OGEP 2010-161

Uncertainly Analysis of Archie's Parameters Determination Techniques in Carbonate Reservoirs

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This paper was prepared for presentation at the 2nd Saudi Meeting on Oil and Natural Gas Exploration and Production Technologies (OGEP 2010) held at the King Fahd University of Petroleum & Minerals (KFUPM) Campus in Dhahran, Kingdom of Saudi Arabia, December 18-20, 2010.

Abstract

Determination of hydrocarbon saturation is the vital parameter in oil reserve calculation processes. Archie's formula is the water saturation model for the determination of hydrocarbon saturation. The parameters of Archie's formula (a, m and n) are determined through laboratory core analysis program. Determination techniques of Archie's parameters are relatively well known and validated for sandstone reservoirs. But in case of carbonate rocks, there are considerable variations in texture and pore type, so, Archie's parameters become more sensitive to pores pattern distribution and lithofacies properties. Uncertainty in these parameters will lead to non acceptable errors in the water saturation values.

In this study three techniques are presented to determine Archie's parameters using carbonate core samples. These techniques are; conventional technique, core Archie's parameters estimate (CAPE) technique and three dimension (3-D) technique. The main objective of this study is to determine Archie's parameters in order to get the most accurate estimate of water saturation by using the above three techniques. Water saturation profiles were produced using different Archie parameters already determined by the three techniques for the studied sections in the wells. These profiles have shown a significant difference in water saturation values, such difference could be mainly attributed to the uncertainty level for Archie parameters from each technique.

Introduction

Determination of recoverable hydrocarbons or at least of hydrocarbon in place is the primary goal of a designed formation evaluation program. In routine formation evaluation Archie's parameters a, m and n are held constants. There are cases where saturation exponent n, varies from the common value of 2 in strongly water wet reservoir rocks to more than 20 in strongly oil wet reservoir rocks. Wettability effects become important in case of partial water saturation reservoir pore spaces. Petroleum literature presents an extensive review of the results determining Archie's parameters and also water saturation computation processes. Accuracy water saturation values relies on the uncertainty of Archie's parameters used either in Archie saturation equation in clean formation or in a shaly sand water saturation model in shaly formation (Archie, 1942; Atkins and Smits, 1961; Kennedy et al, 2001; Bori 1987 and Dernika et al, 2007).

This paper presents the results of the application of three techniques to determine Archie's parameters; 1)Three dimensional regression (3-D) technique which is based on the analytical expression of three dimension plot of Rt/Rw versus Sw and ϕ, 2)Core Archie's parameters estimate (CAPE) and 3) Conventional technique.

Discussion

Electrical Measurements

A total of twenty nine core samples were tested for electrical. Two-and four-pole resistivities, temperature, confining pressure, pore pressure, and brine displacement are monitored continuously and recorded by a computer attached to the system. Electrical measurements were taken continuously until resistivity and desaturation equilibriums were reached at each step.

All resistivity measurements were corrected for a reservoir temperature of $80^{\circ}C$ during data processing. After temperature equilibrium, the confining pressure was raised to 2500 psi and the brine expelled from each sample was measured. After initial electrical measurements, desaturation was performed stepwise from 0 to 120 psi pore pressure. Although four-pole resistivities were used for determining the electrical parameters, two-pole resistivities were also recorded for monitoring the contact problems that might have occurred.

Calculation of Archie's Parameters

An exact computation of water saturation using Archie's formula is based on an accurate values of Archie's parameters a, m and n. In this study, twenty nine carbonate core samples ere selected for wells A & B. For each core sample, the electrical resistivity Ro, at 100% water saturation and Rt at different water saturation percentages were measured at room temperature. The resistivity of simulated brine was prepared to water resistivity 0.2 Ω.m. This ambient water resistivity value corresponds to formation water resistivity 0.09 ohm.m. at reservoir temperature.

Conventional Determination of a, m and n

Archie, 1942 proposed an empirical relationship between rock rsistivity, Rt, with its porosity, ϕ, and water saturation Sw.

$$Sw^n = a\,Rw / \phi^m\,Rt = Ro / Rt = 1/ Ir \quad \text{.........................(1)}$$

Conventional Determination of n The classical process to determine saturation exponent, is based on Eq. 1. This equation is rewritten as:

$$\log Ir = -n \log Sw \quad \text{..(2)}$$

Logarithmic plot of Ir versus Sw gives a straight line with negative slope n. **Fig. 1** illustrates the saturation exponent values for 29 core samples.

Conventional Determination of a **and m** the conventional determination of a and m is based on following equation:

$$\log F = \log a - m \log \phi \quad \text{.......................................(3)}$$

Plot of log F vs. log ϕ is used to determine **a** and m for the core samples. Cementation factor m, is determined from the slope of the least square fit straight line of the plotted points, while tortousity factor is given from the intercept of the line where ϕ= 1. Note that in this plot only points of Sw = 1.0 are used. **Fig. 2** shows F vs. porosity for core samples; average m equals to 1.87 and the coefficient a equal to 1.12. It is obvious that the conventional technique treats the determination of n as a separate problem from a and m. This separation is not physically correct, thereby, it induces an error in the value of water saturation using equation 1.

Core Archie-Parameter Estimation (CAPE)

Maute et al (1992) have presented a data analysis approach to determine Archie's parameters **m, n** and optionally **a** from standard resistivity measurements on core samples. The analysis method, Core Archie- Parameters Estimation (CAPE) determines m and n and optionally a by minimizing the error between computed water and measured water saturations. The mean square saturation error ε, is given by

$$\varepsilon = \sum j \sum i \,[Swij - (aRwij / \phi i^m\, Rt\, ij)^{1/n}\,]^2 \quad \text{.....................(4)}$$

Where j = core index, i = index for each of the core j measurements, Swij = ith laboratory measured water saturation for core j (fraction), Rtij = ith laboratory measured resistivity for core j, Ω.m, and ϕj= core j porosity (fraction). Eq.6 calculates the minimum error between measured core water saturation and computed water saturation by Archie's formula, this is by adjusting m, n and optionally a in the equation.

Three Dimensional Regressions (3-D)

Hamada et al (2002) proposed 3-D technique to determine Archie's parameters a, m and n using standard resistivity measurements on core samples.

Methodology The basis of the 3-D technique is to consider view Sw in Archie's formula (Eq. 1) as a variable in three dimensional regression plot of Sw, Rw/Rt and ϕ. The 3-D technique determines Archie's parameters a, m and n by solving three simultaneous equations of Sw, Rw/Rt and Eq. 1 is rearranged after taking the logarithm of both sides.

$$\log Rw / Rt = -\log a + m \log \phi + n \log Sw \quad ....(5)$$

The left hand side of Eq. 5 is a dependent variable of the two independent variables Sw and ϕ. Eq.57 is an equation of a plane in three dimensional (3D) space of coordinate x, y and z (x = log , y = log Sw and z = log Rw/Rt). The intersection of this plane with the plane (x = 0. 0 gives a straight line of slope m, with the plane (y = 0. 0) giving a straight line with slope n and with the plane (z = 0.0) provides the value of a parameter.

For a given set of data for a core sample, we can obtain an equivalent set of variables x, y and z. Eq. 5 will take the following form for i measurement points:

$$Zi = -A + m\,Xi + n\,Yi \quad ....(6)$$

After normalizing Eq. 8 for N reading, we can have the following three simultaneous equations

$$\Sigma Zi = -N A + m\Sigma Xi + n\Sigma Xi \quad ....(7)$$
$$\Sigma XiZi = -A N\Sigma Xi + m \Sigma Xi2 + n \Sigma XiYi \quad ......(8)$$
$$\Sigma YiZi = -A N\Sigma Yi + m\Sigma XiYi + n\Sigma Yi2 \quad ....(9)$$

The solution of equations 6-9 provides the values of Archie's parameters a, m and n for one core sample. For j core samples, running the same analysis for j core samples produces an average value of Archie’s parameters.

Assumptions First, 3-D technique assumes that Archie formula is applicable to the examined core samples Also, the core samples represent the zone of interest For shaly sandstone, Archie formula must be modified to account for the presence of shale and its effect on resistivity measurements The user is free to select the appropriate clay model , and consequently, the shaly sand water saturation equation The second assumption might be difficult to satisfy, it is dealing with the accuracy of the laboratory measurements under reservoir conditions The third assumption deals with the concept of the 3-D technique, This means that the user must be acquainted with the basis and limitations of each method before using it.

Field Application and Statistical Analysis

Now, the conventional, CAPE, and 3D techniques are applied by considering field examples of effectively carbonate rock. **Table 1** shows typical results from the conventional method, the CAPE method, and the 3D method. Note that for CAPE method, cases where a, is fixed at unity and variable are given. In addition to m, n and values, the five error parameters were used to evaluate techniques regarding to water saturation. These five error parameters are given in **Table 2** (the absolute error, the minimum and maximum absolute error, the correlation coefficient, standard deviation and finally the root mean square relative error). **Figures 3** and **4** shows the average error, the root mean square error, standard deviation, and finally the R-square error consequently that explained the accuracy of different techniques.
We note that the values of a, m and n deduced by the four methods, are different. Also, note that the saturation root mean square, average error and standard deviation decrease as we go as the following methods are used: (1) conventional methods to (2) CAPE method with, a, forced to unity, (3) 3D method, and (4) CAPE with, a, variable. This behavior was expected and it could be attributed to the fact that conventional method tries to optimize the two functions F vs. ϕ, and Rt vs. Sw rather than water saturation, while CAPE, and 3D optimize water saturation. Although the both CAPE types have the lowest root mean square error, but the 3D method still are more credited than CAPE by less computer time consuming and by its optimization technique which is more physically concerned with water saturation and related factors than CAPE method. Therefore, it is recommended to use the 3D or CAPE with, a, variable technique to get an accurate values of a, m and n required for water saturation equation.

Variable Archie's Parameters and Water Saturation Values

Laboratory measured saturation exponent(n) showed some variations An exact value of saturation exponent is necessary for a good log interpretation analysis to a precise water saturation determination There are many factors affecting saturation exponent such as rock wettabilitv, grain pattern, presence of certain authigenic clays, particularly chainosite, which may promote oil wet characteristics and history of fluid displacement. However, it is found that rock wettabilitv is the main factor affecting saturation exponent (n) Archie's saturation equation makes three implicit assumptions 1) the saturation-resistivitv relation is unique, 2) n is constant for a given porous medium and 3) all brine contributes in the electric current flow . It is found that these assumptions are valid only in water wet reservoir. This is because saturation exponent n depends on the distribution of the conducting phase in the porous medium and therefore depends on wettabilitv Saturation exponent (n) is about 2 in water-wet rock where brines spread over grain surface and facilitate the flow of the electric current While it may reach 25 in strongly oil-wet rock, where oil coats grain surface and causes disconnections and isolation of globules of brine and therefore this will be unable to conduct a current flow.
Figure 5A illustrate typical results of measured and estimated water saturation profiles for different Archie's parameters deduced from conventional method, CAPE, and 3D method. **Figure 5B** depicts water saturation relative error profiles calculated by the four options against selected interval for core samples. The examination of water saturation

profiles has shown that (1) the use of conventional values yields water saturation values greater than the correct ones, and that (2) Unlike the case of conventional values the water saturation profiles calculated by CAPE with, a, variable and 3D methods have not shown certain departure from each other. For application where highest possible accuracy in water saturation is desired, it is recommended to leave the conventional method and adopt any of the CAPE or the 3D method. In additional, the CAPE and 3D method is more preferred because of it is more physically representation of the data and because it overcomes the dilemma of whether, a, is to be fixed at unity or not.

Moreover, the CAPE with, a, forced to unity and 3D method is more preferred than the CAPE method with, a, variable because of it is more practically and very fast.

Figure 5A and 5B show clearly the measured and estimated water saturation profile calculated by different methods. These profiles support the accuracy analysis to study the performance of different techniques in order to get the most accurate techniques. Note that water saturation has a good matching when we used the CAPE (a, m, n) method with, a, variable and the 3D method.

Summary/Conclusion

1. Conventional Technique is currently in Use, But It has serious Limitations on Determination of Parameters a & m Separately from Saturation Exponent n. This is Physically not Correct.
2. CAPE technique is based on minimum error between measured water saturation and calculated water saturation values.
3. 3-D technique is based on simultaneous solution of three variable of Archie's formula (a, m and n)
4. Comparison of calculated water saturation values (using Archie's parameters from the three techniques) with Cores water saturation values has shown that CAPE and 3-D technique are more accurate than conventional technique.
5. Error analysis showed that conventional technique has higher error level than CAPE and 3-D techniques.

References

Atkins, E.R. and Smith, G.H., 1961, the significance of particle shape in formation Resistively factor-porosity relationship, JPT, 3, pp. 285-291.

Al-Ruwaiili, S.B. and Alwaheed, H.H., 2004, Improved petrophysical methods and techniques for shaly sands evaluation, SPE# 89735 presented at SPE Annual Technical Conference, Houston Texas, USA, 26-29 November, 2004.

Archie, G.E., 1942, The electrical resistivity log as an aid in determining some reservoir Characteristics, Trans. AIME, 146, pp.54-62.

Bori, A.M., 1987, A New correlation for the cementation factor in low-porosity Carbonates, SPE Formation Evaluation, December, pp.495-498.7.

Clavier, C., Coates, G. and Demanoir, Theoretical and experimental bases for Dual water model for interpretation of shaly sands, JPT, vol.24, no.2, 1984, pp.153-168.

Dernaika, M, Efnik, M.S., Koronful, M.S., Mansoori, M., Hafez, H. and Kalam, M.Z., 2007, Case Study for represtative water saturation from laboratory to logs and the effect of pore geometry on capillarity, SCA # 2007-38 presented at SCA International symposium, Calgary, Canada 10-12 September, 2007

DeWhite, L., 1950, Relation between resistivities and fluid contents of porous rocks, Oil and Gas J., August, pp. 120-132.

Fertl, W.H., "Log-derived evaluation of shaly clastic reservoirs", JPT, vol.39, no.2, pp.175-194.

Hamada, G.M, Al-Awad, M.N, Al-Sughayer, 2002, Water Saturation Computation from Laboratory, 3-D

Regression, Oil &Gas and Technology Rev., IFP, vol.57, no.6, pp.637-651.
Kennedy, W.D., Herrick, D.C. and Yao, T., 2001, Calculating water saturation in electrically anisotropic media", Petrophysics, vol.42, no.2, pp.118-136.
Maute, R.E., Lyle, W.D. and Sprunt, E., 1992, Improved data- analysis method determines Archie parameters from core data, JPT, January, pp.103-107.
Morgan, W.B. and Pirson, S.J., 1964, The effect of fractional wettability on the Archie saturation exponent" Paper B presented at 5th SPLWAL Annual Technical Conférence, Midlands, USA, 13-15 May, 1964.
Simadoux, P, 1963, Measures diélectriques on milieu poreux, application a measure des saturations en eau, étude du comportement des massifs argileux Revue de L'IFP, pp. 193- 215.
Waxman, M.H. and Smits 1968, Electrical conductivities in oil –bearing shaly sands", JPT, 8, 1968, pp. 107-122.

Table1 Archie's parameters values from four techniques

Method	a	m	n
Conventional Method	1.12	1.87	2.04
CAPE (1,m,n) Method	1.00	1.52	1.92
CAPE (a,m,n) Method	0.23	2.15	2.87
3-D.Method	0.28	2.34	2.12

Table 2 shows error analysis of Archie's parameters determination techniques

Methods	Absolute Error			E_{rms}	S	R
	E_a	E_{min}	E_{max}			
Conventional Method	0.206	0.004	1.09	0.31	0.23	0.90
CAPE (1,m,n) Method	0.125	0.001	0.38	0.16	0.10	0.90
CAPE (a,m,n) Method	0.095	0.001	0.33	0.12	0.08	0.92
3-D.Method	0.102	0.002	0.51	0.14	0.10	0.91

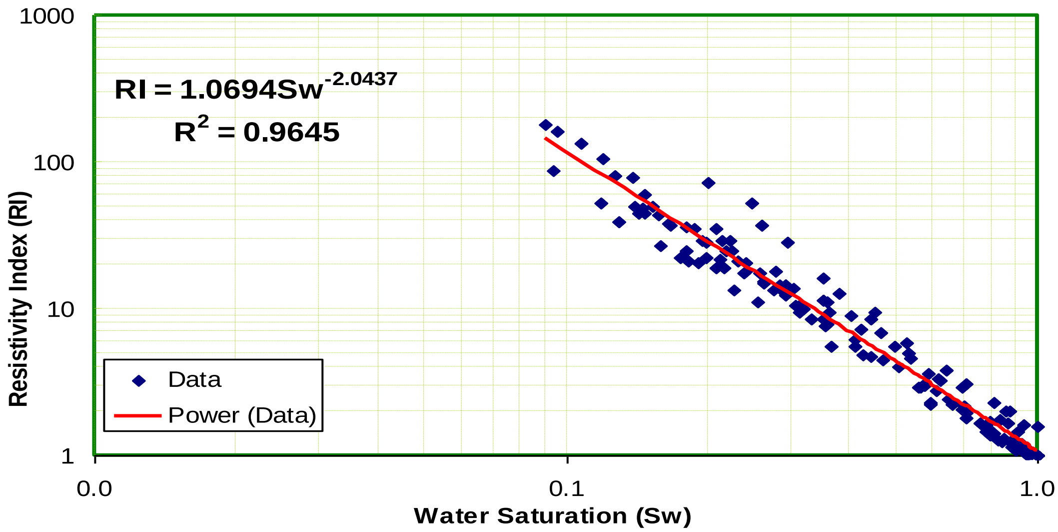

Figure 1 Resistivity vs. water saturation for 29 core samples

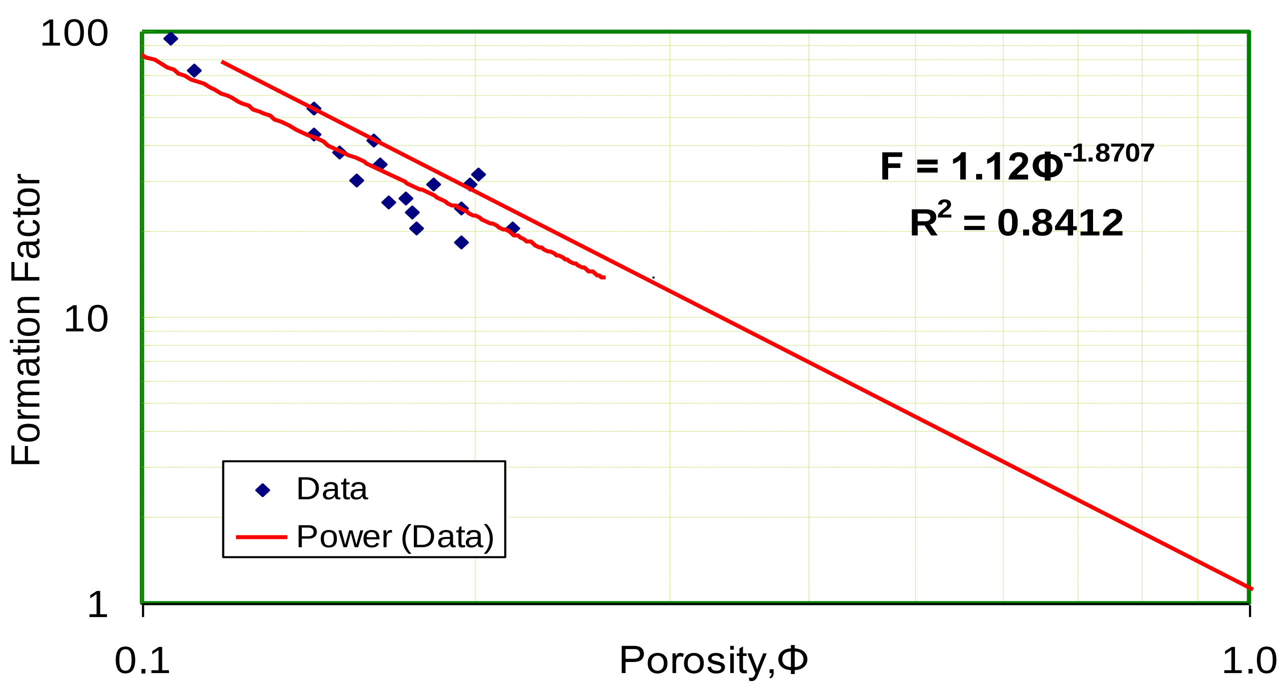

Figure 2 Formation factor vs. porosity for 29 core samples

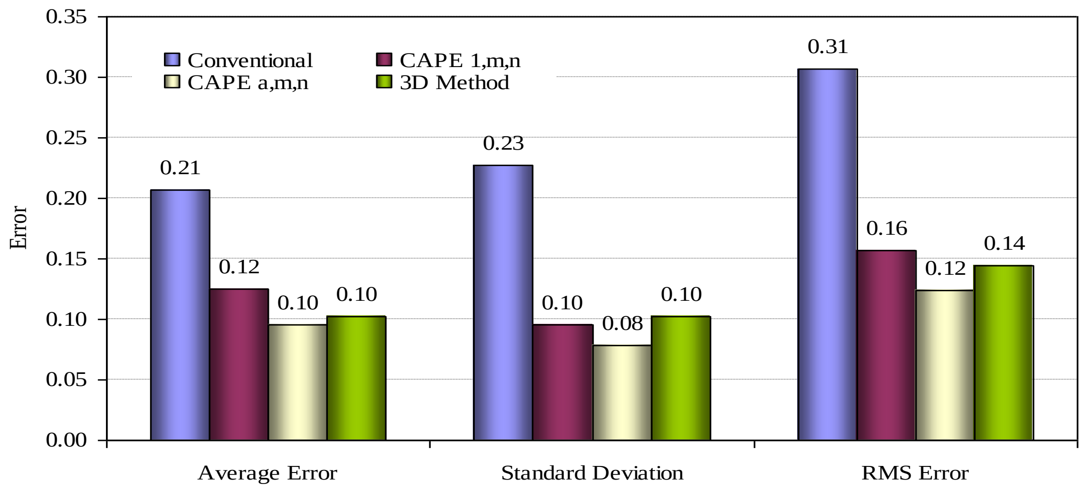

Figure 3 The average error, RMS error and standard deviation between the four techniques

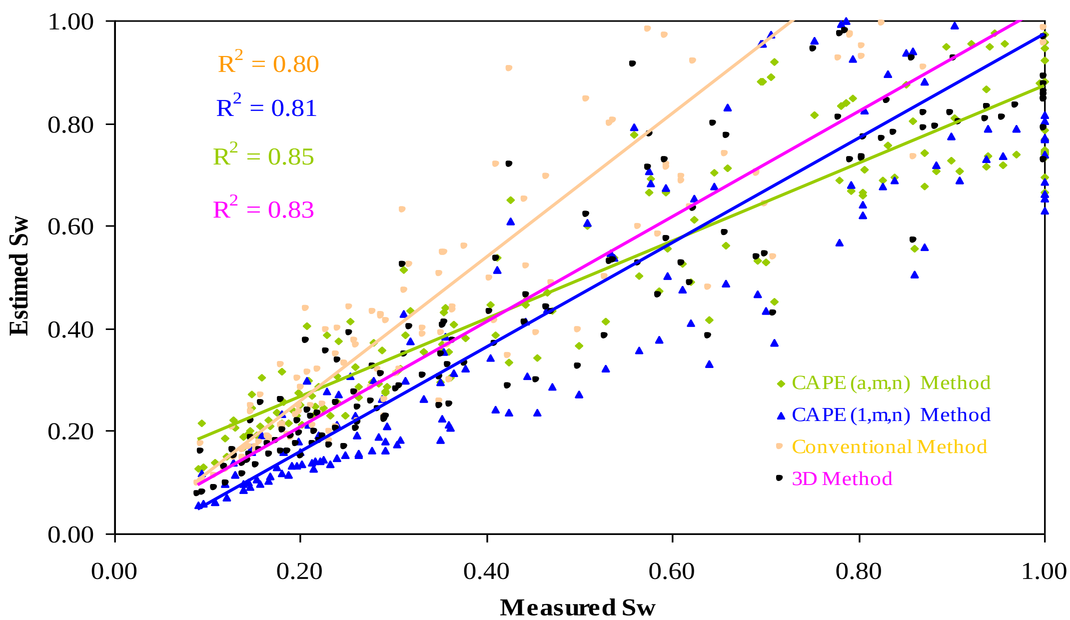

Figure 4 The R-squared values for the different techniques

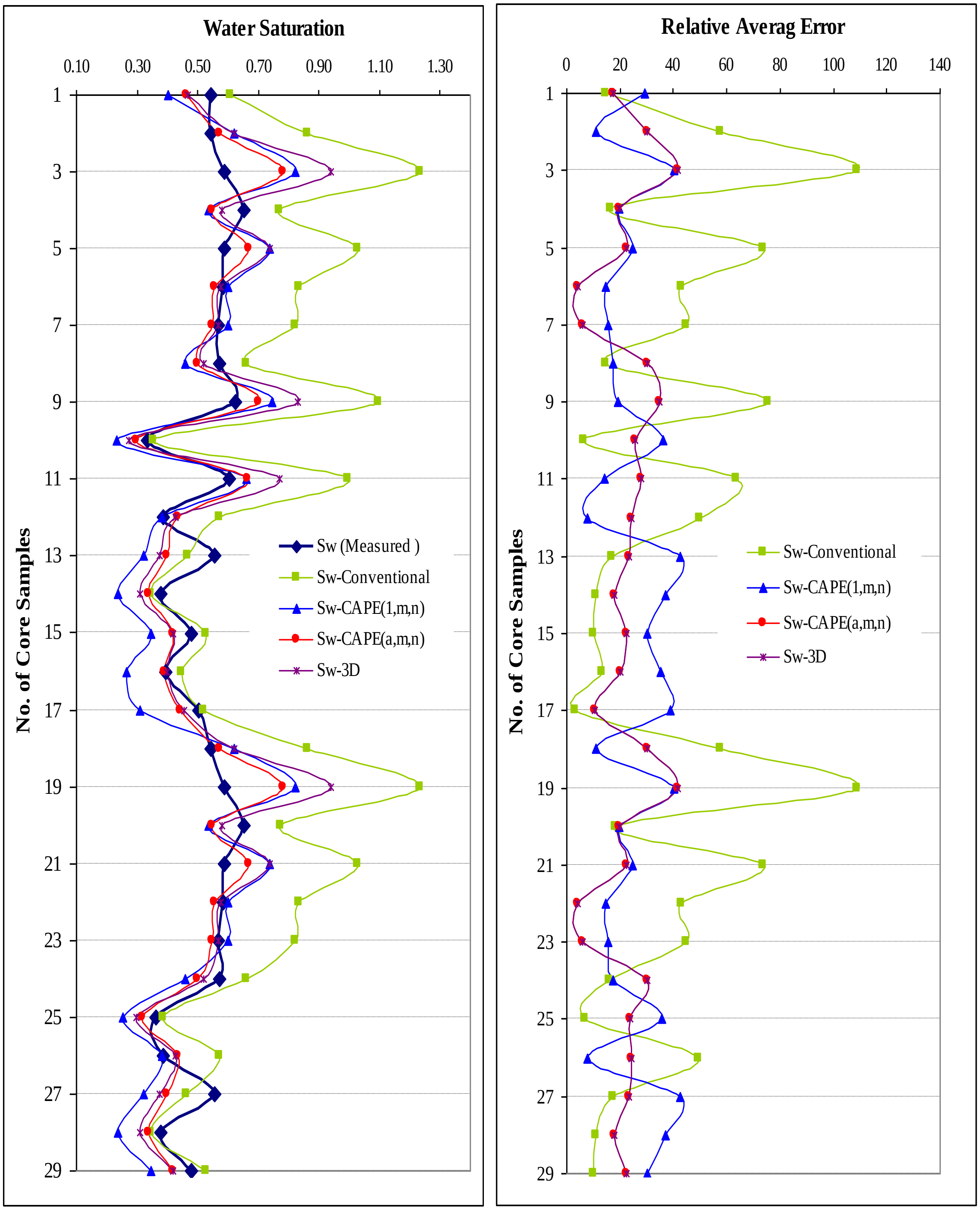

Figure 5, A) Comparison between measured with calculated water saturation from four techniques**,** and **B)** Relative error between four techniques