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Performance Evaluation of Mechanistic Pore Pressure Prediction Models in Deepwater Niger Delta

TIMI IBUCHI OLAWUYI[1], BONIFACE A. ORIJI[2], EMEKA E. OKORO[3]
[1, 2, 3]*Department of Petroleum and Gas Engineering, University of Port Harcourt*

Abstract- Prediction models exist through which pore pressure estimation can be made, however, there exists some discrepancies between measured values and predicted values. This study explores the performance of mechanistic pore pressure prediction models rooted in Terzaghi's principle (Eaton, Bower, and Miller's models) in four (4) Deepwater wells in the Niger Delta region. The study presented the predictions and quantitatively measured their performance using mean absolute error and percentage average absolute deviation. Quantitatively, Bower's model had the lowest mean absolute error (MAE) and percentage average absolute error (PAAD) for the 4 Deepwater wells, followed by Eaton, then Millers. In one of the wells (Well3), The mean absolute error was 761.62, 1709.22, and 2759.11 for Bowers, Eaton, and Millers models respectively. For the same well, the percentage average absolute error was 17.75%, 38.14%, and 62.79% for Bowers, Eaton, and Millers models respectively. Caution should be exhibited in the application of the models with proper fine tuning, if they are to be used in predicting pore pressures in Deepwater Niger Delta. This study has significantly advanced the understanding of pore pressure prediction in Deepwater Niger Delta, by revealing in a quantified manner, the deviations of pressure predictions with these models from measured values.

Index Terms- Deepwater, Performance Evaluation, Pore Pressure Prediction, Niger Delta

I. INTRODUCTION

Pressure evaluation plays a crucial role in well planning and safe drilling operations. Understanding both pore pressure and fracture pressure is essential for defining an appropriate mud weight window, which ensures wellbore stability and prevents formation damage or blowouts. These pressure estimates are also critical when determining the correct setting depths for casing strings throughout the drilling process. Accurate pressure data allows engineers to anticipate formation behavior and avoid costly complications. Drilling techniques such as underbalanced drilling (where the mud hydrostatic pressure is lower than the formation's pore pressure), overbalanced drilling (where it exceeds the pore pressure), and managed pressure drilling (which involves actively controlling the annular pressure profile) require precise pressure knowledge for effectiveness and depends heavily on accurate pressure models. Without a solid understanding of both pore and fracture pressures, these techniques cannot be effectively or safely implemented. Thus, pressure analysis remains a foundational component in planning and executing efficient drilling operations.

Pore pressure data can be gotten using direct or indirect approaches. Direct methods provide accurate results and involve direct measurements of pore pressure with tools and approaches like the Repeat Formation Tester (RFT), Drill Stem Test (DST), and Reservoir Characterization Instrument (RCI). Although the direct method is accurate, but it is very expensive and often limited to specific depths. The indirect methods involve the use of models to predict pore pressure. This approach is used to estimate pore pressure for the entire well. Some of these models are specifically tailored to some specific geological basins or formation types and may not be universally applicable. Also, to effectively use these models requires an understanding of how the Normal Compaction Trend (NCT) line can be determined. The Normal Compaction Trend (NCT) line serves as a baseline to identify abnormal pressure zones. Wrongful interpretation of the Normal Compaction Trend (NCT) line or an incorrect application of the

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model can lead to significant drilling risks. To this end, combining direct measurement data where feasible and carefully selected empirical models backed by thorough knowledge in geology is vital for reliable pore pressure prediction. This would lead to safe drilling operations, selection of optimum mud weight, effective wellbore stability management [1].

Formation pressure is the pressure exerted by the fluids in the pore spaces of a rock. Normal pressures gradients are within the range of 0.433 psi/ft. and 0.465 psi/ft. Abnormal pressure gradients can either be subnormal or overpressure/geo-pressured. Subnormal pressure gradient is less than 0.433 psi/ft., while overpressure/geo-pressured has a pressure gradient is greater than 0.465 psi/ft. [2]. Figure 1 displays pressure gradients plots [3].

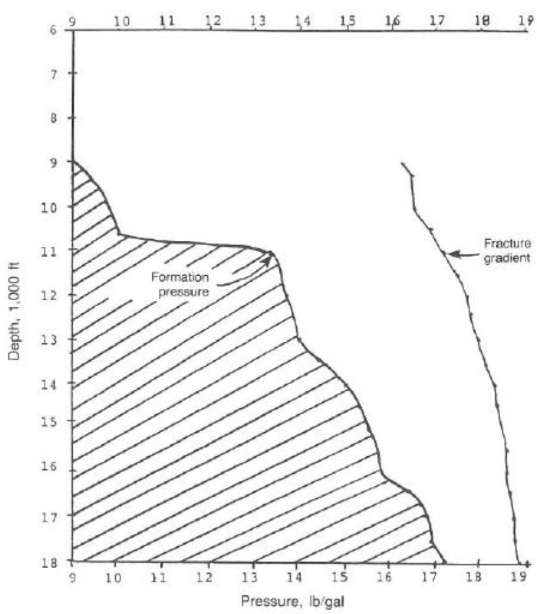

Figure 1: Pressure gradient plot

Given the growing challenges of high drilling costs and increasingly stringent environmental regulations, there is a strong need for more accurate and efficient pore pressure prediction methods.

The root causes of abnormal pressure (under-compaction, fluid expansion, or hydrocarbon generation) needs to be understood and knowledge obtained used to build models. One technique involves estimating pore pressure using the ratio between the compaction exponent and effective stress. This method has been noted to be more accurate than the standard exponent method, specifically for shale formations because it provides a more objective basis for defining the normal compaction trend. Unlike well-specific models, this approach allows the compaction trend to be applied across an entire field, reducing subjectivity and improving consistency in pressure estimates. To understand better, rock and fluid properties in the context of overpressure estimation, three primary sources of subsurface data are commonly used: Logging While Drilling (LWD), wireline logging, and seismic reflection surveys. These data sources provide complementary information which when integrated effectively, can enhance the reliability of pore pressure models and support safer, more cost-effective drilling operations [4].

Drilling Engineers can also infer the relative pore pressure of subsurface formations in real time by carefully monitoring the mud weight, gas readings, fluid influxes, and mud losses. This is crucial for maintain well control and ensuring safe drilling operations. Drilling Engineers can detect variations in formation pressure and make prompt adjustments to the mud weight by analyzing the changes in these parameters [5].

The Deepwater in the Niger Delta region has garnered continuous interest, although the reserves observed are considerably significant, challenges in extracting the hydrocarbons are also significant. These challenges increase the costs of production from assets in these areas. It is thus vital for fundamental aspects of drilling operations in this area to be evaluated. One of such fundamental aspects is the prediction of pore pressures at the well design stage

The degree of compaction was evaluated in order to predict pore pressure. Established models including Einsele equation was employed. A combination of Hubbert and Rubey modeified Athy's pore pressure model with Terzaghi's effective stress principle was used to enhance pore pressure estimation accuracy. Well logs were obtained from the Niger Delta to support these analysis and model calibrations [6].

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Forecast on pore pressure in the Niger Delta region was done using available field data. Eaton's resistivity model and his transit time model were used. It was noted that Eaton's model is simple and its prediction performance is reliable in similar geological setting [7].

Eaton and Bowers' models were used to predict pore pressure in the Niger Delta. They were noted to have been selected so as to provide a comparative understanding of pressure behavior across different depth intervals and geology. It was concluded as noted that Bowers' model is better suited for pore pressure prediction in areas like the Niger Delta where both compaction and unloading mechanisms influence subsurface pressure regimes [8]. Pore pressure was also evaluated and predicted in the Malcom Field, situated offshore in the Niger Delta, using wireline log data. The prediction used Eaton's model [9].

Well logs from three (3) offset wells were used to predict pore pressure. Eaton's, Bowers', and Tau's models were used. It was noted that from observation, Eaton's model under predicted the formation pressure of the area in all the wells used and could be the least appropriate model for pore pressure prediction in the region [10].

Studies more numerous than these have been done in estimating pore pressures in the Niger Delta, but the Deepwater Niger Delta still lacks investigation. Quantitively measuring the deviations between the measured pore pressure and estimated pore pressure using models of Eaton, Bower's and Millers in Deepwater Niger Delta fills this gap.

It has been noted that although there exist models to predict pore pressures, the pressures encountered are quite different from those estimated using existing models at the well design stage. This resultant effect is an increase in the well construction costs as a result of the non-productive time (NPT) that arises from problems encountered during the drilling process and additional costs made to mitigate those problems.

Eaton, Bowers, and Millers are pore pressure estimation models rooted in Terzaghi's principle and widely used in the industry. While Eaton, Bowers, and Miller models have been widely adopted, their performance under the unique overpressure regimes and lithological variability of the Deepwater Niger Delta remains under-investigated. Also, there has been disparity in literature as regards the prediction superiority between Eaton and Bowers' models in the Niger Delta. This study bridges this gap by investigating the performance of these empirical pore pressure estimation models in predicting pore pressures in Deepwater Niger Delta. This investigation compares the prediction performance of these empirical models with actual measured pore pressure data in the Deepwater fields. A quantitative approach using percentage average absolute deviation was utilized in the performance evaluation. This investigation into the performance of widely used pore pressure prediction models with respect to actual measure data can aid in better understanding the predictions and shortfalls. The study focused only on the widely used models of Eaton, Bowers, and Miller. Economic analysis was not considered.

II. MATERIALS AND METHOD

A structured and quantitative methodology was applied in this study to investigate the performance of empirical pore prediction models of Eaton, Bowers, and Miller in Deepwater, Niger Delta.

The Niger Delta region covers an area between latitude 3ºN and 6ºN and Longitude 4ºE and 8ºE. The Niger Delta basin is bounded to east and west by the Calabar Flank and Benin Flank respectively, the Gulf of Guinea to the South and in the North by older (Cretaceous) tectonic structures like Anambra Basin, Abakiliki uplift and Afikpo Syncline. It has a thickness of more than 10km that is composed of overall regressive clastic sequence, and a delta which prograde southwestward to form major active depobelts. The Niger Delta is rated amongst the productive hydrocarbon tertiary deltas in the world and covers an area of 75,000 square kilometers [11]. The Niger Delta is situated on the Gulf of Guinea in the southern part of Nigeria as shown in Figure 3.1.

The Niger Delta Basin is the most prolific and economic sedimentary basin in Nigeria by the virtue

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of the size of petroleum accumulations, discovered and produced as well as the spatial distribution of the petroleum resources [12].

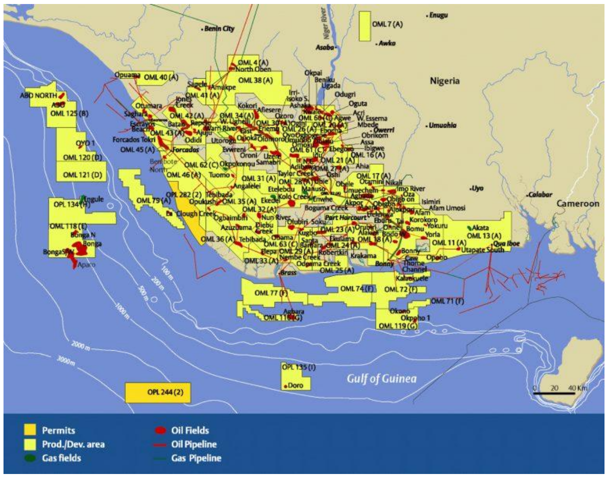

Figure 2: Map of the Niger Delta showing reserve portfolio (OpeOluwani, 2019)

A. Data Acquisition

The dataset utilized for this study were derived from well logging measurements and pressure data acquired from four (4) drilled wells in Deepwater Niger Delta region of Nigeria, a geologically diverse and hydrocarbon-rich region in southern Nigeria, under strict confidentiality.

These multiple drilled wells in Deepwater Niger Delta region of Nigeria span formations with mixed lithologies, including alternating sequences of shale, sandstone, and siltstone, which are representative of the complex depositional environments characteristic of the deltaic system.

These datasets typically include both direct measurements and derived logs relevant to pore pressure estimation. Specifically, the primary well logs used as part of the sample include: sonic (Δt), resistivity (RT), density (RHOB), neutron porosity (NPHI), Gamma Ray (GR), True Vertical depth (TVD), and measured Pore Pressure data. The sample was chosen to represent various geological formations, lithologies, and depth ranges to ensure that the developed models are robust and generalizable across different subsurface environments.

Before the research was carried out, the collated data was first processed. The data processing involved data cleaning such as removing outliers and null values. The dataset was then transformed. The dataset was in separate files, they were then merged into one single file for each well. Units of measurements were checked and converted to ensure that all parameters were in the same units of measurements.

The sampling technique adopted for this study is a combination of purposive sampling and stratified random sampling. Purposive Sampling was used initially to select wells that had complete and high-quality data. Wells with known anomalies, incomplete logs, or missing pressure data were excluded to maintain data integrity. Stratified Random Sampling was then used within the selected wells to ensure that the data represents all depth intervals and lithological variations. Each stratification layer represented a zone or formation of interest (e.g., shale, sandstone, or reservoir intervals), and within each stratum, random sampling was performed to select data points.

B. Mechanistic Models

Empirical models are widely used in estimating pore pressure and most widely used models in the industry have roots in Terzaghi's principle and include Eaton's model, Bower's model, and Miller's model.

Eaton, based on his work in the Gulf of Mexico, developed the following models for prediction of pore pressure in shales using resistivity and sonic logs. Eaton's resistivity model [13] is as presented in equation 1:

$$P_P = \sigma_v - (\sigma_v - P_n)\left(\frac{R}{R_n}\right)^n \quad (1)$$

Where, σ_v is the vertical stress, P_n is normal pore pressure, R is a value from the resistivity log, R_n is a measurement value assuming that the formation is frequently pressured, n= 1.2.

Eaton's sonic model [14] is as presented in equation 2:

$$P_P = \sigma_v - (\sigma_v - P_n)\left(\frac{\Delta t_n}{\Delta t}\right)^n \quad (2)$$

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Where, σ_v is the vertical stress, P_n is normal pore pressure, Δt is the sonic transit time in shales obtained from well log, Δt_n is the sonic transit time in shales, n= 3.

The resistivity (R_n) or sonic transit time (Δt_n) in the normal compaction trend (NCT) needs to be obtained to apply Eaton's Method. The Eaton's equation expressed in terms of the D-Exponent is as presented in equation 3 [15]:

$$\frac{P}{Z} = \left[\frac{S}{Z} - \left[\left(\frac{S}{Z} - \frac{P_n}{Z}\right) x \left(\frac{D}{D_n}\right)^{1.2}\right]\right] \quad (3)$$

Where P is the pore pressure (psi), Z is the depth (ft.), P_n is the normal pressure (psi), S is the overburden pressure (psi), D is the observed d-exponent, D_n is the NCT d-exponent.

Bowers proposed the model for sonic velocity of shale and effective stress is as presented in equation 6 but obtained from equations 4 and 5 [16]:

$$V_p = V_{ml} + A\sigma_e^B \quad (4)$$

Where V_p is the compressional velocity at a given depth, V_{ml} is the compressional velocity in the mudline (that is the seafloor or the ground surface, normally $V_{ml} \approx 5000, or\ 1520\ m/s$), σ_e is the vertical effective stress, A and B are the parameters obtained from calibrating regional offset velocity versus effective stress data.

Replacing,

$$\sigma_e = \sigma_v - P \quad (5)$$

Where P is the pore pressure

$$P = \sigma_v - \left(\frac{V_p - V_{ml}}{A}\right)^{\frac{1}{B}} \quad (6)$$

Where A= 10-20 and B=0.7 – 0.75, where P, σ_v, are in psi, and V_p, V_{ml} are in ft/s

Miller's sonic method was presented to describe a relationship between velocity and effective stress that can be used to relate sonic/seismic transit time to formation pore pressure, as presented in equation 7:

$$P = \sigma_v - \frac{1}{\lambda}\ln\left(\frac{V_m - V_{ml}}{V_m - V_p}\right) \quad (7)$$

Where V_m is the sonic interval velocity in the matrix of the shale (asymptotic travel time at infinite effective stress, V_p is the compressional velocity at a given depth, λ is the empirical parameter defining the rate of increase in velocity with effective stress (normally 0.00025).

C. *Model Performance*

The analysis was focused on performing pore pressure predictions with models of Eaton, Bowers, and Millers as provided in Equations 1 to 7 and making quantitative comparisons between models' predictions and measured pore pressure data. Statistical analysis was first carried out on the dataset to get a description of it. The models utilized were those of Eaton, Bower, and Miller. Mean absolute error (MAE) as presented in equation 8, was calculated for the models' predictions. To measure quantitatively the level of deviation the models' predictions have from the measured pressure data, percentage average absolute deviation (PAAD) as presented in equation 9, was utilized.

Mean Absolute Error (MAE):

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|x_{actual} - x_{predicted}\right| \quad (8)$$

Percentage Average Absolute Deviation (%AAD):

$$\%AAD = \frac{1}{n}\sum\left|\frac{x_{actual} - x_{model}}{x_{actual}}\right| \quad (9)$$

III. RESULTS

This section begins by outlining the key findings derived from the analysis, offering insights into the data trends and observed behaviors within the subsurface formations. Table 1 and Table 2 presents the performance analysis of the models using Mean Absolute Error (MAE) and Percentage Average Absolute Deviation (PAAD) for the four (4) wells. respectively. Figures 3 to 6 displays the predictions from the models for the four Deepwater wells.

Table 1: Mean absolute error of prediction models for different Deepwater wells

	Well 1	Well 2	Well 3	Well 4
Eaton	976.77	1310.36	1709.22	1391.43
Bowers	837.55	975.74	761.62	896.38

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Millers	2787.95	3006.04	2759.11	2594.89

Table 2: Percentage average absolute deviation of predictions for different Deepwater wells

	Well 1	Well 2	Well 3	Well 4
Eaton	976.77	1310.36	1709.22	1391.43
Bowers	837.55	975.74	761.62	896.38
Millers	2787.95	3006.04	2759.11	2594.89

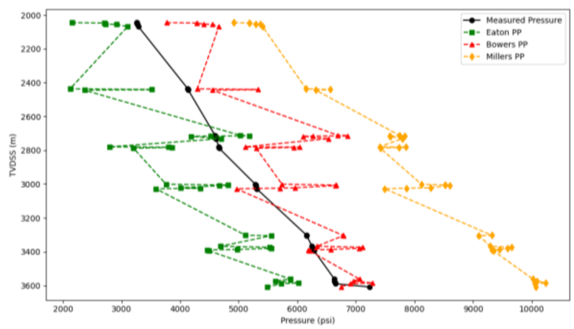

Figure 3: Models prediction plot for Well 1

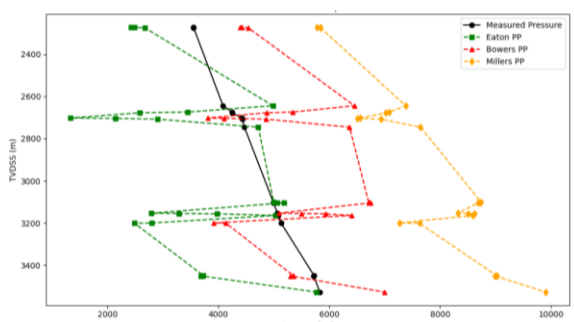

Figure 4: Models prediction plot for Well 2

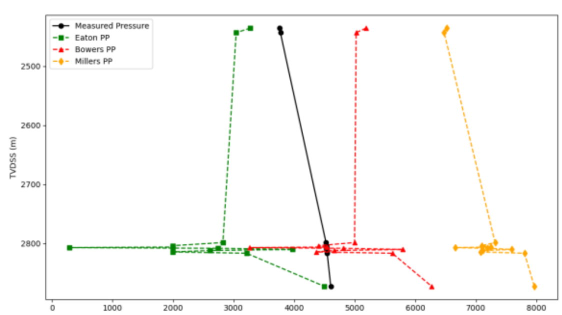

Figure 5: Models prediction plot for Well 3

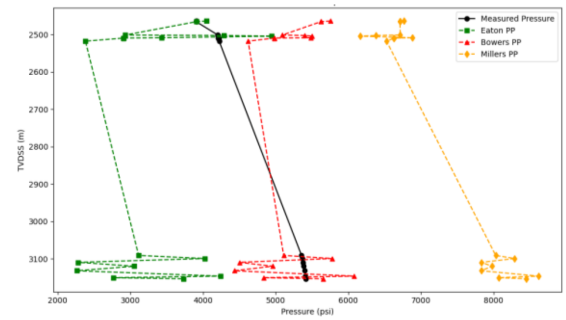

Figure 6: Models prediction plot for Well 4

Pore pressure prediction was done using Eaton, Bowers, and Millers for each of the four wells using the data obtained. Comparative analysis was performed on the predicted pore pressures and measured pressure data for each well as seen in Figures 3 to 6. From the plots, it is visible that the predictions of Miller would indicate an overpressure and this prediction could be, in reality closer to the fracture pressure. The predictions of Bower's. although not as high as that of Miller's, is still not accurate and could be misleading. While the predictions of Eaton shows a prediction below the measured pore pressure data.

Quantitatively, Bower's model had the lowest mean absolute error (MAE) for the 4 Deepwater wells with values of 837.55, 975.74, 761.62, and 896.38 for the wells. This is followed by Eaton with (76.77, 1310.36, 1709.22, and 1391.43. Millers model had a high mean absolute error (MAE) for the 4 Deepwater wells with values of 2787.95, 3006.04, 2759.11, and 2594.89. Quantifying the error from the measured values in percentages, Bowers' model also had the lowest with a percentage average absolute error of 18.53%, 21.20%, 17.75%, and 20.59%. This is followed by Eaton's model with values of 19.8%, 27.82%, 38.14%, and 28.22%. Millers's model had the highest percentage average absolute error with values of 56.09%, 63.29%, 62.79%, and 56.41%.

CONCLUSION

This study aimed at investigating the performance of industry established pore pressure prediction models in Deepwater Niger Delta with respect to actual measure data so as to aid in better understanding the predictions and shortfalls. By analyzing pore pressure predictions from these models, the study identified quantifiable prediction performance deviations.

Caution should be exhibited in the application of the models with proper fine tuning, if they are to be used in predicting pore pressures in the Niger Delta.

Further works should be done on exploring existing fracture pressure prediction models in Deepwater Niger Delta. This would aid in ensuring a safe mud weight window is utilized while performing drilling operations.

This study has significantly advanced the understanding of pore pressure prediction in Deepwater Niger Delta, by revealing in a quantified manner, the deviations of pressure predictions from the reality. This work lays a strong foundation for continued progress in pore pressure prediction.

This study has contributed to the advancement of literature in Drilling Engineering.

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