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Evaluation of Optimum Mud Weight Window for Prevention of Wellbore Instability in Niger Delta Wells

Nmegbu Godwin Chukwuma, Bright Bariakpoa Kinate and Samuel Nmezi Frances
Department of Petroleum Engineering, Rivers State University, Nigeria
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Abstract: A Borehole instability problem contributes significantly to increase in non-productive time (NPT) and overall cost of the drilling. These problems can occur in a variety of forms including stuck pipe, loss circulation, hole enlargement, breakout. Borehole problems such as drill pipe sticking, hole collapse, breakout, ,caving and tight holes have been experienced during drilling of wells in an oil field in the Niger Delta. This work analyzed the major cause of wellbore instability in a field in the Niger Delta by using data from two wells drilled and proposes an optimum mud window for cost-effective and safe drilling operations. Geomechanical model was used to evaluate the in-situ stress and induced stresses with Mogi Coulomb and Mohr Coulomb failure criteria to predict the breakout profile and estimate the optimum mud weight to avoid sticking of the drill string. The result shows that the Mogi failure criterion was 1.46sg and 1.39sg while Mohr failure criteria were 1.48sg and 1.42sg for well 1 and well 2 respectively. Based on the results obtained, Mogi coloumb is preferable to Mohr coloumb criteria. Mogi failure criteria give more accurate result to obtain optimum mud weight window for the field considered in the Niger Delta. Therefore, in the prediction of an optimum mud weight window for any well in the Niger Delta, mohr failure criteria should be employed and adopted.
Keywords: wellbore instability, Mohr Criterion, Mogi Criterion, Geochemical Property, mud weight window

I. INTRODUCTION

Wellbore instability problems are very common in the drilling of oil and gas wells. During drilling process, the wellbore may collapse or cave-in. Formation rock may fracture resulting to loss of substantial volume of drilling fluid. This can lead to a number of severe problems during drilling operation like; stuck drill string and consequent fishing, sidetracking and reaming operations, reduction in fluid hydrostatic pressure due to decrease in mud column height, drilling string twisting or parting due to excessive torque and drag, or even a complete loss of wellbore. Generally, the issue of wellbore instability and other similar challenges significantly contribute to the already high cost of well construction. Wellbore instability is more common and severe in shale rock formations. Wellbore instability issues in wells drilling results to lose of budget due to unexpected and unplanned events caused, which translates to huge amount of money wasted during the well delivery process.

In this research project, wellbore instability issues in an oilfield in the Niger Delta are investigated. The oilfield, which is designated “S” Field in this research work, contains oil and gas reservoirs and is located in the Niger Delta sedimentary basin, Nigeria. The field was first explored in 1993 but has not been producing due to the fact that no well has been successfully drilled and put to production in the field. The non-production has resulted to loss of the huge revenue that would have been accruing to the economy, as well as loss of jobs. For almost 25 years no drilling campaign has been carried out since the two wells drilled in the field experienced instability issues during drilling, including stuck pipe and loss circulation incidents. These problems led to the plugging and abandonment of the wells and field after costing the company a huge fortune.

Wellbore instability is a function of formation pore pressure, in-situ stresses, and rock strength properties. Before a well is drilled, the formation is in equilibrium. Once drilling starts, formation rock is removed. The wellbore becomes subjected to the stresses surrounding it due to removal of the rock. This changes the in-situ stresses near the wellbore wall, resulting to stress concentration. This stress concentration will lead to a failure in the wellbore wall. The basic problem therefore, is the accurate prediction of the rock reaction to mechanical loading during drilling of a borehole.

In order to avoid wellbore failure an appropriate wellbore pressure (mud pressure) need to be altered to redistribute the stress concentration near the wellbore. Moreover, wellbore orientation with respect to the in-situ stresses needs to be taken into consideration to prevent the wellbore failure. The easily controllable parameter in any drilling operation is the drilling mud pressure. The drilling mud pressure can prevent wellbore failure if it lies between the collapse pressure and formation fracture gradients. It has the added advantage of controlling or reducing the effect of mechanical wellbore failure **(**Bourgoyne *et al*., 1986). Drilling mud performs many functions, such as cooling and lubrication of the drill bit and drill string, cleaning of the drill bit, transport of drill cuttings to the surface, transmission of hydraulic energy to mud motors and bit through the drill string, and control of formation pressure. Traditionally, the drilling mud pressure is designed to control the influx of flow of the formation fluid into the wellbore regardless of the field stresses and the rock strength effects. Normally, in practice the mud pressure is designed in excess of the formation fluid pressure by 100 to 200 psi (0.3 to 0.5 lb/gal), the exact value depending on the well operator (French & McLean, 1992; Awal *et al., 2001*).This creates a positive overbalance between the mud pressure and formation pore pressure which helps to prevent the flow of the formation fluid into the wellbore. Thus, due to the in-situ stresses, the mud pressure required to sustain the wellbore should be greater than the pressure required to balance. Therefore, better approaches are sought to obtain optimum mud pressure based on the accurate evaluation of rock properties, stresses around the wellbore, and wellbore trajectory to safe and cost-effective delivery of a well.

II. METHODOLOGY

Data used for this investigation were obtained from daily mud reports for determining daily losses and cutting size, mud logging report for formation lithology, final well report for productive and NPT, well logging data for borehole breakout zone and stress orientation from two wells drilled in the oil field.

2.1 Geomechanical models for “S” field

From theoretical to experimental aspects, a comprehensive model on the mechanical effects on wellbore stability in the “S” field was considered in this study. The process of building a geomechanical model implies the prediction of the elastic and mechanical properties of the formation rock from physical equations and correlations (Zoback, 2007; Aadnoy,& Looyeh 2019). Then, the magnitudes of three principle stresses (vertical stress, minimum horizontal stress, and maximum horizontal stress) and pore pressure are calculated. Hence, pore pressure, rock mechanical properties, and in-situ stresses are considered among the main factors for building a geomechanical model. In this study, the two wells so far drilled, located 9 km apart are examined.

2.2 Mohr – Coulomb Failure Criteria.

The Mohr-Coulomb model was considered in the analysis of the failure criteria and is presented below

$$\tau = c + \tau_n tan\varphi \quad (1)$$

Where τ is the shear stress, c is the rock cohesion τ_n is the normal stress, and φ is the internal friction angle. The coefficient of internal friction angle can be formulated as:

$$\mu = tan\varphi \quad (2)$$

Mohr failure criteria can also be expressed by the maximum and minimum principle stresses, as follows:

$$\sigma_1 = c_o + q\sigma_3 \quad (3)$$

Where σ_1 and σ_3 are the maximum and minimum principle stresses, respectively. c_o is the unconfined compressive strength, which is a function of cohesion and internal friction angle and *q* is the flow factor, which is related to internal friction angle and can be obtained by:

$$q = \frac{1+sin\varphi}{1-sin\varphi} \quad (4)$$

$$c_o = 2c\left(\frac{cos\varphi}{1-sin\varphi}\right) \quad (5)$$

2.3 Mogi-Coulomb criteria

For Proper analysis and comparison, Mogi Coulomb model was also considered and is presented below

$$\sigma_{m,2} = \frac{(\sigma_1 + \sigma_3)}{2} \quad (6)$$

$$\sigma_{oct} = \frac{1}{3}(\sigma_1 + \sigma_3 + \sigma_3) \quad (7)$$

Mogi also suggested new criteria, defined as:

$$\tau_{oct} = f(\sigma_{m,2}) \quad (8)$$

Where the octahedral shear stress is expressed as:

$$\tau_{oct} = \frac{1}{3}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} \quad (9)$$

After this observation, it became obvious the importance of σ_2. Therefore, many 3D failure criteria have been developed. After performing extensive reviews of rock failure models, Al-Ajmi and Zimmerman (2005) introduced a 3D failure criterion called the Mogi-Coulomb criterion. This criterion can be formulated as a linear relation in a similar format to the Mohr-Coulomb criterion as follows:

$$\tau_{oct} = a + b\sigma_{oct} \quad (10)$$

Where a and b are material constant and are related to c and φ as follow:

$$a = \frac{2\sqrt{2}}{3} c\cos\varphi \quad (11)$$

$$b = \frac{2\sqrt{2}}{3} \sin\varphi \quad (12)$$

III. RESULTS

The minimum mud density is estimated by using a constitutive geomechanical model connected with two failure criteria (Mohr and Mogi). The input parameters for the geomechanical model are summarized in Table 1. The recommended mud weight express as specific gravity by using Mohr-Coulomb and Mogi-Coulomb are listed in Table .2**.**

Table 1: Input for the geomechanical model (in-situ stresses, pore pressure, and mechanical properties), Case Study 1.

Parameters	Value	Unit	Source
Depth	2975	m	
S_{v-}	58.21	Mpa	
S_H	56.2	Mpa	Peng (2007)
S_h	47.5	Mpa	Holbrook et al. (1993)
P_p	33	Mpa	RFT
Poisson's ratio	0.21		
Young's modulus	25.2	Gpa	
UCS	22	Mpa	Lal (1999)
Friction angle	22.6		Plumb (1994)

Table 2. The Output of the Geomechanical Models, Case Study 1.

Used	Mohr-Coulomb	Mogi-Coulomb
1.44	1.48	1.46

Well-2 is the second well in the "S" field. Its objective was to test the sands penetrated in Well-1, particularly the zone at which Well-1 failed due to instability. It was also designed to appraise all reservoir sands indicated in Well-1. The well is located 9.3 kilometers away from Well-1. Instability problems such as caving and tight spots were observed during drilling the well-2 formation. The lithology description in the Well-2 shows the same description as Well-1. Case 1 procedure was followed to construct the stress profile, predict the rock strength properties, and optimum mud density for Well-2. Figure 1 shows the in-situ stress and pore pressure. Rock strength properties are displayed in Figure 2. The input (in-situ stresses, rock strength properties, and pore pressure) and output parameters are listed in Table .3 and Table 4., respectively.

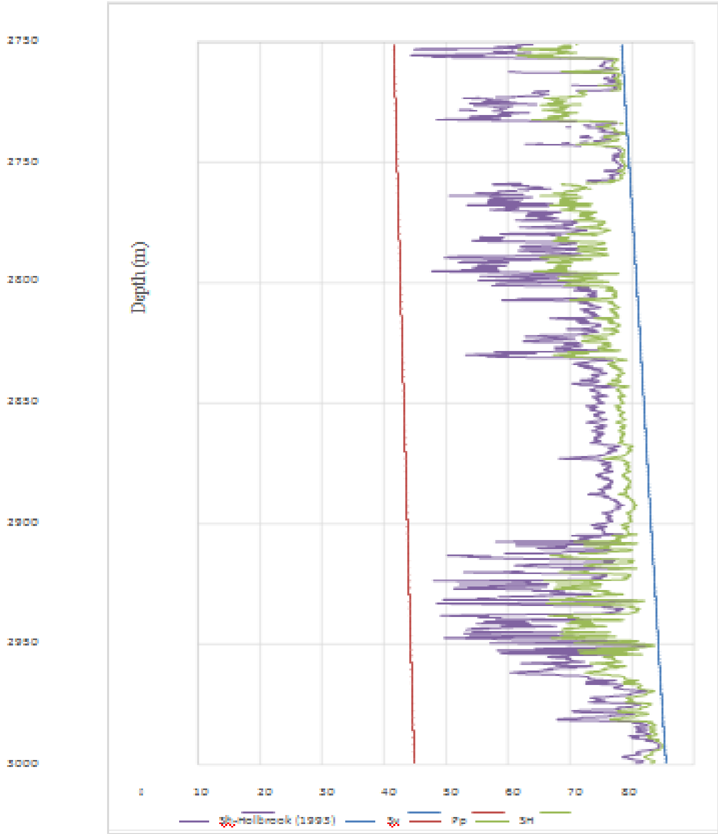

Figure 1. In-situ stresses and pore pressure profile through "S" field Case Study Well-1.

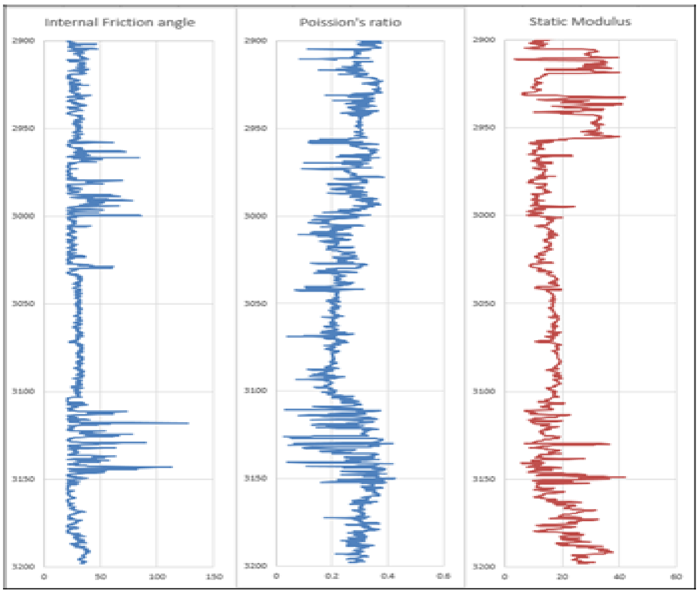

Figure 2.Rock strength parameters, Case Study Well-2

Table3. The Input of the Geomechanical Model, Case Study 2.

Parameters	Value	Unit	Source
Depth	2705	m	
Sv	65.72	Mpa	
S_H	59	Mpa	Peng (2007)
S_h	44	Mpa	Holbrook et al. (1993)
P_p	31.7	Mpa	RFT
Poisson's ratio	0.26		

Static Young's modulus	17.8	Gpa	
UCS	29	Mpa	Lal (1999)
Friction angle	22.3		Plumb (1994)

Table 4. The Output of the Geomechanical Model, Case Study 2.

	Used	Mohr-Coulomb	Mogi-Coulomb
MW (SG)	1.35	1.42	1.39

Table 5: Input and Output of the Geomechanical Model for the Two Cases.

Parameters	**Well-1**	**Well-2**
Depth	2975	2705
S_v	58.61	65.72
S_H	56.2	59
S_h	47.5	44
S_H Orientation	45°-50°	45°-50°
P_p	33	31.7
UCS	20	29
Friction angle	22.6	22.3
Poisson's ratio	0.21	0.26
Young's Modulus	25.2	17.8
Related problems	Breakout, pack-off and stuck pipe	Tight spots, breakout, pack-off and stuck pipe
Mogi-Coulomb	1.46	1.39
Mohr-Coulomb	1.48	1.42

Two wells were drilled with mud weights of 1.44sg and 1.35sg, respectively; the results show that the used mud weights are less than that required to sustain the borehole wall. The Mohr-Coulomb failure criterion predicts the optimum mud weights to be 1.48sg for well-1 and 1.42sg for well-2, while Mogi-Coulomb predicts the optimum mud weighs of 1.46sg for well-1 and 1.39sg for well-2. Vernik and Zoback (1992) pointed out that Mohr-Coulomb failure criterion did not provide realistic results. Recently, Rahimi and Nygaard (2015) stated that the Mohr-Coulomb prediction showed overestimated value, while the Mogi-Coulomb prediction was more reliable. In addition, comparing the mud weights of 1.44sg and 1.35sg used in drilling the two wells and the geomechanical model outputs show that Mogi-Coulomb gives reasonable predictions of 1.46sg for Well-1 and 1.39sg, for Well-2, which are in close agreement with field observation.

IV. CONCLUSION

This research presents a case study in the "S" oil field in Niger Delta. From the results of the geomechanical analysis of wellbore instability in the two wells drilled in the field, the following conclusions were drawn;

- A geomechanical model was developed using two failure criteria. The analysis of the output of the geomechanical model shows that the Mogi-Coulomb criterion gives more appropriate results than the Mohr-Coulomb criterion. Mogi-Coulomb analysis results are in close agreement with field observation. This is because the Mohr-Coulomb criterion underestimates the rock strength by disregarding the effect of intermediate principle stress. In contrast, the Mogi-Coulomb criterion gives a more realistic model by considering the effect of intermediate stress on rock strength.
- Several wellbore collapses, stuck pipe, and shale caving (wellbore failure) were observed in the "S" field. This wellbore failure was due to the use insufficient mud weight without recourse to appropriate geomechanical analysis.

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