Volume 2022, 9 pages | Article ID : IJPGE-2206302112796

International Journal of Petroleum and Geoscience Engineering

Journal homepage: www.htpub.org/ijpge/

ISSN: 2289-4713

Parallel Self Organizing Neural Network Estimation (PSONN) of Water Saturation Using Archie's Formula in Sandstone Reservoirs

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Article

Article history
Received: 15 April 2022
Received in revised form: 02 June 2022
Accepted: 01 July 2022

Keywords:
Water saturation,
Archie' parameters,
Artificial intelligence,
PSONN,
Sandstone reservoir

Abstract

Determination of water saturation in sandstone is vital question to determine initial oil or gas in place in reservoir rocks. Water saturation determination using electrical measurements is mainly on Archie's formula. Consequently, accuracy of Archie's formula parameters affects rigorously water saturation values. Determination of Archie's parameters a, m and n is proceeded by three techniques conventional, CAPE and 3-D. This work introduces the hybrid system of parallel self-organizing neural network (PSONN) targeting an accepted value of Archie's parameters and consequently reliable water saturation values. This work focuses on Archie's parameters determination techniques; conventional technique, CAPE technique and 3-D technique and then calculation of water saturation using current. Using the same data, hybrid parallel self-organizing neural network (PSONN) algorithm is used to estimate Archie's parameters and to predict water saturation. Results have shown that estimated Arche's parameters m, an and n are highly accepted with statistical analysis indicating that PSONN model has lower statistical error and higher correlation coefficient. This study was conducted using high number of measurement points for 144 core plugs from sandstone reservoir. PSONN algorithm can provide reliable water saturation values and it can supplement or even replace the conventional techniques to determine Archie's parameters and thereby calculation of water saturation profiles.

1. Introduction

Prediction of reservoir petrophysical properties from well-logs data has evolved from the use of experts' knowledge and statistics to the use of artificial intelligence (AI) models. Several AI models for this purpose are available in the literature. The main objective of this work is introducing Artificial Neural Network (ANN) algorithms to estimate reliable values of Archie's parameters and then getting accurately the water saturation of reservoir rocks. In order to reach this target, in first place developing a technique to obtain an unbiased accuracy measure from a finite set core samples. This will allow for meaningful comparison between NN method; hybrid system of parallel self-organizing neural network

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(PSONN) and currently used techniques namely CAPE, 3-D and conventional method targeting ultimately an accurate water saturation determination Furthermore, comparing the performance of the developed ANN model with some existing ones indicated that it performed better than some existing models. Additionally, the developed PSONN model is replicable as its threshold weights and biases required to replicate the model are made available, unlike other models in the literature. Hence, the developed ANN model is a more robust tool to predict reservoir's porosity, permeability and water saturation in the Niger Delta region [1-5].

Water saturation is keystone parameter in estimation of initial oil in place. Accurate determination of water saturation is important for good reservoir evaluation and also optimum reservoir recovery from oil fields. Reservoir heterogeneity affect the accuracy of determination techniques of Archie's parameters. Reservoir fluids heterogeneous distribution and changes in lithofacies properties and the inclusion of shale are most important aspects of heterogeneity. The main issue with the understanding of heterogeneous reservoirs is addressing the right relationship between lithofacies properties and petrophysical characteristics and then reservoir performance [6, 7]. Reservoir wettability, pore size distribution and pore geometry mainly affect the saturation exponent (n) and to certain degree cementation exponent (m) and tortuosity factor (a) of Archie's equation. Cementation exponent changes radically with wettability changes induces radical effect on water saturation calculation using electrical measurements. Reservoir rock and mainly carbonates have mixed wettability or fractional wettability. Wettability changes either in reservoir or in coring operation and handling create serious problems in the determination of water saturation exponent. Wettability alteration is embarrassing factor in Archie reservoirs, and for non-Archie reservoirs where it has complications attributed to clay minerals in shaly sandstone reservoirs and perception of heterogeneous reservoir complexity [8-11].

In this study, an artificial intelligence technique, hybrid system (PSONN) was used to produce the required model to estimate Archie's parameters and thereby; predict water saturation curves in the studied well sections. Cementation exponent (m), tortuosity factor (a) and saturation exponent were calculated on the basis of Archie's equation in which water saturation values had already been predicted by the Hybrid Artificial Intelligence model [12-14].

The main objective is to apply the Artificial Intelligence (PSONN) for predicting water saturation profiles using Archie's formula in clean sandstone and heterogeneous sandstone. Therefore, the new technique (PSONN) starts by predicting Archie's parameters m, a, n and then testing and validating results with the currently used techniques' results, CAPE, 3-D and conventional and calculated water saturation profiles and measured water saturation values on sandstone plugs in studied sections of wells under study. An accurate determination of Archie's parameters is vital in water saturation determination either in clean formation or in shaly formation using water saturation models. The prediction performances of AI models highly depend on the quality of the input data. Before feeding any data to the AI system, data analysis and pre-processing steps were performed. Data pre-processing step involved statistical ways to remove outliers and unrealistic values that are highly recommended in NN methods and taking advantage of AI techniques [10, 13, 15-17].

2. Conventional Determination Techniques of Archie Equation Parameters

In the field of formation evaluation and calculation of initial oil in place using electrical logging data, Archie water saturation model is the key stone. Therefore, Archie's parameters should be accurate. Currently there are three techniques for Archie's parameters a, m and n determination; conventional technique, CAPE technique and 3-D technique.

2.1. Conventional Determination of Archie's Parameters

Archie (1942) presented imperial formula relating rock resistivity, R_t, and porosity, $\emptyset$, and water saturation S_w [18];

$$S_w^n = \frac{aR_w}{\emptyset^m R_t} = \frac{R_o}{R_t} = \frac{1}{I_r} \quad (1)$$

To calculate water saturation exponent, Eq.1 is arranged in the form:

$$LogI_r = -nlogS_w \quad (2)$$

The coefficients and m are determined by plotting F vs $\emptyset$ of the equation $F = \frac{a}{\emptyset^m}$:

$$\mathrm{logF = loga - mlog\emptyset} \quad (3)$$

2.2. Core Archie-Parameter Estimation (CAPE)

Maute et al. (1992) had proposed CAPE technique for Archie's parameters m, an and n determination using numbers of electrical measurements (I) for numbers of plugs (j) [19]. CAPE is based on setting accepted minimum error (ε) between measured water saturation and calculated water saturation using assumed a, m and n values on core plugs using following equation.

$$\varepsilon = \sum j \sum i \left[Sw_{ij} - \left(aRw_{ij}/\emptyset_i^m R_{t_{ij}} \right)^{1/n} \right]^2 \quad (4)$$

2.3. Three Dimensional Regressions (3D)

Hamada et al. (2002) introduced new technique to calculate Archie's parameters a, m and n which three dimensional techniques (3-D technique) using electrical measurements on sandstone plugs [10]. 3-D technique arrange water saturation Eq.1 and taking the form of Eq.5 where water saturation, S_w is variable and considering it as three dimensional regression version of $\frac{R_w}{R_t}$, S_w, and $\emptyset$.

$$log\frac{R_w}{R_t} = -loga + mlog\emptyset + nlogS_w \quad (5)$$

3. Artificial Intelligence Determination of Archie's Parameters

Particle swarm optimization (PSO) is based on considering a cluster of point randomly distributed within studied band. Each point was identified as element. Elements fly having definite speed and the task is to find the right location (gbest) followed to certain number of iteration. At the end of iteration process, the particle would be retained as a point in an N-dimensional space that manages relevant speed forwarding to designed momentum and relevant effect of its target (pbest) and also the target position of its surrounding elements (gbest), Figure 1 shows the elements of flying model used in the development of the algorithm [9, 20].

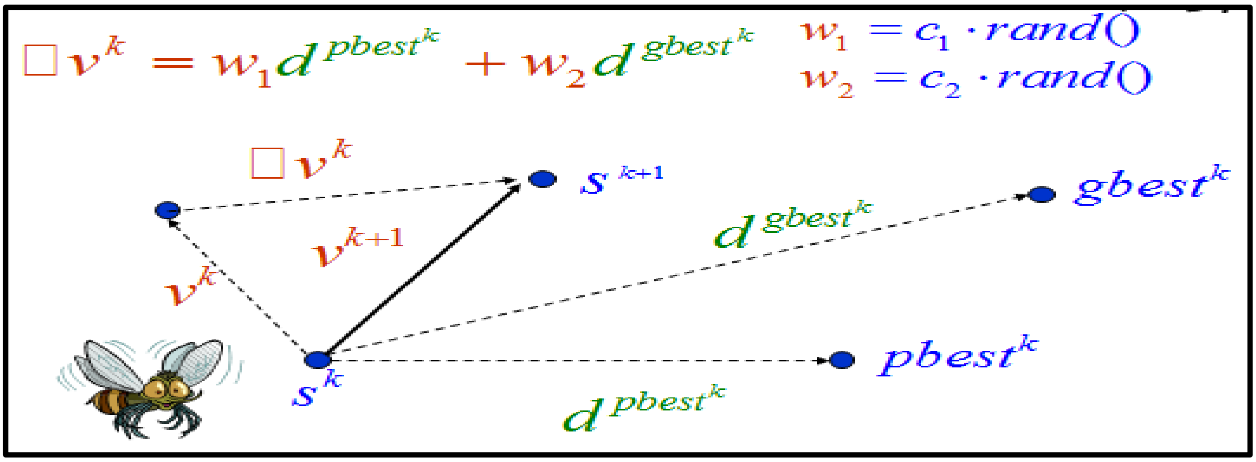

Figure1. Shows particle flying model (adapted from [9])

Following to finding the two best values of PSO, elements continuously changes its speed (V) and locations (S) according to equations [7, 10].

$$V_i^{(k+1)} = \omega V_i^{(k)} + w_1 \left(pbest_i - S_i^{(k)}\right) + w_2 \left(gbest_j - S_j^{(k)}\right) \quad (6)$$

$$S_i^{(k+1)} = S_i^{(k)} + V_i^{(k+1)} \quad (7)$$

3.1. Hybrid Parallel Self-Organizing Neural Network (PSONN) Model

Artificial Neural Network (ANN) is defined as learning and improving where machine learning technique enables it to learn from experience, generalize on their knowledge, make errors and does not need to be reprogrammed. Hybrid system of parallel self-organizing neural network (PSONN) uses the concept of combination algorithm of the Particle Swarm Optimization (PSO) with the back-propagation Neural Network (BPNN). PSO and NN should be integrated to achieve the convergence around global search faster. On the other side, combining of PSO and NN could minimize the constraints of the individual application. PSONN algorithm englobe the aspects of PSO and BB, this would lead to big improvement of Neural Network efficiency. Particles positions in in PSONN are set of weight for current nonlinear iterations. Each particle has a dimension which is the weighting numbers that is connected with the selected network. Root Mean Squared Error (RMSE) is considered as the learning error of this network which have been deduced using particles mobilizing within the weighting spaces targeting minimum learning errors. Learning process of PSONN was based on two steps: First step; PSO is designed for an optimal connected weights during neural networks, second step; Back propagation learning rule and training algorithm were applied to manipulate the final weights. Figure 2 illustrates the learning performance of PSONN technique, training performance reached 0.049926 at epoch of 417. In this case study, the neural network parameters (weights and basis) have been optimized by the PSO algorithm and the selected input parameters of neural network and system have been adopted as three layers. One hidden layer (tansig) is taken as intermediate function and other two hidden layers (purelin) are used as a transfer function to get final output [5, 16].

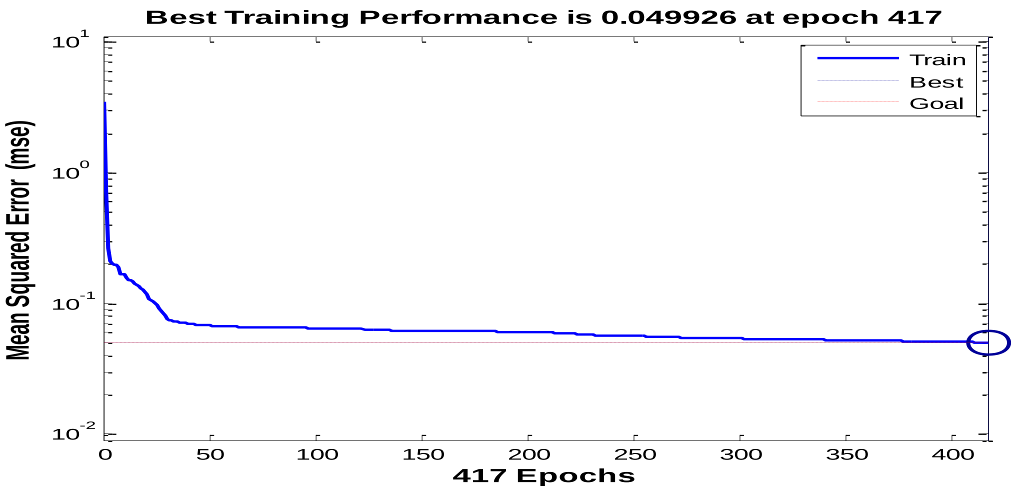

Figure 2. Training performance of PSONN.

3.2. Data Description

Using 144 sandstone core samples from three wells seventy core plugs, well I; fifty core plugs from well II, and twenty four core plugs, well III. Artificial intelligence technique has been trained, tested and validated. The design of hybrid system (PSONN) was tailored according to the number of points available keeping in mind reaching the minimum absolute average percent relative error (AAPRE) and also optimizing the relative absolute error, correlation coefficient and root mean square error for given set points for studied ore plugs.

3.3. Validation

The statistical analyses showed a good agreement between actual and calculated water saturation using parallel self-organizing neural network (PSONN). Figure 3 illustrates the statistical errors of the current techniques namely conventional, CAPE and 3-D methods and PSONN algorithm, it is obvious that the average error, standard deviation and RMS errors of PSONN is lower than the current methods and conventional method has higher error. Table 1 shows the absolute errors and correlation coefficients of the current methods and PSONN algorithm, and it is found that PSONN has high correlation coefficient (0.95) and minimum error (0.092).

3.4. Results and Discussion

In order to reach minimum error and getting reliable values, PSONN network configuration was designed as follow: numbers of hidden Layers = 3., Hidden Neurons numbers= 35., Max Iteration essay = 120., Conjugate factor (c1, set number 80, number of particles 600, no. of generated points 700, inertia weight (w), 0.67., maximum speed 3.75 and dimension numbers 150, dimension numbers have to be referred to numbers of bias and weights that are direct function of the feeding parameters in PSONN modelling scheme. PSONN arrangement was used to estimate Archie's parameters a, m and n and consequently predicting water saturation values using Archie' formula. It was planned to test the correlation coefficient of the five techniques in water saturation, Figure 4 that shows that CAPE (m,1, n) and conventional methods have low correlation coefficient while PSONN and 3-D have reasonably high correlation coefficients. In this study, conventional, CAPE, and 3D techniques and PSONN are applied on sandstone core samples. Table 1 summarizes statistical error analysis of water saturation values; absolute errors, minimum and maximum absolute error, correlation coefficient, standard deviation and finally the root mean square relative error of the four current techniques and the proposed PSONN algorithm. Figure 5 depicts measured water saturation profile as reference profile and water saturation profiles determined by three techniques; conventional, CAPE and 3-D and PSONN. Water saturation profiles in Figure 5 have shown that PSONN water saturation is closer to measured water saturation profile and conventional water saturation profile is far from measured saturation profile. Comparison of the five water saturation profiles in studied section of a producing well leads to the conclusion that 3-D is better than CAPE and conventional and PSONN approach with its high correlation coefficient and low statistical error can be supplement or may be replacing the conventional methods for determination of Archie's parameters; thereby; reliable calculation of water saturation profile.

This article demonstrates the idea of the application of AI algorithms, such as PSONN to predict water saturation from well-logging data. Figures 3, 4 and 5 revealed that PSONN might be promising tool in water saturation prediction from well log data collected by the authors without relying on a resistivity log. These methods can be applied to reduce the cost of core measurements and well-logging services. In all combinations of predictors considered, Super Learner is proved to be useful to combine the merits of base machine learning algorithms and enhance predictive robustness on water saturation.

Table 1. Statistical errors in Archie's parameters determination techniques

Methods	**Absolute Error**			**Erms**	**S**	**R**
	Ea	**Emin**	**Emax**			
Conventional Technique	0.207	0.005	1.08	0.32	0.22	0.90
CAPE (m,1,n) Technique	0.124	0.0015	0.37	0.17	0.11	0.91
CAPE (m,a,n) Technique	0.094	0.001	0.34	0.13	0.085	0.94
3-D. Technique	0.101	0.003	0.52	0.144	0.109	0.911
PSONN T Technique	0.065	0.0001	0.33	0.092	0.068	0.95

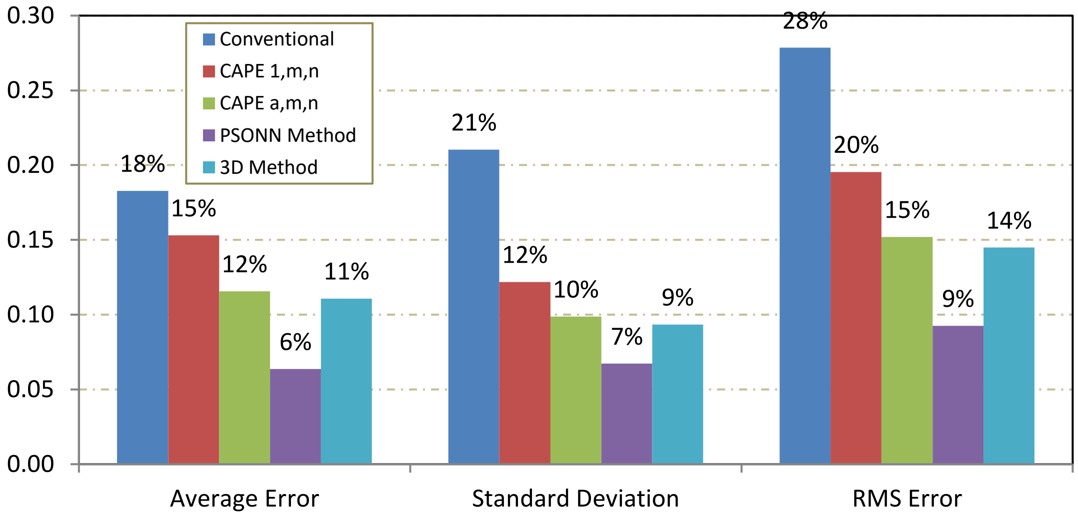

Figure 3. RMS, Standard deviation and average error for five techniques

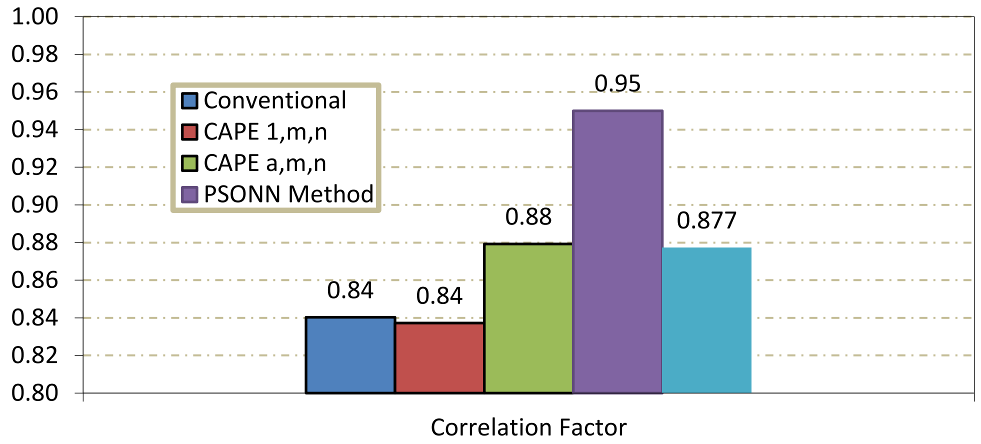

Figure 4. Correlation coefficients values for five techniques

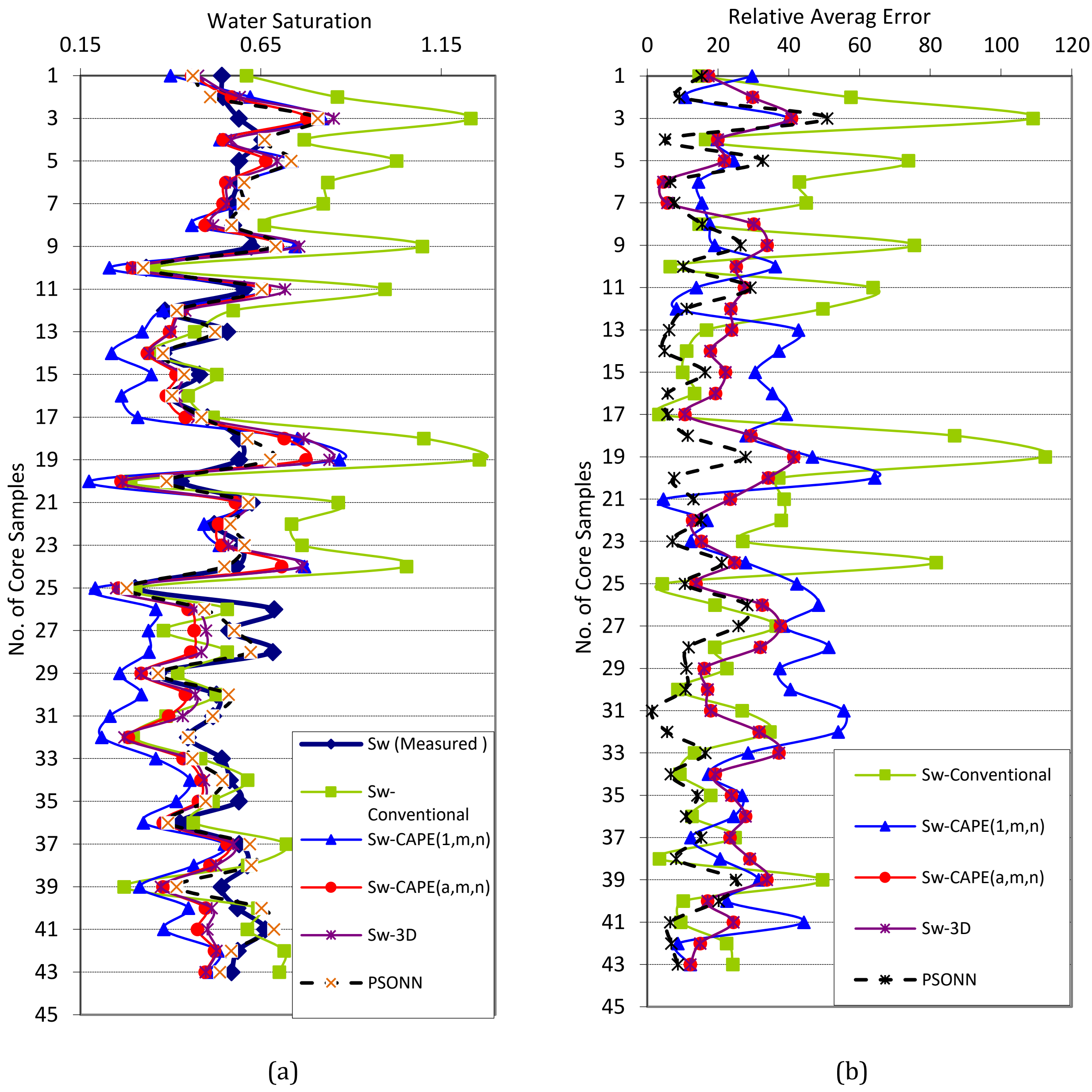

Figure 5. Profiles of water saturation calculated by Archie's formula using five determination techniques and measured water saturation profile, a) water saturation profile and b) Relative errors curves

It is of high potential to increase the accuracy of well logs interpretation in wells, where some data are not available. Two different datasets were used in this study to observe the effect of diverse variables. The main advantage of using intelligent methods in estimation water saturation is that with knowing examples of previous patterns, they can be easily trained and put to effectively solve unknown or untrained instances of the problem. In addition, there is no need to calculate the complex coefficients such as cementation factor, tortuosity factor, saturation exponent, etc. The results confirm the performance of the proposed Ai models and mainly PSONN algorithm in estimation water saturation, particularly never applied super leaner. In addition, in this study, estimated water saturation was achieved without relying on resistivity log, which could be challenging to certain geological structures. The proposed model can be employed in several applications of static reservoir modeling, such as porosity and permeability prediction in the future.

4. Conclusions

- Determination of Archie's parameters must be accurate to get reliable water saturation values for securing an accurate initial oil in place
- 3-D technique, CAPE and conventional techniques determine Archie's parameters m, an and n. But 3-D gives better results than CAPE and conventional techniques
- PSONN algorithm has proved that it can give good estimate of Archie's parameters. PSONN can also provide Archie's parameters where other techniques are not available or difficult to use the technique due to missing parameters.
- Different artificial intelligence techniques such fuzzy and ML in addition to PSONN can contribute heavily in the evaluation of the reservoir petro physical properties. It is imperative to select the right approach giving more accurate results for given data.

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