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Analysis Of Geomechanical Properties In Well Design And Well Optimization

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Abstract

Main aspect in wellbore instability is the selection of an appropriate rock failure criterion. This criterion involves only the maximum and minimum principal stresses σ_1 and σ_3 and therefore assumes that the intermediate stress σ_2 has no influence on the rock strength. When Mohr-Coulomb criterion was developed it justified by experimental evidence from conventional triaxial test ($\sigma_1 > \sigma_2 = \sigma_3$). Based on triaxal failure machine the Mohr-Coulomb criterion has been extensively used to represent rock failure under the polyaxial stress state ($\sigma_1 >$ $\sigma_2 = \sigma_3$). In contrast to the prediction of redistribution Mohr-Coulomb much evidence has been accumulating to suggest that σ_2 thus indeed have a strengthening effect. This research shown that Mohr-Coulomb failure criterion only represent, that triaxial stress state ($\sigma_1 = \sigma_3 or \sigma_2 = \sigma_1$) which only occasionally encountered in-situ. The linear failure criterion has been justified by experimental evidence from triaxial tests as well as polyaxial test. It is natural extension of the classical Mohr-Coulomb criterion into three dimensions. As the Mohr-Coulomb criterion only represents rock failure under triaxial stress state, it is expected to be conservative in predicting well bore instability. The 3D analytical model employed by Mogi-Coulomb has been achieved by using linear elasticity theory to calculate the stresses. A model was developed in analyzing shale intrusion, at depth 6100ft the well bore pressure of the formation was found to be 0.9180psi/ft and decreases to 0.420psi/ft at depth 7300ft. The membrane efficiency of the formation increases from 0.698 to 0.719 at the depth considered above.

Keywords: Wellbore instability, Rock failure criterion, Polyaxial test, pore pressure, membrane efficiency.

Introduction

In recent years the technical challenges arising from highly deviated drilling coupled with the drive to reduce completion and work over costs has increased the application of rock mechanics in wellbore stability and solid production problems. The key to successful rock mechanics solutions lies in the acquisition of materials properties data (elastic module and strength) which are representative of the strata penetrated.

There have been a growing interest in geomechanics simulation, real time wellbore stability monitoring, stimulation job design, or sand management, the value of geomechanics have now been demonstrated and is applicable through out the entire life of a field. Borehole instability during drilling can take many familiar forms, such as stuck pipe, hole squeezing, lost circulation, severely enlarged hole or difficult direction control. Many related problems could arise when such wells are drilled to target, including uncertain formation evaluation, poor cementing, causing deformation and ineffective perforation.

Problems of wellbore instability cost the industry several billions of dollars a year estimated to about 0.5 – 1 Billion USD/ Year around the globe in downturn, well construction costs and lost production.

Most of the instability problems encountered in the industry are mainly shale related, though it could also occur in unconsolidated sandstones as formation washout during drilling and thereby distorting down hole formation evaluation, shale's are low permeability media that does not experiences normal fluid loss and far-field pressure dissipation when exposed to mud at over balance during drilling. As oil reservoirs deplete and costs increases, the need to drill extended reach holes with open holes internal also will increase. This requirement will be interfaced with the need to protect the environment against possible pollution in the past oil based mud (OBM) have been typically justified on the basis of borehole stability, fluid loss filter cake quality, lubricity and temperature stability.

As the environmental regulation restricts the use of oil based mud's, it is clear that the industry must provide innovative means to obtain OBM performance without the environmental impact. Therefore, the design of the mud system must provide for shale stabilizing, lubricity and cake quality characteristics of an OBM while minimizing acute toxicity issues and maximizing biodegradability in such harsh environments (e.g. north sea) currently, efforts within the industry have centered around understanding the fundamental factors when provides the necessary characteristics to the OBM to have improve performance in terms of borehole stability. From this basis then it is hypothesized that implementation of these fundamental concepts associated with OBM can be utilized to design an effective water based mud to meet up with environmental regulations. This is the main aim of this research to understand wellbore instability for further application in mud technology and other related applications in effective well optimization.

Factors Influencing Wellbore Stability

Drilling a well in a formation changes the initial stress state and causes redistribution in the vicinity of the wellbore. The redistributed stress state may exceed the rock strength and hence, failure can occur.

Generally wellbore fails either by exceeding the tensile strength of the formation or by exceeding the shear strength of the formation. These two types of failure are explained below.

Shear Failure: The shear failures occurring at the borehole wall are classified into four modes in terms of the principal stresses as defined in a cylindrical coordinate system.

Breakout and tonic shear failures occurs when the mud pressure is not sufficiently high to support the borehole. On the other hand, when the mud pressure is excessively high, heliptical shear and elongated shear failures can occur. Similar to tensile failure, there exist lower bound and upper bound mud pressures which defines a safe window of mud pressures within which shear failure will not occur.

Tensile Failure: The tensile failures often encountered in practice are classified into two modes in terms of the principal stresses in a cylindrical coordinate system.

Hydraulic fracture will occur when the mud pressure is excessively high. Exfoliation usually occurs when pore pressure becomes higher than the mud pressure as a result of matrix deformations under predominantly untrained conditions. Hence there exist lower bound and upper bound mud pressure between which is the safe windows of mud pressure whereby tensile failure will not occur.

The objective of wellbore stability analysis is to investigate the potential instability of wellbores by calculating the redistributed stress state and company it with an adopted failure criterion. In order to understand borehole failure problems, the factors that affect wellbore stability must be known and they are outlined below:

- Orientation and magnitude of the in-situ stress field.
- Rock mechanical and strength properties.
- Pore pressure.
- Mud pressure.

Traditionally, wellbore stability assessments have been limited to deterministic analysis that yields wellbore pressure for the onset of tensile and compressive shear failure at the wellbore wall. These analyses have proven to be valuable for well planning and in explaining wellbore stability related drilling problems seen in the field. However, these analyses have been of limited practical use because they establish limits for operation failure.

Fundamental Issues

Fundamentally, besides inadequate mud weight, borehole instability is related to the influx of water into the formation which aggravates instability by increasing the near wellbore pore pressure and by decreasing the shale strength.

The movement of water in or out of the shale is governed by several mechanisms; the two most relevant in this contract being hydraulic pressure different (ΔP) between the wellbore pressure (mud weight) and the shale pore fluid pressure and chemical potential difference between the drilling fluid and shale pore fluid.

This research work will analyses the geomechanical factors contributing to the stability of a wellbore and anticipated hole problems.

Objectives

- Review of wellbore stability analysis models.
- Compute the stresses around the wellbore base on the in-situ stresses, mud weight and pore pressures

- Compute the chemical stress due to osmotic potential difference between shale and the drilling fluid when a semi-permeable membrane exist
- Determine if failure of the rock fabric will occur under the calculated stresses
- The research work aims at implementing the combination of pressure difference and chemical potential differences by utilizing the framework of poroelasticity theory to formulate the physico-chemical basis of the borehole stability model.

Methodology

Mechanical instabilities are caused by the drilling operation removal of the cylindrical rock material induces a stress concentration around the Wellbore which usually can be balanced by the hydrostatic pressure of the drilling fluid. The extent of the range of scale operating drilling fluid densities is dependent on local conditions and the well geometry.

Wellbore instability, experience mainly in shale sections, is one of the principal causes of drilling delays and in some cases even suspension of wells prior to reaching the target depth. And as such the drilling engineer does not want to stay on site longer than necessary; this has necessitated a lot of author to try to present a more acceptable method of wellbore stability analysis. Strubhar et al (1975); Scott et al (1953); Daneshy (1973); and Baumgartneretal (1989) conducted laboratory experiment on large blocks subjected to true biaxial loading. The result of the experiments showed that fractures preferably initiate parallel to the borehole axis. This also conforms to the generalized plum strain elastic theory which predicts that the fracture trace (initiation) on a deviated well makes an angle with the borehole walls.

A multiplicity of such inclined echelon features may therefore be initiated. More over, the theory of elasticity predicts that each fracture begin at the same circumferential location on the bore hole, presuming no interaction Except for the case of extremely small flow rates, these fractures may not have a chance to extend before a new echelon fracture is initiated. The consequence on a macro scale is that these fractures may effectively coalesce to form a quasilongitudinal fracture.

On the contrary, Bjarnasson etal (1988) pointed out that it is also feasible to include large enough transverse stresses (generated by Poison's effects) to cause failure perpendicular to the wellbore trajectory. Using a power law variation for Young's Modulus as a function of the confining stress for a vertical wellbore in an elastic medium with isotropic horizontal stresses, a generalized representation of Hooke's law was presented. The observations were as follows.

- The magnum tangential stress concentration occurs within the rock and not at the borehole wall for specific loading conditions.
- The formulations do not take into account pre peak yield. The consequence is an over-estimate of the tangential stress at the well and an under estimate of strain.
- The representation could be improved by incorporating module relationships which do not imply that the modulus approaches zero as the confirming stress approaches zero.

In order to understand borehole failure problems, the factors that affect wellbore stability must be known and they are discussed below.

Orientation And Magnitude Of The In-Situ Stress Field

The in-situ stress state in a locality generally reflects the density of the formations, the history of tectonics movements, residual and thermal stresses in the region. In situ stress measurements in various parts of the world have found that the ratio of mean horizontal stress to vertical stress ranges from 1 to2.25 at a depth 0f 3000m while ratio varies significantly when close to the surface (0.3 to 0.7). General, σ_H/σ_n ranges from 1 to 2 and σ_n/σ_v from 0.3 to 1.5 for typical depths of reservoirs.

Pore Pressure

The existence of pore pressure in the rock formations changes the effective stress tension. Formation pressure normally equals to the hydrostatic head of water extending from the top of water table to the subsurface formation.

However, abnormally high formation pressures are often encountered in impermeable formations, especially shale's.

Rock Mechanical And Strength Properties

Shale is commonly found as cap rock of oil and gas reservoirs. The presence of bedding planes in shale results in the anisotropic behavior of the material. Uniaxial and Triaxial compression tests on transversely isotropic rocks have demonstrated that their peak strength vary with the orientation of the plane of isotropy with respect to principal stress direction. This difference arises since the bedding planes have much lower strength than the intact rock (e.g. the ratio of cohesion of bedding planes to the intact rock, c_b/c_i is 0.53 – 1.0 and the ratio of friction angle, tan ϕ_b /tan ϕ_i is 0.67 – 1.0). In addition, it is found that the average tensile strength is between 20% and 35% lower for testing parallel to bedding planes than testing perpendicular to the planes. Hence, the strength difference between intact rock and bedding planes needs to be considered in wellbore stability analysis.

Hoek Brown Criterion

Laboratory results of triaxial test on rock often show a curved strength envelope {Hoek and Brown, 1980, Hoek 1983}. Various researchers have therefore proposed non line criteria, based laboratory investigations. This criterion was originally developed for estimating the strength of rock masses for application to excavation design. Hoek and Brown {1980} proposed that at failure the relationship between the maximum and minimum principal stresses is give by

$$\sigma_1 = \sigma_3 + \sqrt{mC_v \sigma_3 + SC_v^2} \text{ -- (1)}$$

Where m and S are material constants, S takes the value 1 for intact rock, and less that unity for distured rock. The value for m is different form rock to rock with a ranged between about 1.4 and 40.7 (Sheorey 1997).

Drucker Prager Criterion

The extended Von Mises or Drunker Pager criterion was originally developed for soil mechanics (Druker and Prager 1952).it is expressed in term of principal stresses as

$$\tau_{oct} = k + mr \text{ --- (2)}$$

Where τ_{oct} is the octahedral shear stress according to equation (2) defined by and σ_{oct} is the octahedral normal stress according to eqn (1) defined by $\sigma_{oct} = \dfrac{\sigma_1 + \sigma_2 + \sigma_3}{3}$ and k and m and material constants. The material parameters k and m can be estimated from the intercept and slope of the failure envelope plotted in the $\tau_{oct} - \sigma_{0ct}$ space.

Mogi Criterion

Mogi {1971b) conducted the first extensive poly axial compresses test on rocks. He noted that the intermediate principal stress does have an impact on rock strength, and the brittle fracture occurs along a plane striking in the σ_2 direction sine the fracture plane striking in the σ_2 direction mogi concluded that the mean normal stress τ_{oct} that opposes the creation of the fracture plane is $\left(\sigma_{m_1 2}\right)$, rather than the octahedral normal stress τ_{oct} Consequently mogi suggested a new feature criterion formulated by τ_{oct} =f $\left(\sigma_{m2}\right)$

Chemical Effects In Well Stability

One of the main causes of shale instability is believed to be the unfavorable interactions between the shale and drilling mud (Chenevert, 1970; Bol *et a!.*, 1992; van Oort, 2003). Although such interactions which include chemical, physical, hydraulic, mechanical, thermal, arid electrical phenomena are very complicated (Maury *et al*,, 1987; Mody *el at.*, 1993; van Oort, 2003), their primary cause is related to the movement of water/ions into or out of shale. This movement causes alteration in mechanical and physiochemical properties of the shale, and can lead to wellbore instability problems.

The adsorption of water leads to an increase in pore pressure near the wellbore formation. This excessive pore pressure is difficult to dissipate due to the low permeability of shale, which causes a decrease in the effective stress because the effective stress is equal to the total stress minus the pore pressure. The movement of water from the drilling fluid into the shale also leads to an expansion (swelling) of clay layers and consequently a decrease in the interlayer-bonding and shale strength. The decrease in shale strength resulting from relatively minor increases in water content has been well documented in the literature (Chenevert, 1970; Hale et at, 1992). Both an increase in pore pressure and a decrease in strength cause shale to deteriorate.

Many mechanisms, including convection, diffusion, osmosis, and capillary phenomena are involved in the movement of water/ions (Mody *el al*. 1993; Lomba at al., 2000; Simpson and Peering, 2002). The hydraulic pressure difference between drilling fluids end shale causes a bulk flow of drilling fluid and is governed by the Percy equation. However, this flow is generally considered to be quite low as the result of both the relatively low pressure differential that typically exists for most drilling operations, and the extremely low permeability of shales which is in the range from 5 to l0 darcy (PcI et at, 1992).

Low and Anderson (1958) suggested osmosis as a mechanism for the movement of water, based on the principle that shale itself acts as a semi-permeable membrane, that allows the movement of water but restricts the movement of ions. Fritz at at (1983, 1986) supported the theory of osmosis as the mechanism controlling the movement of water/ions, but they believed that clays are not "ideal" membranes, and that the ideality of a clay membrane is a function of the CEC,Porosity and concentration of fluids. Mody and Hale (1993) suggested that the membrane efficiency is also a function of confining pressures.

From the above review, it is seen that the movement of water/ions is critical when studying wellbore instability in shales. It is of great importance, therefore, to quantitatively measure the movement of water/ions in the interaction of shale/mud.

In addition to chemical effects, thermal effects influence the stress distributions around the wellbore and the shale's mechanical properties.

Using thermodynamic principles and the classical concept of an osmotic cell, Low and Anderson (1958. 1987) derived the following equation to determine the osmotic Pressure that could develop between a shale and mud.

$$p_{\pi} = -\frac{RT}{V_W} In\left(\frac{a_{w,shale}}{a_{w,mud}}\right) \text{--} (3)$$

It should be pointed out that for an osmotic pressure to develop that is equal to the theoretical osmotic potential defined by the above equation, a perfect membrane restricting ion movement must exist as discussed previously, studies have shown that a shale does not set as a perfect semi-permeable membrane when contacted by a WBM, so a membrane efficiency term (I_m) is introduced to correct for the "non-ideality" (Fritz et at, 1983, 1986). The non-ideal osmotic pressure equation becomes;

$$p_{\pi} = -I_m \frac{RT}{V_W} In\left(\frac{a_{w,shale}}{a_{w,mud}}\right) \text{--} (4)$$

The membrane efficiency term (I_m)

As shown, the following asses can be highlighted from Equation (4):

1) $a_{w,shale} \angle a_{w,mud}$, Chemical osmosis flow of water into the shale increases the water content and the pore pressure near the wellborn wall, and thus destabilizes the wellbore;

Shale Permeability

It can be seen that the lower critical weight increases, while the upper critical mud weight decreases with decreasing permeability (assuming all other parameters remain the same). This is because the effective stress in a lower permeability formation is lower at any given time compared to that of a high permeability formation, which causes wellbore instability problems (Yu *et al.*, of, 2001). For example, when the permeability is equal to 2 md, the upper critical mud weight reaches the lower critical mud weight. This means that wellbore instability problems cannot be avoided when drilling through such low permeability formations.

Pore pressure plays a crucial role in wellbore stability. The chemical effects, involving water and ion movement into or out of shale formations, and thermal effects can change the pore pressure distribution around the wellbore, which may cause wellbore instability problems.

We see that the lower critical mud weight increases, while the upper critical mud weight decreases with an increase in pore pressure This means that both compressive and tensile failures easily occur due to an effective stress decrease with increasing pore pressure. Therefore, it is of great importance to prevent pore pressure increases around a wellbore so as to improve wellbore stability.

Diffusion Coefficient

It is seen that the lower critical mud weight decreases while the upper critical mud weight increases with increased diffusion coefficient when the concentration of the drilling fluid is lower than that of the pore fluid, From our discussion on water and ion movement we know that the movement of water and ion occurs simultaneously and that the movement of water is hampered by the movement of ions. When the ion concentrations in the drilling fluid is lower than this in the pore fluid, ions diffuse from the pore fluid into the drilling fluid and water moves in the opposite direction. For a high diffusion coefficient, diffusion of ions from the pore fluid into the drilling fluid helps prevent more water movement into the formation. This, in turn, prevents a high pore pressure increase, which improves wellbore stability.

In addition to the poroelastic effects osmotic pressure is also found to be an important factor affecting the wellbore stability. Swelling pressure can be observed when the shale samples are exposed to difficult drilling fluids. In addition, the shale strength changes with exposure time as hydration or dehydration progresses. It has been shown that osmotic pressure can be treated as a hydraulic potential that drives water into or out of shale formations. Exposure of the drilling fluid to the wellbore surface results in the contacted formation being exposed to both the hydraulic and osmotic potentials. Solute diffusion is not considered in this study.

For shale, the compiling coefficient C_o' is significantly less than C_o thus the pressure term in the temperature equation can be neglected. The finite difference solution of temperature distribution also indicates the Co' term can be ignored for shale's. One may suggest ignoring the hydraulic effect on pore pressure distribution and the pore pressure will be a steady state function of temperature changes for specific redial distances. This approach only applies for large distance and long time, hinder which temperature reaches a pseudo-steady state distribution. Hence, the problem can be partially decoupled.

$$\frac{\partial T}{\partial t} = c_o\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{\gamma}\frac{\partial T}{\partial_r}\right) \text{ - - - - - ------------------------------------} \qquad (5)$$

$$\frac{\partial p}{\partial t} = c_o\left(\frac{\partial^2 p}{\partial r^2} + \frac{1}{\gamma}\frac{\partial p}{\partial r}\right) + c^1\frac{\partial T}{\partial r} \text{ - - - - ------------------------------------} (6)$$

The initial conditions and boundary conditions are considered as;

$$p(r,o) = p_o,\ p(\infty,t) = p_o \text{ - - - - ------------------------------------} \qquad (7)$$

$$p(r_w, t \geq o) = p_{\pi w} = p_w - p_\pi \text{ - - - - ------------------------------------} \qquad (8)$$

$$pf\left(r_w, t \geq 0\right) = p_{\pi w} - p_o = p_w - p_\pi - p_o \text{ ------------------------------} \quad (9)$$

$$T(r,o) = T_o,\ T(\infty,t) = T_o \text{ --} \quad (10)$$

$$T(r_w.t) = T_w, T^f(r_w,t) = T_w - T_o \text{ - - - - ------------------------------------} \quad (11)$$

Where

p^f = pore pressure fluctuations
T^f = Temperature fluctuations
p_o = Initial pore pressure
p_w = Wellbore pressure
$p_{\pi w}$ = near well bore pressure
T_o = Initial temperature
T_w = Well bore wall temperature
r_w = wellbore radius
p = Chemical potential

The osmotic pressure in a mud/shale system can be determined by the following expressions;

$$p_\pi = -P_m \frac{RT}{V} in\left(\frac{\sigma_{wn}}{\sigma_{wsh}}\right) \text{ - - - - - - - - - ------------------------------------}(12)$$

Where

σ_{wm} = mud water activity

σ_{wsh} = shale water activity
R = Gas constant
V = partial molar volume of water
σ_m = membrane efficiency
T = Inlet mud tempt.

Note for a positive osmotic pressure (potential) it implies there is a driving of water out of the chase and vice-versa.

Cation Exchange Capacity (CEC)

The cation exchange capacity, CEC, is defined as quantity of exchangeable captions required balancing the charge deficiency of a clay particle and is expressed as mill equivalents per 100 grams of dry clay. Each clay mineral type is characterized by a range of CEC values but the environmental conditions, mainly the pH and presence of soluble salts, may influence this property.

The determination of CEC was done by two methods: ethylene blue test and the ammonium acetate test Perez describe the sample preparation technique and the whole methodology for the ammonium acetate test. These two methods give similar results for CEC total but the ammonium acetate method allows the identification of the individual /contribution by different captions. This is an important feature of the experiment since it is possible to differentiate between the more reactive sodium steatite from the less reactive calcium steatite.

Table 1.0 presents the results of CEC for four samples, following the ammonium acetate method. The average value of 28 meq/l00g is within the range of possible CEC values for illites. The results also show that potassium and sodium are the most exchangeable captions. Several immersion tests carried out by Rabe, confirmed this result after chemical analysis if the immersion fluid, The knowledge of the exchangeable cation can be valuable for analyzing the cation exchange during ion invasion from the drilling fluid to the shale and the eventual alteration in clay Structure destabilizing the formation such as suggested by Simpson and Dearing.

Table 1.0 Cation Exchange Capacity (CEC) And Interchangeable Cations

Sample	**CEC**	**Interchangeable cations(meg/100$_g$**					
		Li^+	**Mg^{++}**	**Sr^{++}**	**Ca^{++}**	**Ba^+**	**K^+Na^+**
1	**28.99**	**Tr**	**1.43**	**0.43**	**7.61**	**Tr**	**19.53**
2	**30.29**	**Tr**	**`1.67**	**0.56**	**9.23**	**Tr**	**18.84**
3	**25.18**	**Tr**	**1.82**	**0.47**	**8.11**	**Tr**	**14.97**
4	**26.05**	**Tr**	**1.26**	**0.47**	**6.99**	**Tr**	**17.33**

Atoms other then silicon, aluminium and magnesium atoms could be encountered in clay crystal due to a process known as isomorphism substitution. This is the replacement of an atom by other of atoms similar sizes but lower charges without altering the general structure of the crystal lattice. For example, in the tetrahedral sheet,Si^{4+}may replaced with$A1^{3+}$ or Fe^{2+}. An overall change deficit now exists causing a negative potential at the clay surface. The clay is now cation-seeking and will readily adsorb a agnation to adjust this change imbalance. The occurrence of isomorophous substitution and the subsequent adsorption of a cation in clay cause a disparity in their stability. The adsorbed cation is held loosely by the crystal structure and can readily be exchanged for another cation, thus the term cation exchange capacity (CEC). In the presence of water, the cation voluntarily undergoes substitution by hydrogen or hydronium ions present. This results in a high affinity for water molecules which can cause alteration of the shale's physical properties. CEC can be measured in the laboratory by introducing cationic species such as ammonium (NH_4) K^+,Na^+ , and methylene blue to completely balance the change deficiency in the clay, the methlene blue test is the reported in nuits of meq/100g (mill equivalent wightsof ethylene blue/100g of dry clay) .the CEC of common clay minerals have been measured and are present in table

Results

The data presented below in tables 2 and 3 are used in sensitivity analysis which are carried out to see the effect of,

- Swelling pressure against depth
- Membrane effect against depth
- Molar volume against dept

Consequences Of Geomechanical Failure

- Induced fracture causing excessive mud loss
- Heliptical and elongated shear failure when the mud weight exceeds maximum permissible value
- Stuck pipe problems
- Poor hole cleaning
- Spalling and sloughing of shale

Conclusion

Proper knowledge of Geomechanical analysis has turned difficult drilling problems into manageable ones, and as the industry continues to move in directions that present new and even more challenging drilling scenarios, it will become more important to understand how earth reacts to condition presented by drilling operations. The science of geomechanics is the first step in that process

From the technical investigations presented in this work, the following principal conclusions are noted:

- The geomechanical analysis methodology presented provides a method of integrating classical wellbore stability modelling with operational tolerance for instability.
- Drilling in the proximity of faults can promote losses and more extensive instability. Whenever possible well trajectories should be planned to intersect faults in more favourable (normal) directions.
- There is need to integrate knowledge of subsurface conditions and wellbores stability into both well design and operating practice

We believe that Mogi-Coulomb criterion describes the rock failure more accurately that does the traditional Mohr-Coulomb criterion. In all rock engineering applications therefore, it would be advantageous to employ this rock criterion. From the result analysed the wellbore pressures increases as depth increases likewise the membrane efficiency increases with depth.

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Appendix

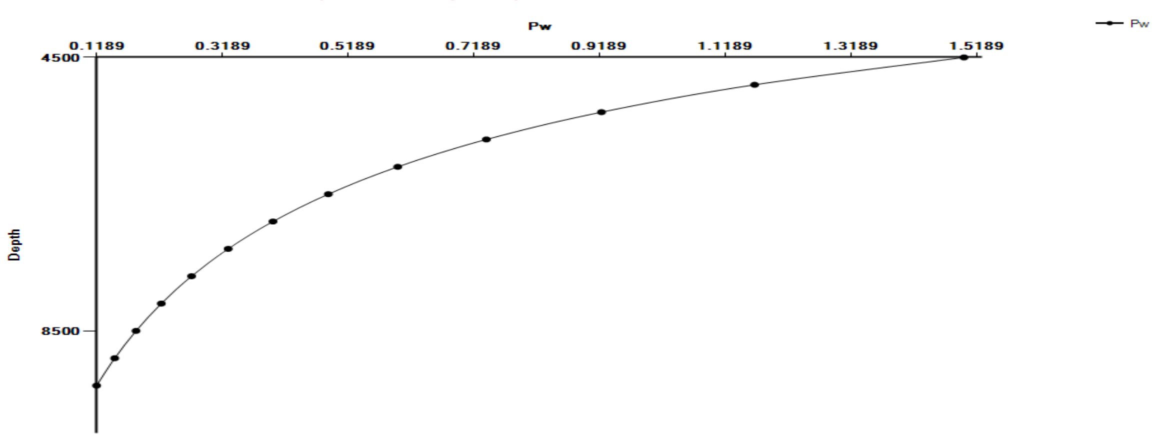

Figure 1: Sensitivity Analysis of Depth and Wellbore Pressure

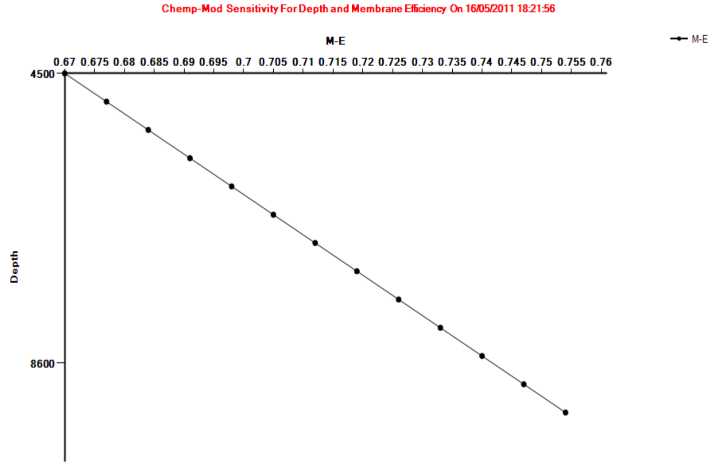

Figure 2: Sensitivity Analysis of Depth and Membrane Efficiency

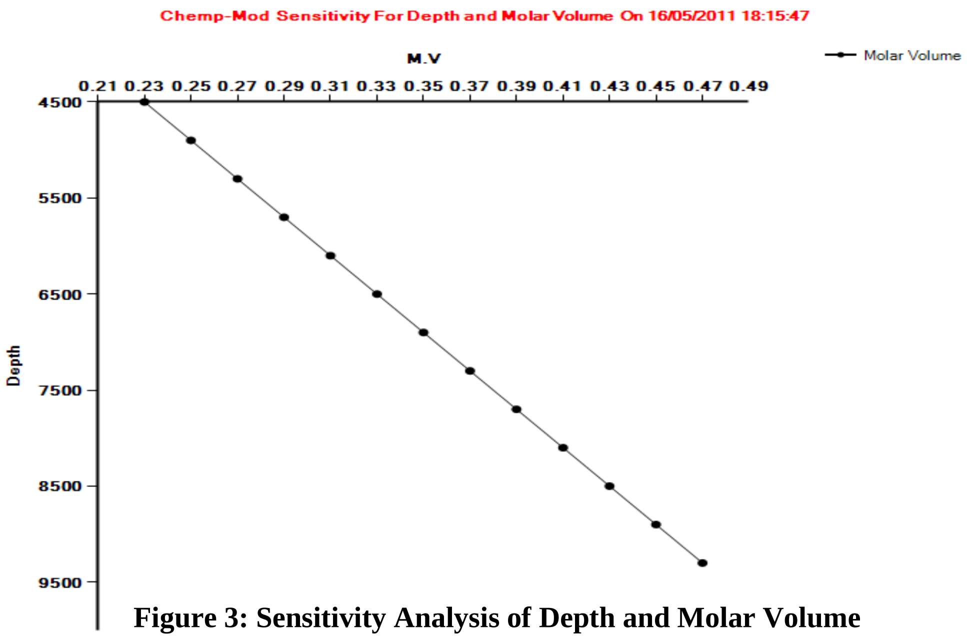

Figure 3: Sensitivity Analysis of Depth and Molar Volume

Table 2: Data for the mud activity, pore pressure, angles and time

Mud Activity	Pore Pressure, Psi/ft	Normalize Pore Pressure,Psi/ft	Inlet-Mud Temperature ,deg F	BHT,deg F	Gas Constant	Inclination, deg	Azimuth, deg	Friction Angle, deg	Time, Hrs
0.123	0.433	0.434	120	150	0.08205	45	45	45	5
0.145	0.434	0.435	124	155	0.08205	45	45	45	7
0.167	0.435	0.436	128	160	0.08205	45	45	45	9
0.189	0.436	0.437	132	165	0.08205	45	45	45	11
0.211	0.437	0.438	136	170	0.08205	45	45	45	13
0.233	0.438	0.439	140	175	0.08205	45	45	45	15
0.255	0.439	0.44	144	180	0.08205	45	45	45	17
0.277	0.44	0.441	148	185	0.08205	45	45	45	19
0.299	0.441	0.442	152	190	0.08205	45	45	45	21

0.321	0.442	0.443	156	195	0.08205	45	45	45	23
0.343	0.443	0.444	160	200	0.08205	45	45	45	25
0.365	0.444	0.445	164	205	0.08205	45	45	45	27
0.387	0.445	0.446	168	210	0.08205	45	45	45	29

Table 3: Data for Shale Intrusion Mode

Depth, ft	OBS, psi/ft	MinH, psi/ft	Cohesion, psi/ft	Poisson Ratio	Young's Modulus,MPa	Membrane Efficiency	Molar Volume Of water	Pore Fluid	Max Hor. Stress psi/ft	Well bore press.n psi/ft
4500	0.96	0.605	0.113	0.25	3600000	0.67	0.23	0.45	0.7825	1.5189
4900	0.96	0.605	0.115	0.25	3600000	0.677	0.25	0.455	0.7835	1.4130
5300	0.96	0.605	0.117	0.25	3600000	0.684	0.27	0.46	0.7845	1.3189
5700	0.96	0.605	0.119	0.25	3600000	0.691	0.29	0.465	0.7855	1.1189
6100	0.96	0.605	0.121	0.25	3600000	0.698	0.31	0.47	0.7865	0.9180
6500	0.96	0.605	0.123	0.25	3600000	0.705	0.33	0.475	0.7875	0.7180
6900	0.96	0.605	0.125	0.25	3600000	0.712	0.35	0.48	0.7885	0.5189
7300	0.96	0.605	0.127	0.25	3600000	0.719	0.37	0.485	0.7895	0.420
7700	0.96	0.605	0.129	0.25	3600000	0.726	0.39	0.49	0.7905	0.4110
8100	0.96	0.605	0.131	0.25	3600000	0.733	0.41	0.495	0.7915	0.3180
8500	0.96	0.605	0.133	0.25	3600000	0.74	0.43	0.5	0.7925	0.210
8900	0.96	0.605	0.135	0.25	3600000	0.747	0.45	0.505	0.7935	0.1210
9300	0.96	0.605	0.137	0.25	3600000	0.754	0.47	0.51	0.7945	0.110