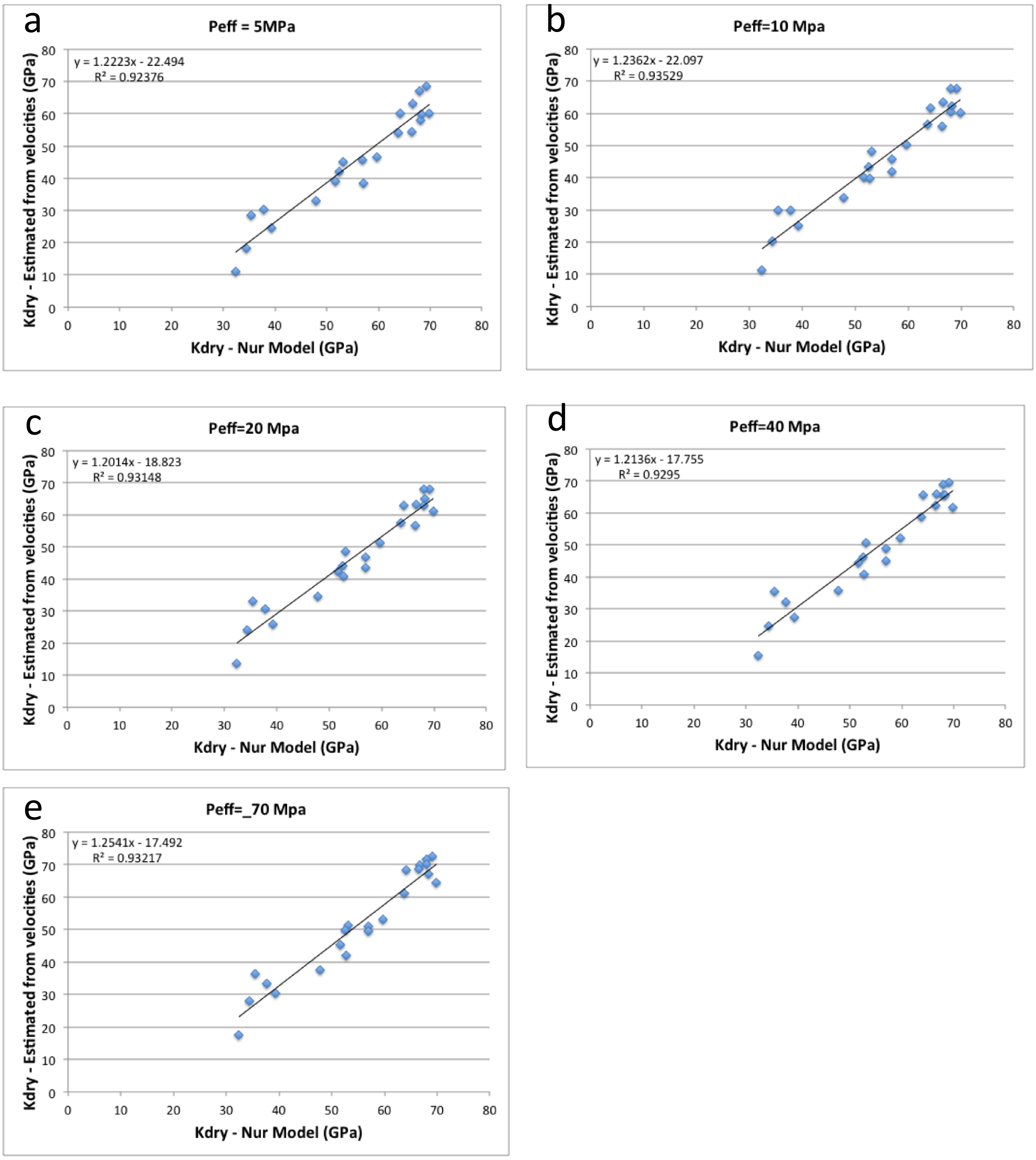

Figure 2 - Graphics of dry bulk modulus estimated from observed velocities versus Nur model results for effective pressures at: (a) 5 MPa, (b) 10 MPa, (c) 20 MPa, (d) 40 MPa and (e) 70 MPa.

This approach provided more accurate results than the use of the entire data set, reporting determination coefficients around 0.93. The same approach could be performed to the dry shear modulus, as shown in Figures 4a, 4b and 4c, which exhibit the variation of the linear relation and the determination coefficients as a function of the effective pressure. Different from what was observed for dry bulk modulus, the coefficient a obtained from linear regressions of dry shear modulus data points displays a variation for effective pressure. The best fit for such variation results in a linear relation. For coefficient b the best fit results in a second order polynomial; however the curve concavity is opposite to the dry bulk modulus result. The determination coefficient is practically constant along the pressure range. The correction of Nur model for dry shear modulus estimates are summarized in Equation 7, as follows:

$$G_{dry\_Nur\_mod} = aG_{dry\_Nur} - b \quad (7)$$

Where:

$a = -0.0011P_{eff} + 0.8624$

$b = -0.0004\left(P_{eff}\right)^2 - 0.0906P_{eff} + 0.5788$

G_{dry_Nur} = Original Nur model estimate for dry shear modulus

$G_{dry\_Nur\_mod}$ = Modified Nur model estimate for dry shear modulus

Results

To evaluate the accuracy of Nur original and modified models, graphics of the distribution of the relative error for both approaches versus porosity was plotted, as shown in Figures 5a and 5b for dry bulk modulus and 6a and 6b for shear modulus. The error for Nur original model (Fig. 5a) increases, as porosity gets higher, resulting in very large errors for porosities greater than 6%. Typical error values vary from 10% to 60 %, while the minimum error was close to 0.02 % and maximum was close to 200%. Pressure increment tends to decrease the error, once the rocks become stiffer and as reported by Mavko et al. (2006), Nur model works better for high consolidated rocks. The use of modified Nur model (Fig. 5b) resulted in lower errors, reporting typical error values ranging from 0% to 20 %, while the minimum error was close to 0.08 % and maximum was close to 59%. As observed in the results for Nur original model, as the pressure increases the error tends to decrease.

In the case of dry shear modulus, Nur original (Fig. 6a) and modified Nur (Fig. 6b) models, shows practically the same error range, from 0% to 20%. Minimum error in Nur original was 0.03% and maximum was 48.27%, while for modified Nur model the minimum was 0.08% and maximum was 59.02%. The influence of the effective pressure on the relative errors for the dry shear modulus were minimal for most of the samples, although in a few samples it was possible to observe the decrease of the errors as pressure increases. For the modified Nur results the estimates of dry shear modulus at highest pressure (70 MPa) resulted in the largest errors.

Fournier and Borgomano (2009) reported that uncertainties in density and velocities implied an error of 5% in bulk modulus and 3% in shear modulus. Thus, the accuracy of such modified model is satisfactory.

Conclusions

The observation of the behavior of the deviation of Nur model results from the expected values allowed the elaboration of a modified Nur model that aims to provide more accurate results. Such model includes the sensibility to effectively pressure, once its increment enhances the consolidation, reducing porosity and making the rock more stiff, which affects the elastic moduli. That sensibility allows for correction when ambient porosity is used in the Nur model for evaluating bulk and shear modulus of dry core plugs. The proposed model worked well for estimating dry rock bulk modulus, however, the results for dry shear modulus provided no significant increment in accuracy regarding to Nur original model. A possible cause for such different behavior is related to the error in the linear fits observed in shear modulus graphics as can be verified by the determination coefficient of roughly 0.8 while the values for the bulk modulus fits was greater than 0.9.

This modified Nur model is empirical and was not tested yet in other data sets or different lithologies, this way the values of the coefficients a and b may vary for different rock types.

The success of Nur model, original or modified, depends on the proper characterization of the critical porosity. In this case, the critical porosity is very different from values reported for limestones in many papers and textbooks, thus caution should be taken to select the proper critical porosity value in order to avoid inaccurate results.

Acknowledgments

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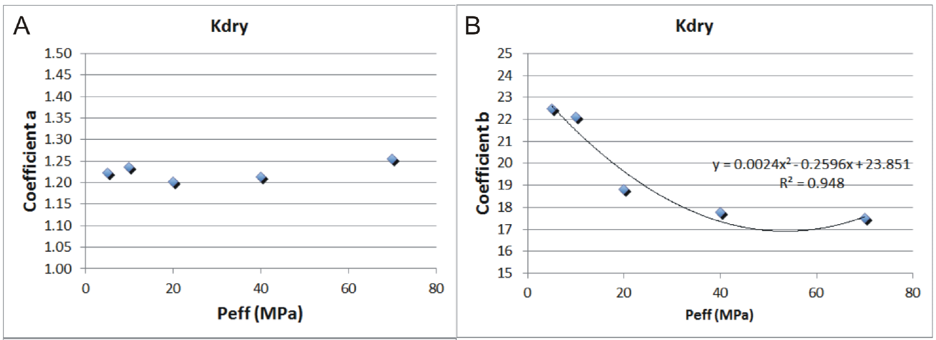


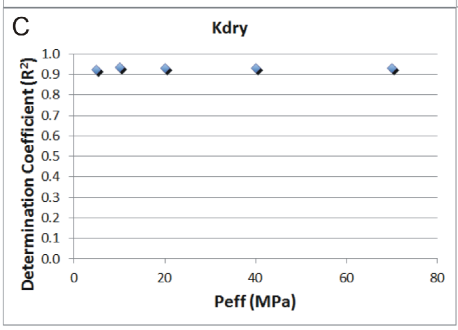
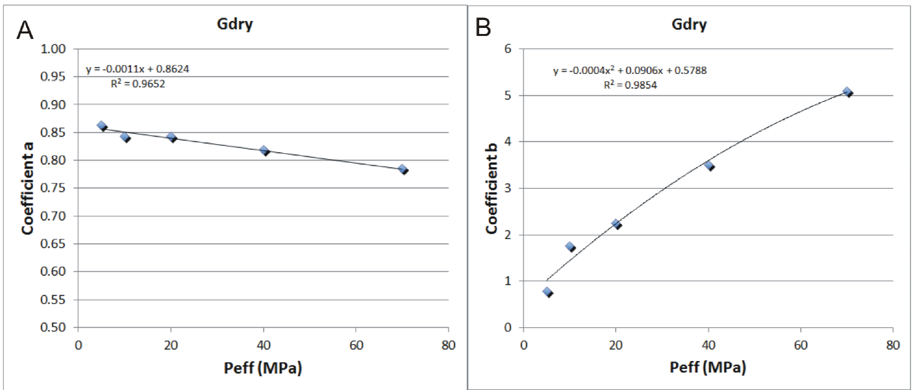


Figure 3 - Graphics of the coefficients of the linear regression analysis for Kdry versus effective pressure. (A) Coefficient a. (B) Coefficient b, solid line represents second order polynomial ft. (C) Determination coefficient.



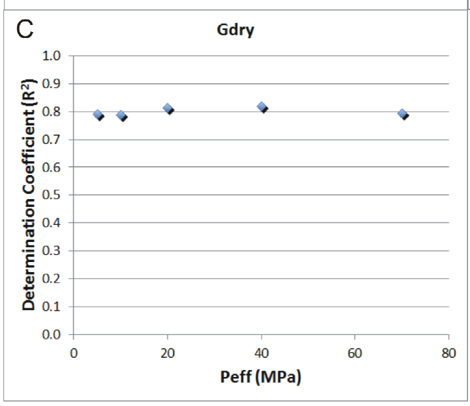


Figure 4 - Graphics of the coefficients of the linear regression analysis for Gdry versus effective pressure. (A) Coefficient a. solid line represents linear fit. (B) Coefficient b, solid line represents second order polynomial fit. (C) Determination coefficient.

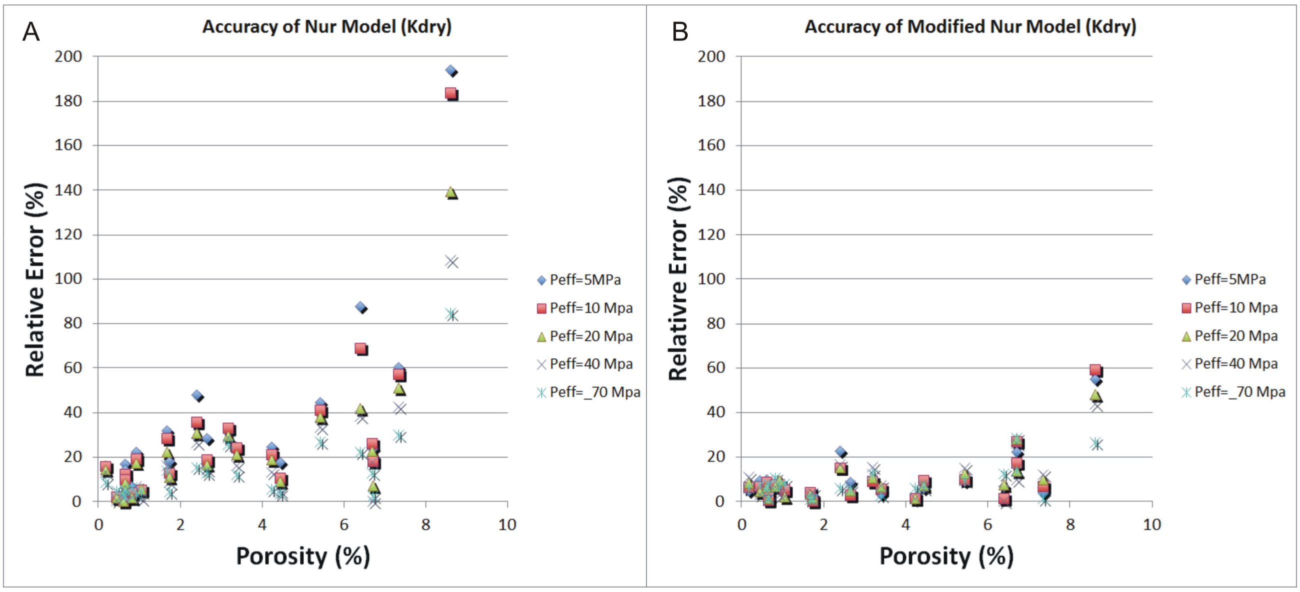


Figure 5 - (A) Accuracy of Nur original model for Kdry versus porosity. (B) Accuracy of modified Nur model for Kdry versus porosity.

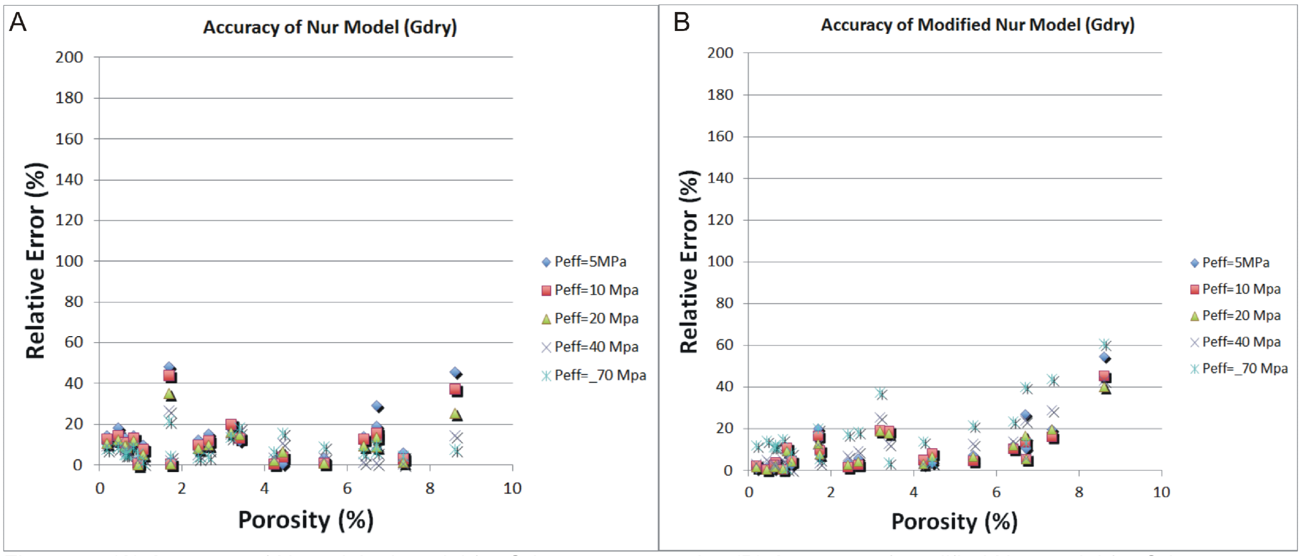


Figure 6 - (A) Accuracy of Nur original model for Gdry versus porosity. (B) Accuracy of modified Nur model for Gdry versus porosity.