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A New Approach to Wellbore Stability Models Using Diagnostic Iteractive Design: Case Study - Niger Delta

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Abstract

The change in stresses around the wellbore can cause compressive failure or tensile failure of the wellbore wall and can lead to wellbore instability. The induced stresses should be adjusted through mud pressure. The case study confirmed that the establishment of safe mud limits for borehole stability is as important as the establishment of the pore pressure and fracture gradient before the commencement of oil and gas well drilling. Mogi-Coulomb and Mohr-Coulomb criterion were applied as part of the fundamentals in supporting a new approach for prediction of safe mud weight window in an iterative manner until convergence is obtained. A Mohr-Coulomb Criterion was applied for comparisons. The actual mud weight and fracture gradient are used as control. Five drilled wells with wellbore instability issues in the Niger Delta were used as case studies. A problem diagnostic was conducted to ascertain the main cause of the instability issues in these wells. An excel-based spreadsheet was developed for the calculations using available data. An improved and modified coupled Mogi-Coulomb criterion gave a broad window between the lower limit mud weight and the upper limit mud weight than the Mohr-Coulomb criterion when compared with the actual mud weight and fracture gradient. This is because the Mohr-Coulomb criterion is free of the intermediate principal stress; therefore, it gave a very slim mud weight window. Proper mud weight determination, therefore, gave good borehole stability and reduction in down time while drilling.

***Keywords**: Compressive failure; Wellbore stability; Safe mud window; Coupled Mogi-Coulomb criterion; Mohr-Coulomb criterion.*

1. Introduction

Drilling fluid is generally perceived as a very vital and the heart of drilling operations. Every aspect of drilling operations, whether directly or indirectly, depends on drilling fluids, which can be properly managed to alleviate a difficult drilling situation. A drilling fluid is termed adequate and good if it fulfills some basic requirements; it has to be generally simple with a number of additives and should be able to perform basic drilling fluid functions ranging from lubricating drilling bit to maintaining wellbore stability. The performance of a drilling fluid should be technically driven and not based on mere assumptions. Care must be taken during drilling fluid selection and application, if not, very dire consequences ranging from wellbore instability, loss of lives, environmental pollution, and degradation to drilling rig equipment destruction [1]. Three important factors that are usually considered before mud selection for drilling of wells include; cost, technical performance, and environmental impact. The most significant of all the three is the technical performance of the drilling mud [2-3]. Even though the cost of implication is very important, but should only be considered on a cost-performance basis. High mud density is associated with high wellbore pressure and could ultimately fracture the formation and may result in loss circulation. The resultant effect will be formation fracturing that will lead the invasion of mud into the formation, resulting in tensile failure. But Gholami *et al.* [4] observed that a lower mud weight could cause shear failures, known as wellbore breakouts. Edwards *et al.* [5] noticed that instability caused by the shear failure of the compacted rock could be mitigated by raising the mud density. However, where pre-existing planes of weakness dominate the mechanism of instability, mud weight increases do not necessarily lead to a more stable hole and can further destabilize the wellbore. Low wellbore pressure due to low mud weight may lead to wellbore collapse, which can result in a kick if it is less than the formation pressure [6]. It is vital to prevent unnecessary pressure increase due to solids contaminated mud, especially in the unstable formations. Some drilling additives can improve borehole stability [7]. The concept of a safe mud window with minimum wellbore instability is shown in Fig.1.

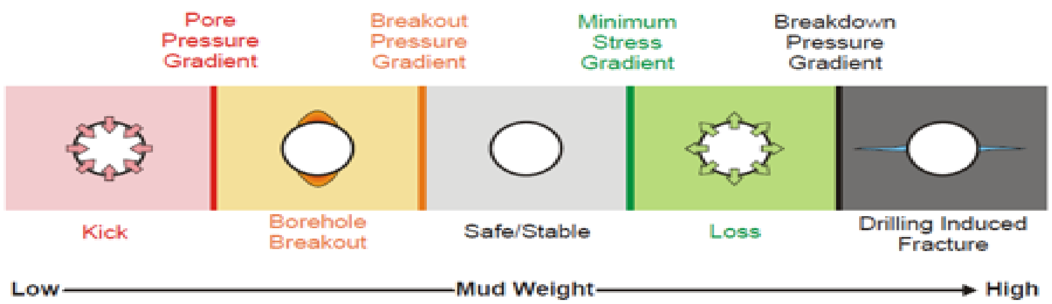

Fig. 1. The concept of safe mud weight Limits for Wellbore drilling [8]

Selection criteria of mud weight have changed; it now becomes imperative to understand it during well operations. Selection of Mud weight for pressure control and wellbore stability requires knowledge of not only pore pressure gradient and fracture gradient but also collapse gradient of formation. The most important point in this research is to show the imperativeness of safe mud window during oil and gas drilling operations. Most Operators only looked at the chemical reactions and fracture gradient, without quantifying the magnitude of minimum and maximum mud limits for successful operations. The mud weight window has three specific paths to attain wellbore stability. In geo-mechanical terms, mud weight window is the value or range of values that might be used to keep safe operation while drilling. This model is the introduction of the estimated principal stresses into the Coupled Mogi-Coulomb rock failure criterion. In this analysis, the only convenient factor is the mud weight; that is, the fluid density of the drilling fluid [9]. Minimum values of this window correspond to the minimum weight required to avoid collapse formation in the borehole; maximum values addressed to prevent hydraulic fracturing while drilling and optimum weight is the suggested mud weight to perform drilling. The predetermined method in the selection of mud weight window during well planning has uncertainties for wellbore stability analysis [9]. Quantitative Risk Assessment (QRA) method has been successfully applied in pre-drill condition solving the problem of the variability of input parameters like principal stresses and rock properties. The output of this process recommends the mud weight window with the probability of drilling success, which can avoid the wellbore collapse and lost circulation [10]. Most criteria and mud weight determination approaches overestimate the predicted mud weight for the safe drilling; thus this paper tends to develop a suitable criterion for designing sufficient mud weights in Niger Delta region by analyzing the well, geo-mechanical and mud data from selected previously drilled wells in the Niger Delta Region, perform thorough wellbore stability analyses to understand the causes of well problems on the selected case studies, generate safe mud weight window for the 5 wells in the case study and to compare new model results prediction against an existing failure model.

1.1. Rock failure modes and criteria

Understanding the types and reasons for formation failures is important as prevention and also for mitigation. Wellbore log data such as caliper and image logs are helpful to provide information identifying wellbore failures during drilling. Analyzing wellbore image data also helps in proving reliable information about the failure mode, whether it is tensile, compression, or shear failure. One of the examples of tensile failure is drilling induced hydraulic fractures. Shear failure is also known as a compressive failure; it takes place when the compressive loading makes the shear stress along the plane high enough to cause the rock to undergo shear failure. Borehole collapse during drilling is an example of shear failure. Creep failure takes place when the rock formation undergoes deformation under constant stress over time. In wellbore instability analysis, rock strength needs to be known in other to evaluate wellbore failure stresses. Depending on the type of formation, the constitutive model that is appropriate should be selected, and an accurate rock failure criterion that defines stress conditions at failure must be chosen. Rock failure criteria can have a linear form of nonlinear form. It can equally be characterized by considering the effect of intermediate principal stress on rock strength, such as models by Modified Lade and Mogi-Coulomb. Mohr-Coulomb and Hoek-Brown, on the contrary, are examples of rock failure criteria that assume the effects of intermediate principal stress to be zero. Many rock failure criteria have been used in wellbore stability analysis to determine the minimum drilling mud weight. McLean *et al.* [11] compared Mohr-Coulomb and different forms of Drucker-Prager to predict the minimum mud weight. The results showed a criterion that can predict a realistic result in one situation but give unrealistic results for other conditions. Ewy [12], in his research, developed the Modified-Lade failure criterion and presented the merits of this new criterion over Mohr-Coulomb and Drucker-Prager. Al-Ajmi *et al.* [13] developed the linear form of Mogi-Coulomb and compared that with the Mohr-Coulomb failure criterion. They proposed the use of Mogi-Coulomb over Mohr-Coulomb with regard to fitting poly-axial test data as well as prediction of the borehole breakout pressure. Colmenares *et al.* [14] evaluated seven different rock failure criteria based on poly-axial test data, and they concluded that the Modified Lade and the Modified Wiebols-Cook fit best with poly-axial test data. Based on the evaluation of four rock failure criteria, Nawrocki [15] predicted borehole breakout pressure. He approved Modified Lade as a reliable failure criterion for wellbore stability analysis. Only a few evaluations of the failure criteria were based on the typical reservoir rock related situations, although many comparisons have been previously studied on some failure criteria.

2. Methodology

For the last two decades, the selection of mud weight was based on formation pressure. It escaped the notice that pore pressure is actually meant to control the influx of fluid in the well and has almost nothing to do with wellbore stability. The workflow developed to achieve this study is shown in Figure 2.

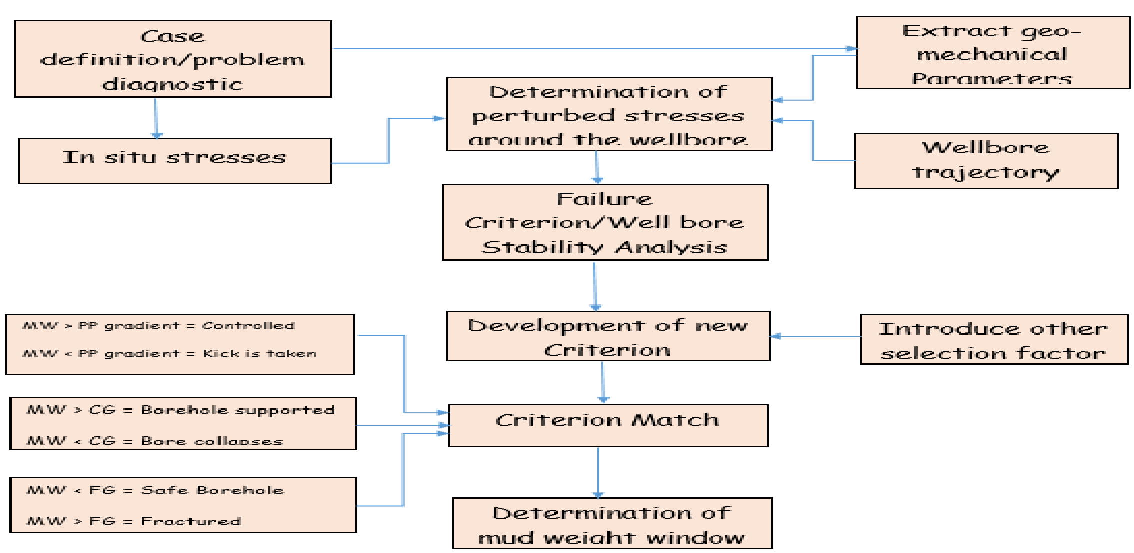

Fig. 2 Workflow for developing suitable criteria for designing sufficient mud weight

2.1. Case definition and problem diagnostic

The cases considered in this research, are wells previously drilled wells with typical wellbore instability problems in the Niger Delta. The effort to drill these wells as part of the field development plan was quite challenging. Out of the wells that were drilled in different blocks where these wells were selected, five (5) had experienced severe wellbore instability issues, failed to reach the target depth, and eventually were abandoned because of mechanical issues encountered. To troubleshoot the causes of the instability problems of the wells, a problem troubleshooting procedure was performed, which includes correlations and the re-evaluations of the well data of all the concerned wells.

- **Case Study 1**: Well T-101 was drilled for oil production. The initial plan was to drill a well with azimuth N 80° and inclination 50°. The kick-off point at 7,200ft, with final depth at 12,750ft measured depth. As per the initial well drilling program, the drilling process would have taken 32 days to complete. 10.34ppg was the planned mud weight for this segment. This mud weight was relatively high, but, wellbore instability still manifested in this segment. The initial problem occurred while pulling out of the hole the drill string; there was the sign of hole collapse, which lead to drill string stuck at 11,330ft measured depth. The over the pull of 60 ton, jarring and optimized circulation was applied but still negative to retrieve the bottom hole assembly. It was finally cut off at 11,000ft, pulled out of the hole, plugged back, and the hole was then side tracked as per the new drilling program.
- **Case Study 2**: Well A-33 was a development oil well, successfully drilled to target depth, with some wellbore instability problems. The well was drilled directionally with inclination 35° and azimuth N 98°. The first wellbore instability problem occurred at 8,830ft measured depth (shale formation) with mud weight of 9.05ppg. The drill string was released, and the mud then weighted up to 9.2ppg, and the formation was therefore successfully drilled. Another hole collapse occurred at 9,660ft measured depth (shale formation) below the pay zone. Finally, 9.49ppg mud was used to drill this segment.
- **Case Study 3**: Well D-705 was the proposed development gas condensate well with an expected production of 5 MMSCFD gas and 10 BCFD of condensate from this sand. The well was planned to be drilled directionally with azimuth N 305° and inclination 25°. The kick-off point is at 6,600ft, with target depth at 10,940ft measured depth. According to the plan, the drilling process would have taken 28days to complete. 9.1ppg mud weight was used in this section. Serious wellbore instability problem was encountered when drilling this hole segment. The drill string got stuck at 9.530ft measured depth due to hole collapse. All the effort, such as optimum mud circulation, using a spotting pill, and jarring proved abortive. The drill string was then cut off, pulled out of the hole, and plugged back. The well was side tracked at 9,780ft and drilled ahead with the increased mud weight from 9.1ppg to 9.33ppg. At 10,080ft measured depth, wellbore instability occurred, and the drill string got stuck. Mud circulation was then optimized, and the drill string was then freed. The drill string sits at 10,200ft measured depth while running in hole. The wash down was carried out, and much shale cuttings were recovered at the shale shakers. Unfortunately, the hole packed off again at 10,940ft measured depth. Tried to free the drill string, no result obtained. The drill string was then cut off at 10,620ft measured depth and retrieved the same. The plug back was done, and the top of cement was at 10,440ft measured depth.
- **Case study 4**: The field where well Z-47 was drilled has shown the past history of wellbore instability in spite of an increasing level of chemical inhibition. Hence, previously drilled wells in the field experienced critical hole pack-offs, stuck pipe incidents, and above all, larger unanticipated non-productive time. As per Well Z-47, which was planned a vertical well, the pore pressure was hydrostatic 0.462psi/ft, and the mud weight needed from the traditional well design approach was 0.4664psi/ft to drill up to 9,200ft measured depth with less than 3° inclination. The well was drilled to 8,820ft measured depth towards the 8½ inches section and then observed caving at shale shakers after pumping tandem pills and circulating bottoms-up done. All efforts proved by engineers to optimize the drilling parameters proved abortive, the

conclusion was that the mud weight was insufficient in spite of the inhibition of the mud leading to a critical stuck pipe incident.

- **Case study 5:** Well Q-01 originally planned to be vertical development oil well, the first wellbore instability problem occurred at 6,250ft measured depth (shale formation) with mud weight 9.12ppg. After successfully freeing the BHA, the drilling of this section was done by using mud weight 9.33ppg until it reaches the sandstone formation (target reservoir). Mud weight slightly increased above the fracture gradient caused the formation to fracture at 6,560 ft measured depth at shale formation (below the target reservoir), causing a severe lost circulation. 9.47ppg mud weight was used in this segment.

2.2. Model formulation

Wellbore failure occurs due to many different mechanisms, and an appropriate failure criterion is therefore highly required in the prediction of borehole stability that represented the true pore pressure and in-situ stress conditions. Several rock failure criteria exist, however for this study, the Mogi-Coulomb Shear and Tensile failure criterion were coupled, and a single model was obtained and was used for case study analysis.

The Mogi-Coulomb Shear failure criterion is given by:

$$T_f = a + b\sigma_{m,2} - \tau_{oct} \quad (1)$$

Where:

$$\tau_{oct} = \frac{1}{3}\sqrt{(\sigma_1-\sigma_3)^2+(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2} \quad (2)$$

$$a = \frac{2\sqrt{2}}{3} cCos\varphi \quad (3)$$

$$b = \frac{2\sqrt{2}}{3} cSin\varphi \quad (4)$$

$$\sigma_{m,2} = \frac{\sigma_1+\sigma_2}{2} \quad (5)$$

Shear failure will occur when $T_f \leq 0$. The Mogi-Coulomb Tensile failure criterion is given by:

$$T_f = \tau_{t\,min} + T_s \quad (6)$$

In this criterion, the formation will fail in tensile mode when the tensile strength of the rock is less than the minimum compressive principle stress at the wellbore,

$$\tau_{t\,min} = \sigma_3 - P_p \quad (7)$$

Substituting equation 7 into equation 6, the Tensile Failure Criterion becomes:

$$T_f = \sigma_3 - P_p + T_s \quad (8)$$

In Eq. 8, Tensile failure will occur when $T_f \leq 0$. A single linear expression Criterion was generated by coupling both the Mogi Coulomb Shear and Tensile failure to obtain the suitable mud weight window.

$$a + b\sigma_{m,2} - \tau_{oct} = \sigma_3 - P_p + T_s \quad (9)$$

$$T_f = \sigma_3 - P_p + T_s - a - b\sigma_{m,2} + \tau_{oct} \quad (10)$$

In Eq. 10, Shear and Tensile failure will occur when $T_f \leq 0$

2.3. Determination of safe mud weight limits

Calculations of Safe Mud Window were done based on the Solution of the interactions relations, which involve radial, tangential, and axial stresses, which are functions of the wellbore pressure; and the faulting regime of which the minimum in-situ may be the minimum vertical or horizontal stress. Fig.2 in the appendix, which is the workflow for the development of suitable criteria for designing sufficient mud weight, was then followed accordingly in the iterative manner until the convergent minimum and maximum safe mud window obtained. Firstly, the wellbore pressure, which is the hydrostatic pressure exerted by the mud equals to the formation pressure (if the well is still on the planning stage), or the mud density at which the failure occurred. Secondly, the wellbore stresses are computed for a point in wall circumference of the well tangential, vertical, and radial stresses were then applied to the failure criterion to know if the rock will be successful. This step is repeated for 50% of wall circumference due to their symmetry. In each step, 25° was added to the angle of internal friction of the rock till 180° was reached. If the rock falls at any angle, 0.0026psi was added to mud pressure (P_w), stresses are determined, and the procedure is repeated using rock and well data shown in Appendix A, Table 1. The iterative process continues until there is no more rock failure around the wellbore. This process, with some differences, is used to gain the upper limit and lower limit the of mud density. These procedures were carefully executed for five case studies. And the safe mud weight window was therefore obtained for each case.

3. Results and discussion

The improved coupled Mogi-Coulomb failure criterion was applied to predict the safe mud density limits by utilizing the local wellbore stresses from the individual wells, Tensile strength of the formations considered, and the mud weights in an iterative manner. The iteration is computed at several points in wall circumference of the well and at different trajectories for the directional wells. The plots of the safe mud weight window for the 5 wells considered shown in Figures 3 to 7 are obtained from Tables 2, 3, and 4.

Shear and Tensile failure will occur at the wellbore for negative values of the failure criterion ≤ 0; thus, from the plot, the safe mud weight window falls between 0.553psi/ft to 0.631psi/ft. Recall that Well T-101 drilled with a mud weight of 0.537psi/ft experienced shear failure in terms of severe hole pack off which lead to stuck BHA at depths around 12,500ft, because of mud weight which was thought to be relatively high. From the calculations, a safe drilling operation can be achieved by operating within the predicted mud weight window.

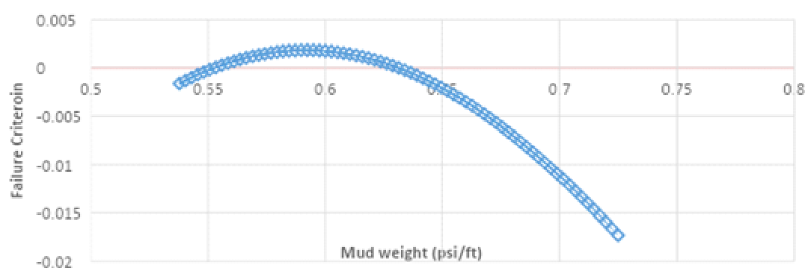

Fig. 3. Failure criterion vs. mud weight for Well T-101

The fracture gradient calculated from LOT at 9,660ft for well A-33 is 0.652psi/ft during the drilling phase, whereas the mud weight used for this hole section is 0.493psi/ft. This mud weight, however, posed serious hole problems, but using the coupled Mogi-Coulomb Failure function, a safe mud weight window between 0.566psi/ft to 0.6261psi/ft was predicted.

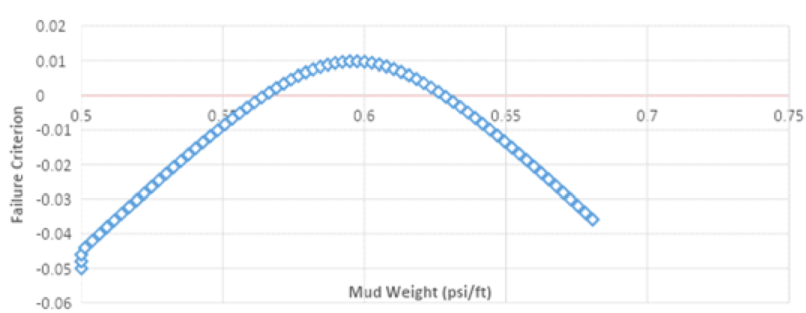

Fig. 4. Failure criterion vs. mud weight for Well A-33

Well D-705 can be drilled safely if the mud pressure falls between 0.498psi/ft. and 0.576psi/ft. The minimum mud weight predicted from this failure function is very close to the mud weight 0.485psi/ft used to drill this well at depths around 10,400ft. Mud weight selection for this well scenario is critical and will require operating between minimum and maximum mud weight window.

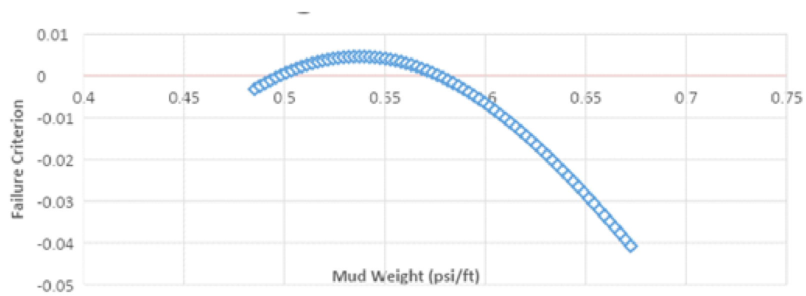

Fig. 5. Criterion vs. mud weight for Well D-705.

The mud weight window predicted for Well-Z47, as seen in Fig. 6 shows that the well can be safely operated at mud weight values between 0.479psi/ft. and 0.541psi/ft. to prevent borehole collapse or wellbore fracture. Looking at the close difference between the upper limit of the mud weight window and the fracture pressure (0.564psi/ft.) from LOT, it will be in the best interest of the drilling engineer to operate at mud weight values away from the predicted maximum mud weight values to prevent tensile failure.

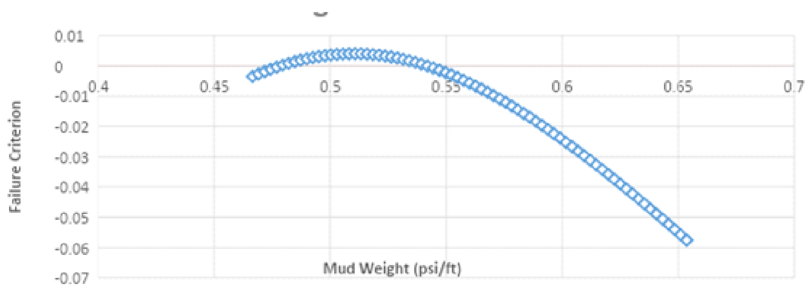

Fig.6. Failure criterion vs. mud weight for Well Z-47

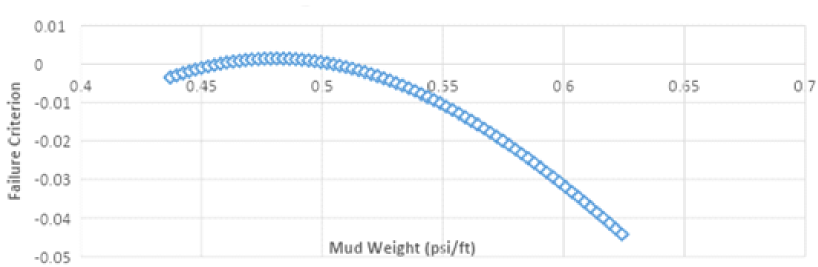

Fig. 7. Failure criterion vs. mud weight for Well Q-01

The Safe MWW for well Q-02 falls between 0.458psi/ft. to 0.502psi/ft. Borehole collapse or tensile failure will occur at the wellbore for negative values of the failure criterion F ≤ 0. The plot of failure function against mud weight for Well Q-01 shows quite a narrow mud weight window with most of the mud weight that satisfies the failure criterion lying almost flat at the X-axis. One key practice to be adopted considering this scenario is to continuously monitor the equivalent circulating density (ECD) during drilling operation as this resulting tensile failure in Well Q-01 is a clear case of the unprecedented increase in mud weight.

3.1. Comparison of the model results

Failure criterion versus mud weight for the five wells as shown in figures 3 to 7 of was applied to obtain the comparative analysis of different failure criteria for lower and upper mud densities, as shown in Figures 8 to 13.

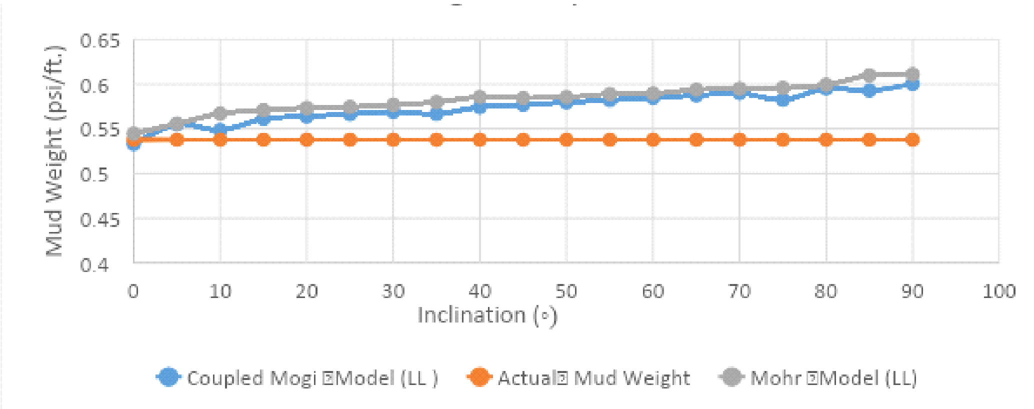

Fig. 8. Comparative analysis of different failure criteria on lower mud density for Well T-101

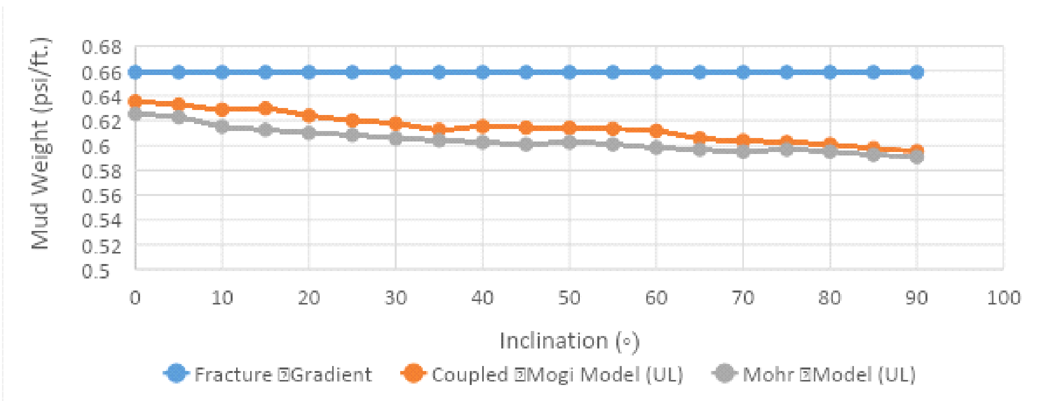

Fig. 9. Comparative analysis of different failure criteria on upper mud density limit for Well T-101

For Well T-101, which has an inclination of 50°, the Coupled Mogi model predicted 0.579psi/ft. as the minimum allowable mud weight whereas Mohr model predicted 0.585psi/ft as minimum allowable mud weight at 50° inclination as against 0.537psi/ft. used mud weight that resulted in the wellbore instability issue. For the maximum allowable mud weight, the coupled-Mogi and Mohr model predicted 0.6141psi/ft and 0.6025psi/ft.

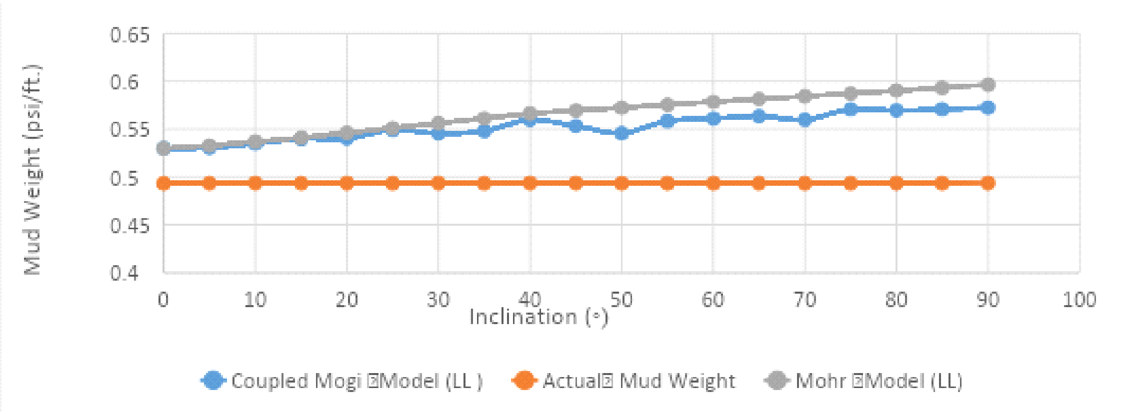

Fig. 10. Comparative analysis of different failure criteria on lower mud density limit for Well A-33

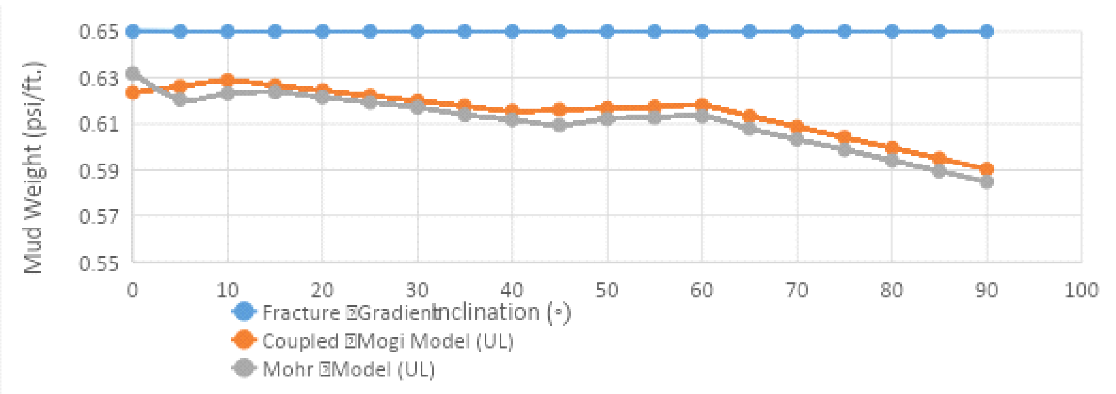

Fig. 11. Comparative analysis of different failure criteria on upper mud density limit for Well A-33

For Well A-33, the coupled Mogi model predicted 0.548psi/ft as the minimum allowable mud weight, whereas Mohr model predicted 0.561psi/ft as minimum allowable mud weight both at 35◦ inclination as against 0.493psi/ft used mud weight that caused hole pack off for this well. For the maximum allowable mud weight, the coupled-Mogi and Mohr model predicted 0.618psi/ft and 0.614psi/ft, respectively, which are still within range. The predicted mud weight for Well A-33 at different inclination are presented in the figures below.

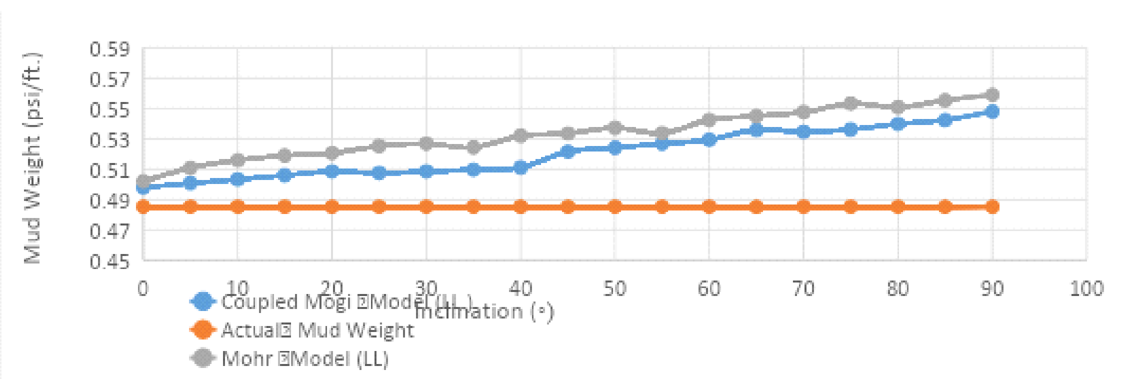

Fig. 12. Comparative analysis of different failure criteria on lower mud density limit for Well D-705

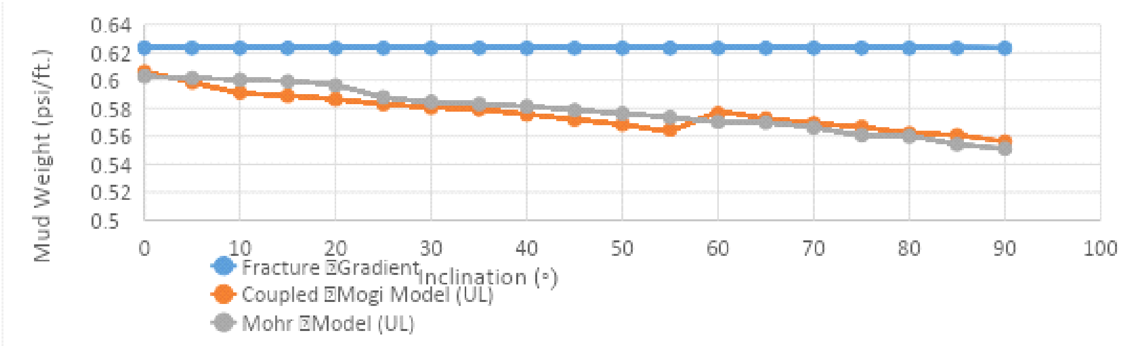

Fig. 13. Comparative analysis of different failure criteria on upper mud density limit for Well D-705

For Well D-705, The Coupled Mogi Model and Mohr model predicted 0.5074psi/ft and 0.5251psi/ft, respectively, as the minimum allowable mud weight at 25° inclination compared to 0.4852psi/ft. For the maximum allowable mud weight, the coupled-Mogi and Mohr model predicted 0.5831psi/ft and 0.5881psi/ft, respectively, at 25°inclination, which are still below the fracture pressure. The predicted mud weight for Well D-705 at different inclination are presented in the figures below.

The Coupled Mogi-Coulomb model and Mohr model predicted 0.4794psi/ft and 0.4082psi/ft, respectively, as the minimum allowable mud weight For Well Z-47 inclined at 0.9° with wellbore azimuth of 17° compared to the actual mud weight of 0.4664psi/ft that posed the stability problems for this well. For the maximum allowable mud weight, the coupled-Mogi and Mohr model predicted 0.5418psi/ft and 0.5372psi/ft, respectively, which are still within range. The predicted mud weight for Well Z-47 is presented in Table 5.

Table 5. Results of the actual and model predicted mud weight for Well Z-47

Hole Inclination (Deg.)	Coupled Mogi Model (LL) (psi/ft.)	Actual Mud weight (psi/ft.)	Mohr Model (LL) (psi/ft.)	Fracture Gradient (psi/ft.)	Coupled Mogi Model (UL) (psi/ft.)	Mohr Model (UL) (psi/ft.)
0.9	0.4794	0.46644	0.4802	0.5843	0.54181	0.5372

For Well Q-01, the Coupled Mogi model predicted 0.458psi/ft as the minimum allowable mud weight, whereas Mohr model predicted 0.45992psi/ft as minimum allowable mud weight. The actual mud weight used to drill Well Q-01, which is 0.49244psi/ft, initiated tensile failure (fractures) around the wellbore resulting in severe loss circulation. For the maximum allowable mud weight, the coupled-Mogi and Mohr model predicted 0.50181psi/ft and 0.4927psi/ft, respectively, which are almost close to the fracture pressure obtained from LOT shown in Table 6.

Table 6. Results of the actual and model predicted mud weight for Well Q-01

Hole Inclination (Deg.)	Coupled Mogi Model (LL) (psi/ft.)	Actual Mud weight (psi/ft.)	Mohr Model (LL) (psi/ft.)	Fracture Gradient (psi/ft.)	Coupled Mogi Model (UL) (psi/ft.)	Mohr Model (UL) (psi/ft.)
3	0.4578	0.49244	0.45992	0.5293	0.50181	0.4927

The variations in field data and methods employed for the evaluation of safe mud weight windows for the studied wells, produced variation in the results because the Mohr-Coulomb failure criterion does not include intermediate principal stress; it, therefore, yields the least allowable mud weight window.

4. Conclusions

In this research, a suitable criterion for selecting sufficient mud weights for drilling operations in the Niger Delta Region has been developed. No core samples or data was available to be used in the study. However, the study was conducted satisfactorily utilizing well log data, drilling reports, geo-mechanical, and geological data to create a wellbore stability model applicable in the study area. The coupled Mogi-Coulomb criterion developed in this research predicts the safe mud weight window in an iterative convergent manner and describes the rock failure more precisely than the traditional Mohr-Coulomb criterion that does not depend on the intermediate principal stress, and presents a very slim mud weight window. For rock analysis applications, therefore, it would be advantageous to employ this rock criterion. It was found that the well trajectory, drilling fluid density, sand type, stress regime, stress magnitude, and orientation have a significant impact on the wellbore stability in the study area. The two dominant stress regimes around the 5wells studied are normal faulting and strike slip faulting. This can vary on other Niger Delta wells/formation depending on the highest of the three principal or in situ stresses. The mud is designed inside a safe range called the mud weight window. For deviated well drilling, as the wellbore deviates, the stability envelope will narrow dramatically, which will increase the possibility of wellbore instability if the mud is not designed properly. Thus, the need for suitable failure criteria was then developed.

Appendix

Table1. Rock and Well data

Parameter	Well T-101 (Deviated)	Well A-33 (Deviated)	Well D-705 (Deviated)	Well Z-47 (Vertical)	Well Q-01 (Vertical)
Depth of consideration (ft)	12750	9660	10940	8820	6560
Formation/Sand type	Shale/Sandstone	Shale/Sandstone	Shale/Sandstone	Sandstone	Shale
Hole inclination (Deg)	50	35	25	0.9	3
Wellbore azimuth (Deg)	80	98	305	17	26
Poisson ration (v)	0.28	0.26	0.2506	0.314	0.33
Shear modulus(G)psi	702525	80910	50750	253750	435000
Bulk modulus (Kb)psi	1297315	21520.9	333500	288550	1370975
Matrix/Grain modulus (Km) psi	101500	3429.25	210250	14210	35235
Young modulus(E) psi	1785240	7999215	4112000	2760030	2703380
Bulk compressibility (Cb) psi	0.00076995	0.42195	0.09802	0.0078735	0.03741
Rock compressibility (Cr) psi	0.087	-0.0018995	0.0111128	0.00794354	0.00007337
Biot constant (α)	0.900	0.870	0.791	0.912	1.000
Uniaxial compressive strength (UCS)psi	7698.05	5611.5	4655.95	4502.25	3617.75
Cohesion (Co) psi/ft	0.251	0.105	0.1134	0.1008	0.1266
Tensile strength psi	640.9	735.15	564.05	572.75	613.35
Shear strength (τi) psi	5.7855E+16	2.581E-11	4.988E-09	2.8826E-07	1247
Vertical stress(σv) psi/ft	0.823	0.712	0.83	0.831	0.8421
Minimum horizontal stress(σh) psi/ft	0.671	0.633	0.591	0.568	0.514
Maximum horizontal stress(σH) psi/ft	0.778	0.827	0.708	0.929	0.722
Fracture gradient psi/ft	0.659	0.652	0.623	0.584	0.5293
Mud weight (Pc) ppg	10.34	9.49	9.33	8.97	9.47
Pore pressure gradient psi/ft	0.531	0.484	0.477	0.458	0.437
Pore pressure psi	6770.25	4675.44	5218.38	4039.56	2866.72
Friction angle (Deg)	27	24.5	19	25	19
Shale content (%)	0.2991	0.3222	0.3519	0.2822	0.3782
Mud weight gradient Psi/ft	0.53768	0.49348	0.48516	0.46644	0.49244
Radial stress	0.53768	0.49348	0.48516	0.46644	0.49244
Tangential stress	0.69732	0.57852	0.57984	0.30856	0.32756
Axial stress	0.76308	0.61112	0.7713596	0.604292	0.70482
A	-0.069133209	0.079830467	0.105706905	0.09419911	0.118011412
B	0.226321648	-0.058541409	0.016024054	-0.0125781	0.017889287
Mean stress	0.7245	0.730	0.6495	0.7485	0.618
Octahedral stress	0.09464229	0.049591365	0.119049136	0.12082434	0.154422144
Mogi failure criterion	0.000194535	-0.012496126	-0.002934608	-0.0360399	-0.02535515

Table 2. Results of in-situ stresses for the 5 wells

Parameter	Well T-101 (Deviated)	Well A-33 (Deviated)	Well D-705 (Deviated)	Well Z-47 (Vertical)	Well Q-01 (Vertical)
Depth of consideration (ft)	12750	9660	10940	8820	6560
Vertical stress (σ_v)psi/ft	0.823	0.712	0.83	0.831	0.8421
Minimum horizontal stress (σ_h) psi/ft	0.671	0.633	0.591	0.568	0.514
Maximum horizontal stress (σ_H) psi/ft	0.778	0.827	0.708	0.929	0.722

Table 3. Relatives magnitude and stress regimes

Well name	σ_v	σ_{Hmax}	σ_{Hmin}	Order	Regime
T-101 (D)	0.8236	0.778	0.671	$\sigma_v > \sigma_{Hmax} > \sigma_{Hmin}$	Normal
A-33 (D)	0.7120	0.827	0.633	$\sigma_{Hmax} > \sigma_v > \sigma_{Hmin}$	Strike-Slip
D-705 (D)	0.9132	0.708	0.591	$\sigma_v > \sigma_{Hmax} > \sigma_{Hmin}$	Normal
Z-47 (V)	0.8771	0.929	0.568	$\sigma_{Hmax} > \sigma_v > \sigma_{Hmin}$	Strike-Slip
Q-01 (V)	0.8421	0.722	0.514	$\sigma_v > \sigma_{Hmax} > \sigma_{Hmin}$	Normal

Table 4. Results of the local stresses for the 5 wells

Parameter	Well T-101 (Deviated)	Well A-33 (Deviated)	Well D-705 (Deviated)	Well Z-47 (Vertical)	Well Q-01 (Vertical)
Depth of consideration (ft)	12750	9660	10940	8820	6560
Radial stress (σ_{rr}) psi/ft	0.53768	0.49348	0.48516	0.46644	0.49244
Tangential stress (σ_{tt}) psi/ft	0.69732	0.57852	0.57984	0.30856	0.32756
Axial Stress (σ_{zz}) psi/ft	0.76308	0.61112	0.7713596	0.604292	0.70482

List of symbols

c	*The natural cohesion of the rock*
φ	*The angle of internal friction of the rock*
τ_{oct}	*The octahedral shear stress*
$\sigma_{m,2}$	*The mean stress and the principal stresses*
σ_1	*The maximum principal stress the intermediate principal stress*
σ_2	*The intermediate principal stress*
σ_3	*The minimum principal stress*
$\tau_{t\,min}$	*Effective minimum compressional principle stress at the wellbore*
T_s	*Tensile strength of formation*
σ_3	*The effective minimum compressional stress*
P_p	*The pore pressure of the formation*

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