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Stability Analysis in Shale using the Mohr Coulomb Failure Criterion

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ABSTRACT

Instability problems in shale formations are closely related to the ‘bulk properties’ of shales such as strength and deformation as a function of porosity, water content, clay content, composition of the shale, and compaction rates. The bulk properties of the drilling fluid such as the concentration of the continuous phase of the mud, the additives used, the chemical composition etc are equally important. This research demonstrates the use of Mohr-coulomb failure criterion in selecting a safe mud weight. Using the Mohr-Coulomb failure criterion and assuming a range of values for the minimum horizontal stress from 2000-6000 psi, the Mohr-Coulomb failure envelope was created. The failure envelope describes shear failure in rocks. The rocks to the left of the line in figure 7 are considered to be unstable while those to the right are stable. The linear elastic theory was applied to determine the horizontal stresses because no direct measurements of the horizontal stresses of the reservoir were available.

Further assumption that the tensile strength is negligible helps us to derive relationships of mud weight against well deviation for the Mohr Coulomb failure criterion. The stability curve shows the minimum mud weight required to prevent hole collapse as 10ppg and the maximum mud weight to prevent tensile fracture to be 21ppg.The wellbore will be stable in that region.

Keywords: *Shale, drilling fluid, wellbore stresses, tensile strength, linear elastic, Mohr coulomb failure criterion*

1. INTRODUCTION

Crude oil is a complex mixture of hydrocarbons and non-hydrocarbons and trace elements. Crude oil is found in sedimentary rocks. Sedimentary rocks are rocks composed of geologically reworked materials formed by the accumulation and sedimentation of organic matter and minerals by the action of water, wind or glacial ice. Sedimentary rocks are classified according to their manner of origin into chemical and mechanical rocks.

Source rocks refer to rocks from which hydrocarbons have been formed or are capable of being generated. Shale is considered to be a source rock. Shale is a fine grained sedimentary rock that forms from the compaction of silt and clay-size mineral particles that we commonly call “mud”.

Troublesome shales have plagued the petroleum industry for over 50 years. Unstable boreholes have been encountered when shale formations are drilled. Wells have been abandoned and plugged after several weeks of drilling because drilling operations have been defeated by severe instability problems. According to many sources in the industry, wellbore-stability problems are responsible for an extra 10 to 15% of drilling costs. Further broad statistical analysis shows that 70 to 90% of these instabilities occur when drilling through shale formations. Even more of a concern is the fact that oil-based muds which have been recognized as a good way to reduce instability problems can no longer be so easily used because of environmental issues.

If the instability in a shale formation is left unchecked, it could result in wellbore failure. Failure mechanisms generally fall into three categories:

- Mechanical
- Chemical
- Hydraulic

Of all the rock formations that show severe instability, shale is widely considered to be the most problematic and this frequent occurrence is due to a number of reasons:

- Many shales are poorly cemented and are easily eroded when mud is circulating.
- Shales contain clay minerals that can react with some types of drilling fluids.
- Shales are mechanically weak and hence fail under lower stresses than other well cemented sandstones or carbonates.
- Shale is a low-permeability rock, often in the nanoDarcy range which results in the absence of the formation of an effective mudcake making the pore pressure around the wellbore to be increased and hence there will be a reduction in effective stress making the rock to become weak.

Before action can be taken to improve stability, it is vital that the problem formations are located and the mechanisms of instability identified. Once the causes are understood, an informed decision can be made on how well planning, drilling practices and drilling fluid formulations can be modified to reduce problems and cost.

Therefore, it is pertinent to understand that to prevent the collapse or enlargement of the wellbore, there must be equilibrium between the stress induced by the drilling mud and the strength of the shale formation. An adequate mud weight must be determined that will not result in the instability of the wellbore.

1.1 Research Methodology

The aims and objectives of this project will be to demonstrate the use of the Mohr-Coulomb failure criterion in selecting a safe mud weight, effect of instability on the formation and the different interactions between drilling fluid and the shale formation.

1.2 Statement Of Theory And Defintions

This project provides an understanding of the application of the Mohr-Coulomb failure criterion in predicting rock failure and an understanding of the mechanisms of wellbore failure in shale formations to the reader essentially the upcoming petroleum engineer.

It demonstrates the use of the Mohr-Coulomb failure criterion, a two dimensional model, on two case studies to predict a safe mud weight to prevent wellbore collapse. It focuses mainly on mechanical failure. It also provides basic information on the causes and types of instability in shales and the interactions between drilling mud and the formation.

2. SYMPTOMS OF WELLBORE INSTABILITY

Wellbore failure can be defined as a collapse of the borehole or the wall of the wellbore due to the formation changes and the stress redistribution within the rock surrounding the wellbore.

Instability problems generally build up over time, beginning with breakages at the borehole wall, followed by a transfer of the broken pieces to the annulus, and eventually resulting in such problems as a sticky or tight hole, hole wash-out, packing off, hole fill, and stuck pipe.

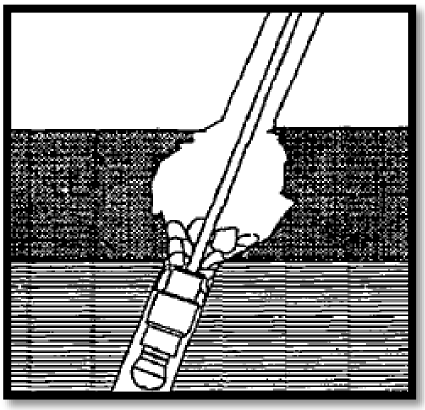

Figure 1: Stuck pipe in hole due to hole cave-in

The most direct symptoms of instability are determined from observations on caliper logs of underguage or overguage holes.

When large volumes of cuttings are excavated from the wellbore in excess of the anticipated volume of rock cuttings to be excavated from a gauged hole, it attests to hole enlargement.

High torque and drag friction, stuck pipe or coiled tubing and hanging up of the drillstring, casing, tubing, or logging tools are commonly caused by wellbore collapse or convergence, especially in inclined or horizontal wells. Excessive doglegs and keyhole seating may result from selective hole enlargement in some formations when drilled at inclined angles (McLellan, 1996).

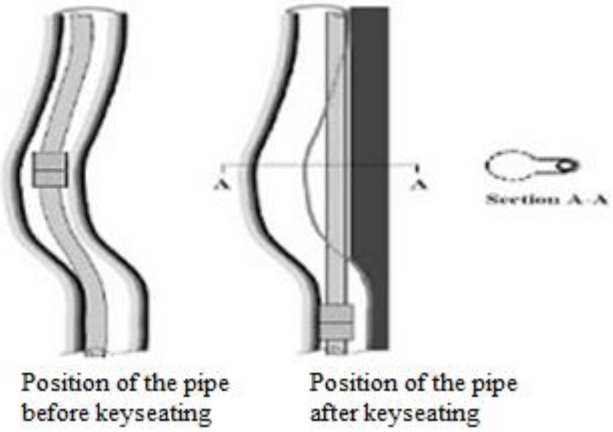

Figure 2: Key seating

2.1 Causes of Wellbore Instability

Wellbore instability is caused by a number of factors which could be broadly classified as being either man-made or natural in origin as shown in the table below.

Table 1: Factors that causes wellbore instability

NATURAL FACTORS	MAN-MADE FACTORS
High pore pressures	Drillstring vibration
Weak rocks	Temperature
Bedding planes	Well inclination
Fractured zones	Wash out

2.1.1 Natural Factors

Shale strength and deformability are greatly affected by high pore pressures causing collapse and convergence. As a result of the low permeability of shales, excess pore pressure will be induced in the formation in response to the volume of the rock that has been removed during drilling. Also, pore penetration may go on for a long time because of the low permeability of the formation before a steady state condition is achieved. In such cases, the yielded zone will increase for correspondingly long periods of time.

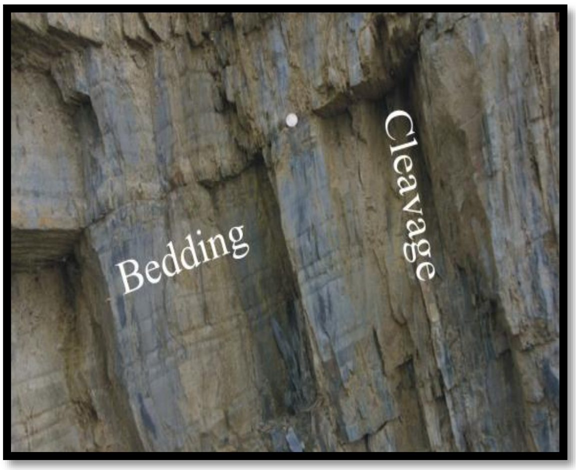

Figure 3: Shale formation showing the bedding planes and cleavage.

The presence of bedding planes in shale may result in wellbore failure to be initiated by shear or tensile failure of the planes of weakness (Tan et al.1999). Wu and Tan (2010) carried out an experiment to determine the effect of bedding plane failure on wellbore stability in a shale formation and they discovered that the strength along the bedding planes of the shale were much weaker than the intact shale material. The results of the experiment also showed that the bedding planes of the shale mainly affect high angle and horizontal wells (greater than 60degrees inclination) drilled close to the minimum horizontal stress direction.

2.2 Man-Made Factors

The drilling fluid often has a temperature different from that of the formation as a result of the thermal gradient down the borehole. The temperature difference between the drilling fluid and the formation will result in heat transfer between the two media. Since the thermal expansion of water is much higher (5-10times) than that of the rock matrix, heating the formation will generate a larger volume expansion of the pore fluid and cause an increase in pore pressure (Choi & Tan Li et al. 1998). Thermal stress will be generated when the rock matrix undergoes thermal expansion. The increase in pore pressure in addition to the thermal stress will result in an unstable condition in the borehole.

When the mud pressure is not high enough to support the wellbore, tensile failure, shear failure, and breakout can occur. However, when the mud pressure is excessive it can cause helical and elongated shear failures and hydraulic fracture.

The inclination of a well with respect to the in situ stresses can affect the risk of hole collapse or breakdown. Where there is a strong stress anisotropy in tectonically stressed regions, it can be used to estimate the fracture breakdown pressure.

2.3 Drilling Fluid/ Shale Interactions

Instability problems in shale formations are closely related to the ‘bulk properties’ of shales such as strength and deformation as a function of porosity, water content, clay content, composition of the shale, and compaction rates. The bulk properties of the drilling fluid such as the concentration of the continuous phase of the mud, the additives used, the chemical composition etc are equally important.

Shales are fine grained sedimentary rocks with high clay contents, low permeability and high porosity that are subject to hydration and swelling upon exposure to water. Shales generally have a high affinity for water and the amount of water adsorbed depends on the characteristics of its clay minerals and the concentration of ion in the surrounding fluid. This adsorption of water results in a reduction of the compressive strength of the material. Mud filtrate invasion into a shale formation depends on the driving force and the resistance to the flow. The two most relevant mechanisms in the driving force are:

- The hydraulic pressure difference (the difference between the mud weight and the pore pressure of the shale formation).
- The chemical potential difference (the difference between the drilling fluid and the pore fluid).

The resistance to filtrate invasion is a function of the physical properties of the mud filtrate (adhesion and viscosity) and the properties of the shale (Tan & Rahman, 1994).

The fine pore size and negative charge of clay on pore surfaces makes shale exhibit membrane behavior (Whitworth & Fritz, 1994). The chemical potential gradient across the shale membrane would result in osmosis. Osmosis is a process in which solvent flows from a solution containing a lower concentration of solute into a solution that has a higher solute concentration through a semi-permeable membrane. The solute in this case is salt. When there is a difference between the activity of the drilling fluid and the shale, there will be an osmotic flow of pore fluids between the drilling fluid and the formation. Shale exhibits a ‘leaky’ membrane to water based solutions because it has wide pore throats that result in significant permeability to solutes.

The total aqueous potential (pore pressure and chemical potential) of the pore fluid increases with the increase in pore pressure and/or chemical potential (Chenevert & Osisanya, 1992).

2.4 Rock Failure

Instability is caused by the tensile or compressive failure of the borehole wall as a result of the imbalance created between the rock stress and strength when a hole is drilled. The borehole fails in tension when the pressure exerted by the drilling mud induces stress in the borehole wall that exceeds the tensile strength of the rock.

Borehole stability is dominated by the in situ stress system. When a well is drilled, the formation rock surrounding the wellbore must take the load that was previously taken by the removed rock. As a result, the in situ stresses around the wellbore are highly modified around the wellbore. This is indicated by an increase in stress concentration around the borehole wall leading to rock failure depending on the existing rock strength. In order to avoid borehole failure, drilling engineers must adjust the stress concentration by altering the mud pressure and the orientation of the wellbore with respect

to the in situ stresses. Mechanical wellbore instability is described in terms of critical wellbore pressures that are related to rock stresses around a wellbore.
There are three principal components:

- A radial stress component that acts along the radius of the wellbore (σ_r).
- Hoop stress acting around the circumference of the wellbore (tangential),(σ_θ).
- Axial stress acting parallel to the well path and additional shear stress components (σ_z).

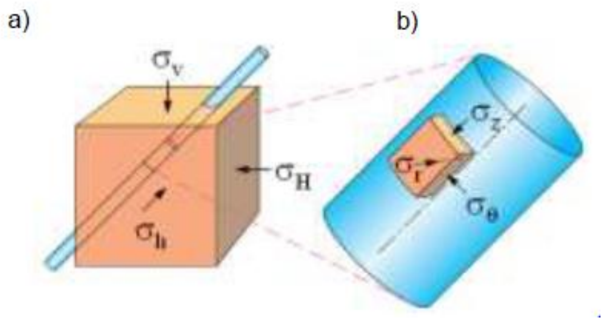

Figure 4: (a) in situ stresses (b) borehole stresses

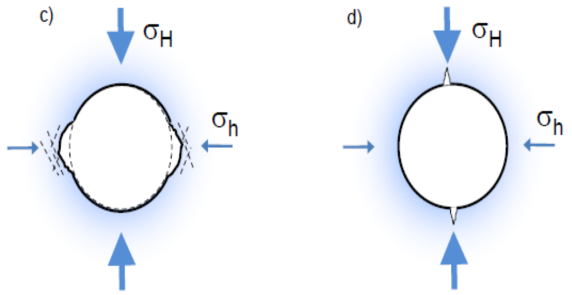

Figure 4: (c) and (d) vertical borehole in shear tension.

When a rigid body is subjected to normal stresses (fig. 4a) then these stresses will generate shear and normal stresses within the body. In fig. 4b, an imaginary plane at an angle θ to stress $\sigma 1$ will have a normal stress σ and a shear stress τ acting on it. The normal stresses push the surface of the plane together. The induced shear stress τ tends to cause the surfaces of this imaginary plane to slide relative to each other. When the induced shear strength exceeds that of the shear strength of the rock, then the rock will fail in shear.

To prevent shear failure, the shear-stress state, obtained from the difference between the stress components (hoop stress and radial stress), should not go above the shear strength failure envelope. To prevent tensile failure causing fracturing, hoop stress should not decrease to the point that it becomes tensile and exceeds the tensile strength of the rock.

Radial stresses increase with mud weight (wellbore pressure) and hoop stress decreases with mud weight causing mechanical stability problem. The consequences of wellbore instability to lost drilling time and equipment have prompted service companies to apply rock mechanics principles to define working limits for mud weights to avoid tensile or compressive failure.

2.5 Failure Criteria

The stress-strain behavior chosen to model the formation under a loaded condition is determined by the ease with which the borehole stresses can be computed. It is commonly assumed that the formation exhibits a homogenous, isotropic, linear and elastic behavior, which allows the stresses to be computed with a set of fairly simple mathematical equations. Therefore, in wellbore stability analysis a linear elastic model is assumed.

Geo-mechanical stability refers to the stability of a formation under load or stress. The elements that form the basis of the geo-mechanical model include the state of the stresses, the pore pressure penetration, the temperature effects and the rock properties. Three principal stresses have been accounted for:

- Vertical stress.
- Minimum horizontal stress
- Maximum horizontal stress.

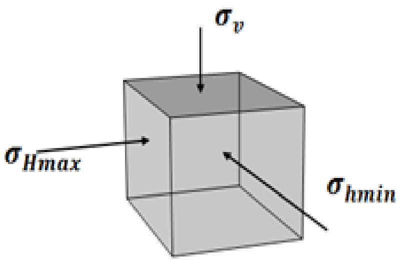

Figure 5: Diagram of the earth stresses.

Reservoir rocks are constantly under stress due to tectonic movements of the earth crust and they attain dynamic equilibrium with time with respect to each other. When the formation is drilled the equilibrium is altered.
It is necessary to define the failure surfaces of the failure criteria used in a stability analysis. The elastic properties and strength of the rock must be determined and this can be done in two ways:

- Laboratory testing: This is done by triaxially testing core samples. The tests are carried out over a range of axial and confining pressures, with some samples tested to failure. The test conditions are made to simulate the rock conditions as close to reality as possible. Some of the properties measured are, tensile strength, angle of internal friction, Poisson’s ratio, etc.

- Borehole log analysis: The elastic properties of the rock can be related to the shear and compressive wave velocities through rock as obtained from the gamma-ray log and sonic log

Many failure criteria have been developed over the years. Failure criteria provide limits to wellbore stresses and knowledge of rock strength that is essential for predicting wellbore instability. Many failure models exist but this research focuses on the Mohr-Coulomb failure criterion.

3. MOHR-COULOMB FAILURE CRITERION

Mohr-coulomb criterion suggests that failure will take place when the shear stress across the failure plain is related to the corresponding normal stress by:

$$\tau = \int (\sigma_n)$$

Where f (σ_n) is a function assumed to obtained from conventional triaxial tests. Based on triaxial failure mechanics, the Mohr-Coulomb criterion has been used extensively to represent rock failure under the polyaxial stress state.

This criterion only takes into account the maximum and minimum stress and assumes that the intermediate stress does not contribute to the rock strength.

3.1 Mohr-Coulomb Model

Mohr-Coulomb failure criterion suggests that the shear stress across a plain is resisted by the material cohesion and normal stress so that

$$|\tau| = C + \sigma^{'} \tan \emptyset$$

Where C is the cohesion and $\sigma^{'}$ is the effective stress.
The failure criterion is represented in terms of the principal effective stresses as,

$$2C = \sigma_1^{'}\left[(tan^2\emptyset + 1)^{1/2} - \tan\emptyset\right] - \sigma_3^{'}\left[(tan^2\emptyset + 1)^{1/2} + \tan\emptyset\right]$$

3.2 Determination Of In Situ Stresses

In this case the linear elastic theory is applied with the following assumptions:

- The rock material is linear elastic,
- The vertical principal stress equals the overburden stress,
- An isotropic homogenous rock mass,
- The principal stresses are orientated vertically and horizontally,
- No tectonic forces are acting and therefore the horizontal principal stresses are equal.

At the selected depth (H), of the reservoir

$$\sigma_1 = 0.052\rho_b \text{H}\ldots\ldots\ldots\ldots\ldots\ldots\ldots 1$$

Where ρ_b is the bulk density in ppg.

$$\sigma_3 = \sigma_2 = \left\{\frac{v}{1-v}\right\}(\sigma_1 + Pf)\ldots\ldots\ldots 2$$

In this case the bulk compressibility and the matrix compressibility are equal so the both constant is removed from the above equation.

3.3 Mohr-Coulomb Failure Criterion

Implementation

$$\sigma_1 - Pf = \frac{1+\sin\emptyset}{1-\sin\emptyset}(\sigma_3 - Pf) + \frac{2C\cos\emptyset}{1-\sin\emptyset}\ldots.3$$

The values of cohesion and angle of internal friction are 1041psi/ft and 32° as gotten from the field data.
The failure surface will be calculated using equation (3.3) using a range of values from 2000-6000psi for σ_3 and a plot of $\sigma_1$vs. $\sigma_3$for the given formation pressure of 4350psi.

3.4 Calculation Of Stresses At The Borehole Wall

The in situ principal stresses are transposed relative to a coordinate system with a vertical and horizontal axis using the following equations in table 2

Table 2: Formulae for transposing the principal stresses to a coordinate system

$$\sigma_x = \sigma_3$$
$$\sigma_y = \sigma_3 cos^2\alpha + \sigma_1 sin^2\alpha$$
$$\sigma_z = \sigma_3 \sin^2\alpha + \sigma_1 cos^2\alpha$$
$$\tau_{xy} = \cos\alpha \sin\beta \cos\beta(\sigma_2 - \sigma_3) = 0$$
$$\tau_{zy} = \sin\alpha \cos\alpha(\sigma_1 - \sigma_3)$$
$$\tau_{zx} = \sin\alpha \sin \cos\beta\,(\sigma_3 - \sigma_2) = 0$$

This is done for different well inclinations: 0, 30, 50, 70, and 90 degrees. The radial and tangential stresses at the wellbore are also calculated using the equations in table 3.2.

Table 3: Formulae for converting coordinate stresses to radial and tangential stresses.

$$\sigma_{rr} = Pw$$
$$\sigma_{\theta\theta} = (\sigma_x + \sigma_y) - Pw - 2(\sigma_x - \sigma_y)\cos 2\theta$$
$$\sigma_{zz} = \sigma_z - v\{2(\sigma_x - \sigma_y)\}\cos 2\theta$$
$$\tau_{r\theta} = 0$$
$$\tau_{\theta z} = \tau_{yz}\cos\theta$$
$$\tau_{zr} = 0$$

The stresses as determined above are converted to principal stresses so they can be used in the failure criterion.
The equations used are shown in the table 4.

Table 4: Formulae for converting radial and tangential stresses to principal stresses

$$\frac{\sigma_{\theta\theta} + \sigma_{zz}}{2} + \left[\left(\frac{\sigma_{\theta\theta} - \sigma_{zz}}{2}\right) + \tau_{\theta z}^2\right]^{0.5}$$
$$\frac{\sigma_{\theta\theta} + \sigma_{zz}}{2} - \left[\left(\frac{\sigma_{\theta\theta} - \sigma_{zz}}{2}\right) + \tau_{\theta z}^2\right]^{0.5}$$
$$Pw$$

3.5 Assessing The Stability Of The Borehole

A plot of the failure surface of the Mohr-Coulomb failure criterion as a function of the appropriate stresses is made to assess the borehole stability. The intersection points of the existing stresses with the failure envelope are used to deduce the wellbore stability.

3.6 Determination Of The Safe Mud Weght To Prevent Hole Fracturing

The equation below is used to calculate safe mud weights to prevent hole fracturing by tension.

$$FBP = \sigma_3(3 - cos^2\alpha) - \sigma_1 sin^2\alpha + T - Pf \text{.........5}$$

4. RESULTS AND DISCUSSION

Well X is a well that was drilled in the Niger Delta region in the Agbada field in the year 2011.
The reservoir properties are as listed:

- Cohesion= 1041psi
- Angle of internal friction= 32degrees
- Angle of inclination=0
- Azimuth= 130.46
- Pore pressure= 4350psi
- Poisson's ratio= 0.25
- Bulk density= 22ppg
- Mud density= 8.3ppg

Applying the linear elastic theory

σ_1= 11440ft
σ_3= 5263ft

4.1 Mohr-Coulomb Failure Envelope

The results from using the Mohr-Coulomb failure equation assuming values of 2000-6000psi for σ_3 are shown in table 5

Table 5: Values of the maximum and minimum horizontal stresses

σ_3,psi	σ_1, psi
2000	469
3000	3719
4000	6969
5000	10219
6000	13469

The values in table 5 are plotted resulting in the Mohr-Coulomb failure envelope as shown in the Figure 7 below.

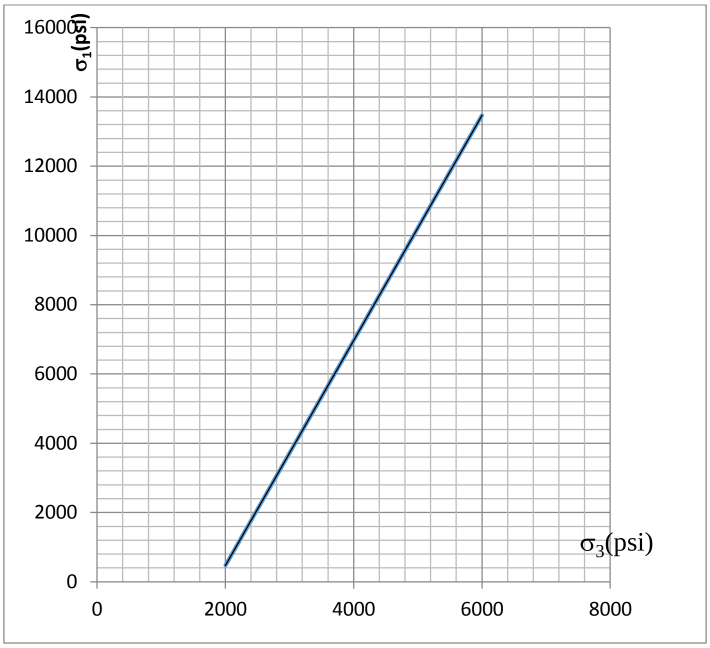

Figure 7: The Mohr-Coulomb failure envelope

4.2 Wellbore Stresses

The in situ principal stresses are transposed as shown in Table 8

Table 8: Transposed stresses at different angles

STRESS, PSI		WELLBORE INCLINATION, DEGREES				
		0	**30**	**50**	**70**	**90**
	σ_X	5263	5263	5263	5263	5263
	σ_y	5263	6807	8888	10718	11440
	σ_Z	11440	9896	7815	5985	5263
	τ_{Xy}	0	0	0	0	0
	τ_{yZ}	0	2675	3042	1985	0
	τ_{ZX}	0	0	0	0	0

Table 9: Induced stresses at borehole wall

HOLE ANGLE	**0**		**30**		**50**		**70**		**90**	
MUD WEIGHT	**8.3**	**11.3**	**8.3**	**11.3**	**8.3**	**11.3**	**8.3**	**11.3**	**8.3**	**11.3**
σ_{rr}	4316	5876	4316	5876	4316	5876	4316	5876	4316	5876
$\sigma_{\theta\theta}$	6210	4650	9298	7738	14495	12935	15396	15836	24633	23181
σ_{zz}	11440	11440	10282	10282	8980	8980	6918	6918	8351	8351
$\tau_{\theta z}$	0	0	2317	2317	1955	1955	679	679	0	0

Table 10:Borehole stresses as principal stresses

HOLE ANGLE	**0**		**30**		**50**		**70**		**90**	
MUD WEIGHT	**8.3**	**11.3**	**8.3**	**11.3**	**8.3**	**11.3**	**8.3**	**11.3**	**8.3**	**11.3**
$\boldsymbol{\sigma_1}$	11440	11440	12159	11653	15118	13793	15450	15888	24633	23181
$\boldsymbol{\sigma_2}$	6210	4650	7421	6367	8358	8177	6864	6930	8351	8352
$\boldsymbol{\sigma_3}$	4316	5876	4316	5876	4316	5876	4316	5876	4316	5876

Figure 8 below shows the intersection between the failure envelope and the principal stresses at the wellbore which helps to determine the minimum mud weight to prevent hole collapse.

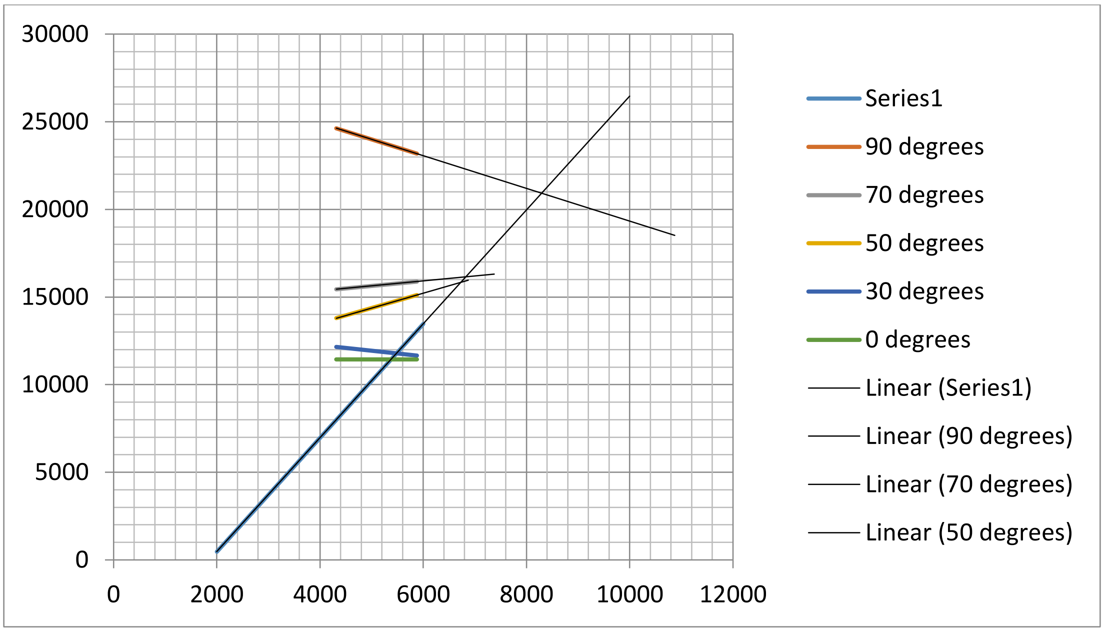

Figure 8: Intersection of the failure envelope with the principal stresses of the wellbore

Table 11: Mud weight needed to prevent hole collapse

HOLE ANGLE (^{0})	MUD PRESSURE (PSI)	MUD WEIGHT (PPG)
0	5200	10
30	5500	10.6
50	6800	13
70	7000	13.5
90	8200	15.8

Table 12: Mud weight needed to prevent hole collapse and fracture

HOLE ANGLE	MUD WEIGHT TO PREVENT HOLE COLLAPSE, PSI	MUD WEIGHT TO PREVENT HOLE FRACTURE, PSI
0	10	21.2
30	10.6	19.3
50	13	17
70	13.5	16.5

90	15.8	16.1

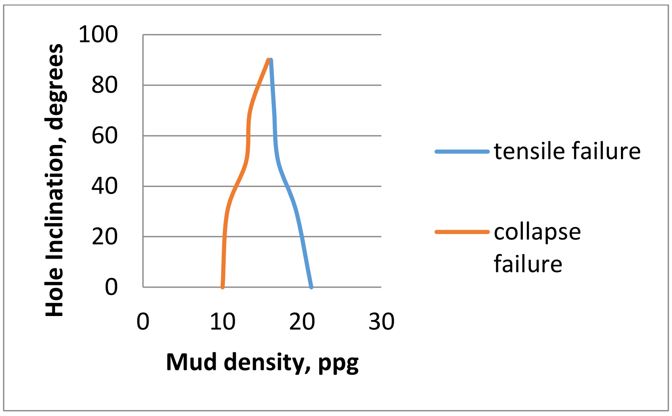

Figure 9: Region of stable mud weight

5. DISCUSSION

The linear elastic theory was applied to determine the horizontal stresses because no direct measurements of the horizontal stresses of the reservoir were available.

Using the Mohr-Coulomb failure criterion and assuming a range of values for the minimum horizontal stress from 2000-6000 psi, the Mohr-Coulomb failure envelope was created. The failure envelope describes shear failure in rocks. The rocks to the left of the line in figure 7 are considered to be unstable while those to the right are stable.

Prior to drilling the wellbore stresses are in a state of equilibrium but after excavation of rock mass from the wellbore the equilibrium is destroyed. As a result a stress concentration around the well is produced resulting in modification of the in situ principal stresses. The in situ principal stresses were transposed to give a better description of the stresses in the wellbore. Table 8, 9 and10 show the gradual transformation of the in situ principal stresses which finally result in the principal stresses for different hole inclinations and mud weights of 8.3ppg and 11.3ppg.

Further assumption that the tensile strength is negligible helps us to derive relationships of mud weight against well deviation for the Mohr Coulomb failure criterion. Figure 9 is the stability curve that shows the minimum mud weight required to prevent hole collapse as 10ppg and the maximum mud weight to prevent tensile fracture to be 21ppg.The wellbore will be stable in that region. However the mud weight prediction is seen to be inconsistent as the wellbore inclination increases.

6. CONCLUSION

The Mohr-Coulomb failure criterion can be used as a standard to compare with the computed stresses when determining the stability of a wellbore. The linear-elastic analysis is often applied to determine the stress state around a wellbore because of the simplicity of the analysis.

When using the Mohr-Coulomb failure criterion a marked difference in mud weight was noticed as the hole inclination increased. As a result of the linear elastic analysis, the criterion may prove successful in one situation and give extremely unrealistic predictions in another. In previous publications it has been suggested that the linear elastic analysis is unlikely to provide a qualitative analysis of the wellbore stability. The Mohr-Coulomb failure criterion is however considered to be fairly realistic. Using the Mohr-Coulomb failure criterion, a safer range of mud weight that will allow the wellbore to be stable was determined

In conclusion, the Mohr-Coulomb failure criterion coupled with the linear-elastic theory is considered to be a useful tool in gaining insight into the wellbore instability problems. However, we do not consider it to be a consistent qualitative tool for providing field recommendations of mud weight.

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APPENDIX

Determination of the In situ stresses

$$\sigma_1 = 0.052\rho_b H$$
$$= (0.052 \times 22 \times 10000)$$
$$= 11440\text{psi}$$

$$\sigma_3 = \left(\frac{0.25}{1-0.25}\right)(11440 + 4350)$$
$$= 5263\text{psi}$$

Determination of the Failure Envelope

The failure envelope equation is determined thus:

$$\sigma_1 - P_f = \left(\frac{1+\sin 32}{1-\sin 32}\right)(\sigma_3 - P_f) + \frac{2 \times 1041 \cos 32}{1-\sin 32}$$

$$\sigma_1 - P_f = 3.25(\sigma_3 - P_f) + 3756$$

$$\sigma_1 = 3.25\sigma_3 - 2.25P_f + 3756$$

Taking a range of values from 2000-6000psi

When σ_3=2000psi

$\sigma_1 = (3.25 \times 2000) - (2.25 \times 4350) + 3756 = 468.5psi$

When σ_3=3000psi

$\sigma_1 =(3.25 \times 3000) - (2.25 \times 4350) + 3756 = 3719psi$

When σ_3=4000psi

$\sigma_1 =(3.25 \times 4000) - (2.25 \times 4350) + 3756 = 6969psi$

When σ_3=5000psi

$\sigma_1 =(3.25 \times 5000) - (2.25 \times 4350) + 3756 = 10219psi$

When σ_3=6000psi

$\sigma_1 =(3.25 \times 6000) - (2.25 \times 4350) + 3756 = 13469psi$

Transposition of the In Situ Stresses

The stresses at different angles of inclination are calculated

For 0°

$\sigma_x = 5263\text{psi}$

$\sigma_y = (5263 \times cos^2 0) + (11440 \times sin^2 0) = 5263psi$

$\sigma_z = (5263 \times sin^2 0) + (11440 \times cos^2 0) = 11440psi$

$\tau_{xy} = 0$

$\tau_{yz} = \sin 0 \cos 0\,(11440 - 5263) = 0$

$$\tau_{zx} = 0$$

The same calculations are performed for well inclination angles of 30, 50, 70 and 90.

Conversion of Coordinate Stresses into Radial, Hoop and Tangential Stresses

When mud weight is 8.3ppg:

$$\sigma_1 = 11440psi$$
$$\sigma_3 = 5263psi$$
$$Pw = 0.052 \times 8.3 \times 10000 = 4316psi$$

For 0 degrees:

$$\sigma_{rr} = Pw = 4316psi$$
$$\sigma_{\theta\theta} = (5263 + 5263) - 4316 - 2(5263 - 5263)\cos 0 = 6210psi$$
$$\sigma_{zz} = 11440 - 0.25[2(5263 - 5263)]\cos 0 = 11440psi$$
$$\tau_{\theta z} = 0 \times \cos 0 = 0$$

The same thing is done for the other angles.
For mud weight of 11.3ppg:

$$\sigma_1 = 11440psi$$
$$\sigma_2 = 5263psi$$
$$Pw = 0.052 \times 11.3 \times 10000 = 5876psi$$

Transposition of the Radial, Hoop and Tangential Stresses into Principal Stresses

The same procedure is carried out for the different well inclinations at the different mud weights.
For 0 degrees at 8.3ppg:

$$\sigma_1 = \frac{6210+11440}{2} + \left[\left(\frac{6210-11440}{2}\right)^2 + 0^2\right]^{0.5} = 11440\text{psi}$$

$$\sigma_2 = \frac{6210+11440}{2} - \left[\left(\frac{6210-11440}{2}\right)^2 + 0^2\right]^{0.5} = 6210\text{psi}$$

$$\sigma_3 = Pw = 4316psi$$