Permeability Estimation Model from Grain Size Sieve Analysis: Data of Onshore Central Niger Delta

Chikwendu E. Ubani, Goodness O. Ani, and Toluope T. Womiloju

Abstract—Permeability is an important property of the soil and studies have shown that grain size distribution is a controlling factor to this property. Establishing an empirical equation that shows the relationship between permeability and grain size has been previously investigated by several researchers, all of whom have been able to develop models for fast permeability prediction using grain size data. But because of the complexity of permeability and the Earth’s anisotropic nature, the confidence level of using this models is low as was seen when a comparison was carried out in this project using some of these models. The aim of this project is to develop a model using grain sieve analysis data for permeability prediction tailored to the Niger Delta region. Using statistica7 software, multiple regression analysis was performed on the grain size distribution data from sieve analysis using parameters P10, P90 and mean grain size distribution. Three models were developed for permeability ranges of less than 10mD to greater than 10000mD with R2 values of (0.857, 0.820, 0.939) showing a good data and regression fitting and R values of (0.926, 0.906, 0.969) showing strong positive correlation between variables. Permeability values obtained from routine core analysis was compared to the predicted permeability gotten from the model equation produced by the regression analysis. The models displayed good correlation with the routine core analysis values as seen on the validation charts plotted. A coloured schemed 3-D surface plot was generated to display the integrated effect of the grain size and density on permeability. The sensitivity analysis carried out showed that proper grain sorting is essential in permeability prediction.

Index Terms—Permeability; Grain Size; Niger Delta Region; P10 and P90 Percentile; Routine Core Analysis.

I. INTRODUCTION

Recovering of hydrocarbons from the reservoir is the essence of petroleum exploration and permeability prediction or estimation aids in the determination of the quantity that can be recovered from a reservoir. Permeability is a measure of the ease of flow of liquid through a porous media [1], [2]. The knowledge of permeability is an important parameter in determining flow characteristics for hydrocarbon reservoirs and ground water aquifers. It is also used during reservoir stimulation and rock type descriptions. Permeability is measured in m², but practically in Darcy (D) or milli-Darcy (mD), (1D ≈ 10⁻¹² m²).

Permeability is defined in three types, based on the flow of hydrocarbon in the reservoir:

Absolute permeability (Kₐ): Permeability calculated with only one fluid present in the pores of a formation is called absolute permeability.

Effective Permeability (Kₑ): the permeability of a formation with immiscible fluids but able to conduct one fluid in the presence of the other(s) is called Effective Permeability (Kₑ).

Relative Permeability (Kᵣ): this is the ratio of effective permeability of a fluid to the formation’s absolute permeability (100% saturated with that fluid).

Permeability measurement is performed in the Laboratory using a permeameter, this measures the flows of liquid or gas through a samples. Another method of measuring or predicting permeability is by estimating from logs by the use of different equations such as Timur, Tixier, etc. and in situ Darcy test for horizontal permeability [3] and shallow zones [4].

Grain size and other variables such as porosity, density, sorting, grain packing, and grain shape are essential is permeability determination of unconsolidated soils and as such used to establish empirical equations for the estimation of permeability. Researchers such as [5], and many others made efforts in developing empirical equations for predicting permeability from grain size, porosity, sorting, packing and grain shapes.

Darcy’s law (fundamental relationship) gives the basis for permeability determination. Darcy law was transformed into an equation, given as:

\[ q = kA \frac{\Delta h}{L} \]  \hspace{1cm} (1)

Further investigations into Darcy law reveals that the constant of proportionality ‘K’, if replaced by ‘K/µ’ can be extended to other liquids. This modification makes Darcy’s law suitable for this study as:

\[ q = -\frac{kA}{\mu L} \Delta P \]  \hspace{1cm} (2)

Where; k is the Permeability of the rock (mD), q is flowrate (cm³/s), µ is the viscosity of the fluid flowing through the rock (cP), A is Cross-sectional area (cm²), L is Length (cm), ΔP is Pressure change (atm).

Empirical based equations are not assuredly transferrable from region to region due to soil heterogeneity [6]. Sediments in the Niger Delta are deposited in layers which can make them exhibit anisotropies. Therefore, it is imperative to determine the appropriate equation for the Niger delta basin.

Published on December 25, 2018.

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DOI: http://dx.doi.org/10.24018/ejers.2018.3.12.503
This work aimed at developing a model that predicts permeability from grain size sieve analysis, in the Niger Delta Region. Empirical relationship to predict/estimate permeability for Niger delta basin using grain size sieve analysis data will be established, the result obtained will be correlated with results from standard routine core analysis as a check means for accuracy and compare with a previous developed models.

II. FACTORS CONTROLLING PERMEABILITY

Permeability is an intricate property that is affected by physical properties of the soil and the fluid passing through it. [3]. In sandstones, grain size, size distribution, grain orientation, grain packing and arrangement, cementation, clay content, bedding and sorting controls how permeable the rock unit is. In carbonates, permeability is controlled by the degree of mineral diagenetic change (dolomitization), fractures and porosity development [7], [8].

A. Porosity:
For a system to be permeable, it must have interconnected pore spaces (Porosity), and the relationship between permeability and porosity, which in most cases is said to be linear i.e, as porosity increase, permeability increase.

B. Grain Texture and Structure:
This relates to the arrangement of grains, its shape and size in the rock unit, grain shape influences its size and the interconnection of the pores. The less rounded the grains are, the smaller the pore spaces and more tortuous the flow paths [2].

C. Grain Packing and Confining Pressures:
Packing refers to the spacing and density of grains. Strongly lithified rocks (more dense) have reduced permeability under confining pressure.

D. Grain Density:
This is the proportion of the bulk of solids contained in a soil to the soil’s absolute volume i.e. the addition of solids and voids volume [9].

III. GRAIN SIZE

Grain size is the measure of individual grain diameter of a sediment and other granular material. This ranges from boulders to gravel through sand, silt and clay. The grain size scales commonly used are the Wentworth and Krumbine phi (φ) scale and the International Scale ISO 14688-1:2002. How the grain sizes are distributed affects permeability [10], this distribution is commonly characterised using indices such as constant of uniformity (cu = \( \frac{P_{60}}{P_{10}} \)), constant of curvature (cc = \( \frac{P_{30}^2}{P_{10}P_{50}} \)) and particle size percentiles (P10, P30 etc.). The larger the constant of uniformity, the better the soil grading and the smaller the permeability and vice versa [11].

In particle size analysis, the following methods can be used to derive grain size:

A. Sieve (Sifter) Analysis:
This is a devise that separate disaggregated rock samples into their various particle size distribution using a mesh or sifts wanted material from unwanted materials. Sieve analysis is carried out using a stack of sieves, Fig. 1.

B. Image Particle Analysis:
Measurements using this technique is done using digital imaging. It includes particle size, particle shape and colour (basically grey scale). The basic process of this technique is shown in Fig. 2. The instrument records a spread based on the length of the particle and shapes rather than how spherical it is.

Fig. 1. Automated Sifter with different sieve sizes stacked on it [12].

Fig. 2. (a) The principle behind the Camsizer (b) Typical Camsizer [13]
Reference [16], in their work to determine the ease of flow in an aquitard, employed the use of a modified version of the above equation as given by Peck and Terzaghi.

\[ k = \frac{g}{v}C_i\left(\frac{g^{-0.13}}{1-g^{-0.13}}\right)^3D_{10}^2 \]  

(5)

where; \( C_i \) – coefficient of sorting (6.1 x 10^{-3} to 10.7 x 10^{-3}), other parameters are as defined above.

Reference [17] determined the hydraulic conductivity of a particular location using grain size analysis data by employing Sen and Alyamani equation, that allows for the use of the slope intercept of the 50th and 10th line of grain weight (%) against mesh size. This equation is suitable for well graded soils and is stated below;

\[ k = 1.5046[I_0 + 0.025(D_{50} - D_{10})]^2 \]  

(6)

Where; \( K \) – permeability (m/day), \( I_0 \) – slope intercept, \( D_{10} \) - Grain size mesh equivalent of the 5th cumulative weight percentage (mm), and \( D_{50} \) – Grain size mesh equivalent of the 50th cumulative weight percentage (mm).

Reference [18] published his model for the unconsolidated sands of Niger delta, using grain size result obtained from sieve analysis and he came up with two equations for permeability of less than 1000 and greater than 1000. He verified his finding by correlating his result with the values of permeability obtained from routine core analysis. The permeability expression is stated as:

\[ k \leq 1000 \text{ mD} \]

\[ k = 15.27 \text{cov}^{-0.03} - 16.28 \text{d}_{0.07} + 0.7668 \text{Davg}^{0.5} + 1.7 \]  

(7)

\[ k \geq 1000 \text{ mD} \]

\[ k = 71068.35 \text{Davg}^{1.2} \times \exp\left(\frac{\text{cov}}{\text{s.d.}} \times 1.63\right) \]  

(8)

Where; \( K \) - permeability (D), \( \text{Davg} \) – average grain diameter (mm), s.d - sorting term (phi), and cov - coefficient of variation (phi/mm)

V. METHOD

Data obtained from the laboratory are subjected to analysis, to develop a model that can be used to predict permeability based on cumulative frequency distribution curve of weight (%) and mesh size (phi). Data are obtained from 35 samples in the Central Niger Delta in Nigeria.

A. Developing the Model

The grain size fractions obtained from sieve analysis, their weight percentages and percentiles are used to carryout multiple regression to develop the model. Cumulative weight percent obtained from each samples are plotted against mesh size. This is to enable the extraction of data points from the curve. Fig. 4, shows the cumulative frequency distribution curve of one of the sample ID (Sample 9). Tenth and ninety percentiles (P10 & P90) are read off from the curve of each sample. The mean of the
distribution is estimated from each sample using the equation below:

\[ x_{ms} = \frac{\sum_{i=1}^{n}(cwi \cdot x_{msi})}{\sum_{i=1}^{n}(cwi)} \]  \hspace{1cm} (9)

Where; cwi – Cumulative weight (%), x_{msi} – Mesh size (phi), n – Number data point in the series.

The model function is defined as:

\[ k = f(x_{ms}, P10, P90) \]  \hspace{1cm} (10)

STATISTICA 7 software was utilized in developing the model. The choice of the software is to generate statistical indicators, which are used in the analysis of the model.

The data points are imported from Microsoft excel file into the software. Three models, each were entered into the user-special model environment and was simulated to determine the model parameters.

VI. RESULTS AND DISCUSSION

The multiple regression analysis performed on the grain size data obtained from sieve analysis resulted in the development of three permeability prediction models with their statistical indicators. The models were developed for three different permeability ranges from less than 10mD to greater than 10000 mD. The models are shown below:

**Model A:** For \( K < 10 \) (\( R^2 = 0.857, \ R = 0.926 \))

\[ k = -a_0 P10 + a_1 \left( \frac{P90}{P10} \right)^{-a_2 x_{ms}} \exp \left( -a_3 \left( \frac{P10+P90}{x_{ms}} \right) \right) \]  \hspace{1cm} (11)

Where \( a_0, a_1, a_2 \) and \( a_3 \) are constants denoted by -1.2260, 106.1442, -0.1386 and -1.2887 respectively.

**Model B:** For \( 10 < K < 10000 \) (\( R^2 = 0.82, \ R = 0.906 \))

\[ k = -9358.13 + \omega_1 x_{ms}^{6.38} + \omega_2 x_{ms}^{4.55} \]  \hspace{1cm} (12)

where

\[ \omega_1 = 12.6 P10 - 20.38 x_{ms} + 4.27 P90 \]

\[ \omega_2 = -81.85 P10 + 201 x_{ms} - 48.54 P90 \]

**Model C:** \( K > 10,000 \) (\( R^2 = 0.9394, \ R = 0.969 \))

\[ k = -a_0 P10 - (a_1 P90^{-a_2 x_{ms}}) - \frac{a_3}{P10 - P90} \]  \hspace{1cm} (13)

Where \( a_0, a_1, a_2 \) and \( a_3 \) are -17884, 6526, -0.238 and 126145 respectively.

The developed models are non-linear with normal distribution curve skewed to the left as shown in Fig. 5, 6, and 7 below.

**A. 3D Prediction Plot**

Considering the effect of density on permeability, a relationship was established between permeability, density and grain size to develop a 3D prediction surface as shown in the Figure below. The colour represents permeability values at different ranges. As shown in the Figure, with increase in density there is a decrease in permeability, since the higher density values tends toward green colour which indicates lower permeability values.
B. Model Validation

Adetiloye (2016), model, was compared with the model developed in this work. The choice for selecting this model is the fact that it was developed for the Niger Delta region using parameters such as the average grain diameter ($D_{avg}$), sorting term ($s.d$), covariance ($cov$) and model constants as shown in Equations (7) and (8). Equation 8 of the two Models was used in comparison with Model C developed in this work, because both models allow for calculation of permeability values that are greater than 1000 mD.

The analysis result is seen in Table 1, and it is observed that there are large variations in the predicted permeability which can result from the parameters used in the models. Adetiloye’s model considered constants that may have caused the variation as a result of the heterogeneity of the Niger Delta sands. Kenny and Hazen’s model equation considered a fraction of the grain distribution which doesn’t represent the whole distribution.

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<th>Sample ID</th>
<th>RCA Observed</th>
<th>Adetiloye Predicted</th>
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C. Model Validation Chart

The developed models are validated with the permeability values gotten from the routine core analysis and it is plotted alongside the predicted permeability for each of the developed model as shown in Fig. 8, 9, and 10 below, which gives a visual representation of the model and analysis differences.

D. Model Sensitivity

To examine the changes in permeability when mean mesh size distribution, P10 and P90 are varied, a sensitivity analysis was carried out. To properly understand the changes in the target variable (permeability) as the input variables are varied, a MATLAB program was developed to generate a surface plot of the three models.

The permeability and mean mesh size axis of Model A, reveals that mean mesh size above 3.45, are good prediction
of permeability. Similarly, value of P10 and P90 above 4.3, shows that an increase in grain size leads to an increase in permeability.

As P10 and P90 value increase, the permeability of Model B increases signifying that P10/P90 are good indicators for permeability estimation. The value of P10/P90 above 1.5 shows that permeability increases as mean mesh size decreases and below this value, permeability increase as mean mesh size increase. The later signifies that proper sorting of the grain size can lead to high permeability.

Sensitivity plot for Model C, exhibits similar analysis as that of Model B. it differs in that the value of P10/P90 above 0.0 shows that permeability increase as mean mesh size decrease and below this value, permeability increases as mean mesh size increases. These variations are as a result of grain sorting and grading. At higher permeability values, because of Vugs, fractures and heterogeneity, the uncertainty level is increased. The importance of proper grain sorting can be observed from this plot.

VII. CONCLUSION

The complexities of permeability are dependent on grain size, distribution, shape and density which acts as determinants as to the interconnectivity of the pores in sands. Therefore, the developed models for permeability prediction were built to accommodate different ranges of permeability from as low as<10 to as high >10000. Because of these permeability controlling factors, developing a prediction model of 100% accuracy is impossible.

Variables used in developing the model are gotten from percentile grain distribution and a mean distribution index calculated from the cumulative weight percentage so as to get a proper representation of the whole sample distribution. Correlation of parameters in the models show strong positive affinity between parameters. All three models are advanced non-linear models with constants and coefficients.

Succeeding literature review, laboratory procedure and statistical analysis, and the outcomes of this work, are outlined as follows;

1) The models developed have multiple determination coefficients of 0.82 to 0.94 showing that the model fits well with the data.
2) The result from the comparison affirms the reason why empirical equations are not certainly transferable from region to region due to soil heterogeneity.
3) The sensitivity analysis shows the importance of proper grain sorting in permeability determination.
4) The 3D surface plot displays the relationship between permeability, density and grain size distribution. This surface can be used concurrently to assess the impact of grain size distribution and density on permeability.

APPENDIX

Statistic Indicators of the Models

Model A

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DOI: [http://dx.doi.org/10.24018/ejers.2018.3.12.503](http://dx.doi.org/10.24018/ejers.2018.3.12.503)
MODEL B

TABLE B-6: Parameter Estimate

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MODEL C

TABLE B-10: Parameter Estimate

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REFERENCES


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