PREDICTION AND EVALUATION OF BOREHOLES SHEAR FAILURES RISK IN SHALE UNDER IN-SITU STRESS STATE - A SENSITIVITY ANALYSIS

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ABSTRACT

Borehole instability during drilling in shale is more pronounced than in any other formations. No well is drilled in shale without problems. A Major instability risk is borehole shear failure. This paper evaluates different shear failure modes under in-situ stress state during underbalanced drilling (UBD). The generation of input data to "geomechanical model" by presenting extensively used correlations for estimating rock strength, in-situ acting stresses and formation pore pressure. Such generated data were used as input to an upgraded analytical model to estimate borehole shear failures. Borehole sensitivity analysis was extended to evaluating the borehole collapse risk of the effect on differential stress and loads, stress anisotropy, cohesion, pore pressure and friction angle. The analytical model relies on the Mohr- Coulomb (M-C) failure criterion. Matlab codes were developed to simulate the analytical model and to validate it through Gullfaks well data. The results showed that the developed geomechanical model is capable of assessing in-situ stresses with a certain degree of quality. The sensitivity analysis results showed that the mud weight and rock strength are the most critical parameters for determining borehole collapse risks for UBD candidates. The borehole collapse model is quantifying the risk of shear failure modes with acceptable accuracy. The generality of this study is to provide a standard workflow to assess in-situ stresses along with borehole failure risks for vertical and horizontal wells.

Keywords: Oil Well Drilling, Shale, Geomechanical Model, Borehole Instability.

1. Introduction

Shale is specifically mentioned in this setting, due to the fact that borehole instability is more pronounced in such formations than in any other formation [9,10,11, 13 14 & 16]. From field experience, it was found that shales (hard rock) make up of more than 80 % of the sediments and rocks in siliclastic environments and about three quarters of borehole problems are caused by shale instability, troubles such as sloughing shale and stuck pipe. At best, an unstable wellbore would mean that drilling performance is impeded through lost time. At worst it could mean a hole collapse and total loss of a well. All this means extra costs. A significant amount of lost time and extra cost (about 20 billion USD/year) is accounted to overcome shale related problems.

The problem addressed in this study is the borehole shear failures risks in shale during UBD through in- situ stress regimes. Based on in-situ stress magnitudes, Anderson (1951) classified three types of earth's in-situ stress states: extensional ($\sigma_V > \sigma_H > \sigma_h$), strike-slip ($\sigma_H > \sigma_V > \sigma_h$) and compressional ($\sigma_H > \sigma_h > \sigma_V$). Borehole instability is in most of the cases, a direct reflection of these stress states. An anisotropic stress pattern is characterized by a specific failure position in the borehole circumference, and this position is controlled by in-situ stresses [9-14]. A brief description of these stresses and their impact on stable drilling were presented through previous publications [9, 11 & 15]. This paper aims to evaluate the shear failure risk in shale through in-situ stress regimes. A stress field model is therefore presented in Fig.1. This model represents wellbores drilled in shallow (case-I), medium-deep (case- II) and deep basins (case-III). These three cases are defined based on the in-situ stress magnitudes vs. depth of investigation.

Wellbore stability models that include some aspects of shear failure analysis in shale have already been developed [9-15]. Inspection to these models, found that the assessment of in- situ stress is the focal weak side in borehole instability analysis [9 & 11-15]. A standard geomechanical model is essential for evaluating the
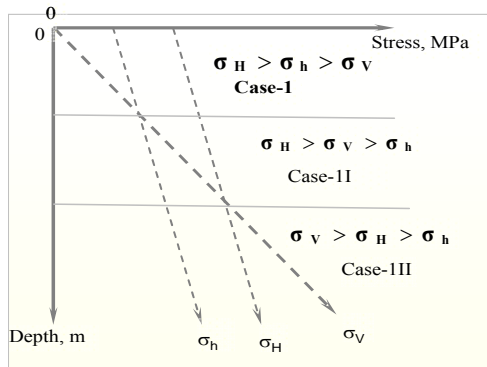
failure modes with reasonable accuracy.

Fig 1. Stress field model.

This paper presents a geomechanical model based on extensively used correlations for estimating rock strength, in-situ acting stresses and formation pore pressure. This current investigation enhanced the insight on borehole collapse risk.

It is not exactly known how rock fails. The processes associated with failure are complex and not subject to convenient characterization through simplified models. The Collapse criterion defines a state where the borehole is no longer stable, but becomes unstable to a degree where it is defined as collapsing. Many different arguments can be used to define collapse criteria, e.g. scientific arguments based on mechanical criteria or operational argument based on practical limitations. Operational arguments which belong to amount of cavings or breakouts present in the drilling fluid, degree of wellbore instability with respect to section of angle & length, and the extension from the borehole. Scientific arguments are fulfillment of a failure criterion, choice of failure criteria with respect to stress conditions, type of formation, and type of analysis method (analytical or numerical).

The selection of a failure criterion for borehole stability analysis is difficult and confusing [5]. Proper selection of failure criteria for borehole stability analysis is therefore unclear to drilling engineers. Rock mechanics experts have applied several failure criteria in an attempt to relate rock strength measured in different simple tests to borehole stability. Some of the predicting methods are M-C criterion, Hoek- Brown criterion, Drucker- Prager criterion, Yield Zone criterion, Cam – Clay model, Modified Lade criterion and Griffith failure criterion. The theoretical backgrounds and limitations of these models have been extensively covered in the literatures [5, 6, 7, 9 & 12]. This study applied M-C failure model due to its simplicity and level of acceptability. For quantifying failure risk the total work is divided into the following phases:

- Develop and investigate the geomechanical model to estimate in-situ stresses.

- Quantify borehole shear failure risk for UBD in shales.
- Conduct sensitivity analysis to define critical parameters on borehole failure state by accounting for the effect of differential stress and loads magnitudes, cohesion, friction angle, pore pressure and well trajectory.

The M-C linear elastic failure model was used to quantify failure risk. Matlab codes were developed to simulate both the geomechanical and the shear failure models dynamically.

2. Construction of Geomechanical Model

2.1 Generation of input parameters
One challenge for constructing a geomechanical model is the generation of consistent input data. Many of the required parameters can be inferred from different sources, using some of empirical correlations, theoretical expressions, or analogue data previously experienced. Both stress field and rock mechanical properties are part of the GMM. Various methods and techniques have been used to calculate necessary input to generate GMM. This study developed a standard GMM based on updated published work [3, 8, 12 &16]. Details of present GMM along with data integration techniques are presented through **Table A1**. Our developed model is fairly well structured.

2.2 Assessment of the in- situ stresses
For typical depths of oil reservoirs, the ratio of the σ_h / σ_v ranges from 0.3 to 1.5, and σ_H / σ_h ranges from 1 to 2 [1,2, 4, 6 & 8]. In particular, the horizontal stress magnitude and orientation are not usually measured. This will definitely increase the uncertainty in the results. This work assesses in- situ stresses based on developed geomechanical model, validated through Gullfaks well data. Estimating results are presented through **Fig. 2.** It is seen that the in-situ stress regimes is identified and varies with depth. For example, at shallow and medium deep formation (1000- 1800 m), the σ_H is largest while at deep formation (2000-3000 m), σ_V dominates. Over pressure zones are identified between 1500- 23000 m. The minimum horizontal stress was estimated by using Breckels and van Eeklelen [3] correlation (developed & tested for US Gulf Coast wells). However, the authors experience is that the relation for depths down to 2500 m gives fairly good estimates in most parts of the North Sea with water depths up to approximately 300 m. Though the water depth of this well was greater than 300 m, estimation of σ_h in shallow formation depth up to 1500 m did not show a good trend **(Fig.2)**. Thus these relations should only be considered as a first estimate and should always be checked or calibrated against proper data from each field. To get a better accuracy of σ_h we need some adjustment into Breckels empirical correlation. Several well data with regression analysis may provide updated correlations to estimate σ_h in North Sea wells.

The pore pressure assessment is the most critical part of our GMM because up until now, very limited options are found for using prediction pore pressure in shale. The Eaton (1975) correlation was used in this study. The exponent (i.e., n = 3, 3.5, 4, 5 & 6) is playing a major role to assess pore pressure in the North Sea area. The assessment of pore pressure vs. different exponents is presented in **Fig. 3.** The pore pressure trend for exponent n = 4.0 gives reasonable accuracy for Gullfaks well, as supported by others studied also [9, 17 & 18].
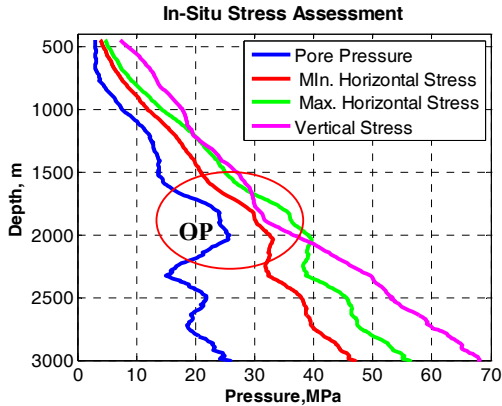
In-Situ Stress Assessment

Fig 2. Assessment of the in-situ-stress based on GMM. Data from Gullfaks field (well # 34/10-16)

It is seen that the developed geomechanical model is capable of assessing the in-situ stresses. The accuracy of this GMM can be obtained by verifying it through further investigations. GMM can be revised and upgraded through field data, lab investigation or more case studies throughout this research project. On the other hand, pore pressure prediction in shale is of critical concern, and needs to be focused separately. The combined use of well logs and experimental compaction trends may improve the ability to predict trends of porosity, permeability, density, or velocity versus depth, leading to a prediction of overpressure in shales. **Fig. 2** was used as calibration chart for estimating the in- situ stresses at depth of interest. These calibrated data were used for conducting the sensitivity analysis to evaluate the shear failure risks in terms of minimum MW for avoiding borehole collapse. A complete set of wellbore stability analysis data are presented in **Table A2**. Further verification is essential to improve the confidence of the developed GMM.

3. EVALUATION OF BOREHOLE FAILURE MODES

The evaluation of shear failure modes is dependent on the assessment of near borehole stresses. Near wellbore stress are generated after a wellbore drilled to support the rock that was originally supported by the removed solids in the borehole. Near wellbore stresses (σ_r, σ_θ, $\sigma_{Z,}$) are normally of higher magnitudes and act on the formation at the wellbore wall. It is believed that, the near wellbore stress concentration is created immediately during drilling (unless the far field stresses would change much during a drilling period). Depending on the prediction of magnitudes and direction of wellbore stresses, prior indications whether a borehole will be failed would be available.
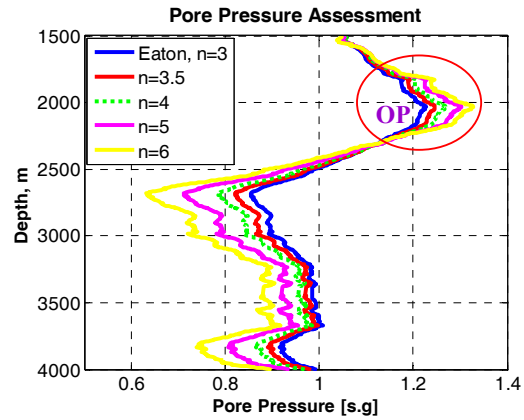
Pore Pressure Assessment

Fig 3. Assessment of the pore pressure based on GMM with different exponents. Data from Gullfaks field (well # 34/10-16)

A near borehole stress model (σ_r, σ_θ, σ_z) is essential to evaluate shear failure risks in shale. Many publications [5, 9-15] have been focused on borehole stress modeling. From their studies, it was found that stress related failures are the major reasons for borehole instabilities. Having anisotropic horizontal stresses, which is the common situation, will change the borehole stress. Detailed and in-depth discussions on the near borehole stress model in shale have been extensively covered through many publications [9-16]. From their studies it was found that hoop stress, rock strength and mud weight design are the more influential parameters to cause shear failure during UBD in shale. Classical Kirch solution [7] explains how hoop stress does lead to shear failure for UBD candidates in shale. At a later part of this paper hoop stress based on Kirch solution are estimated. By arranging permutation and combination of the near borehole stresses, six possible shear failure modes may exist. All modes are influenced borehole instability, but the following three shear failure modes are the most applicable in this study:

- Mode A: $\sigma_\theta \geq \sigma_z \geq \sigma_r$; axial stress is the intermediate concern; M-C failure state = f (σ'_θ, σ'_r).
- Mode B: $\sigma_z \geq \sigma_\theta \geq \sigma_r$; tangential stress is the intermediate concern; M-C failure state = f (σ'_z, σ'_r).
- Mode C: $\sigma_z \geq \sigma_r \geq \sigma_\theta$; radial stress is the intermediate concern ; MC failure state = f (σ'_z, σ'_θ).

Modes "A" and "B" appear as collapse of the wellbore, but mode "C" appears as collapse of the wellbore first where subjected to excessive internal pressure when compared to the external stress, either in shear or extension mode. This theoretical interpretation was evaluated through analytical simulation based on the M-C failure criteria. The mathematical formulations and

assumptions to determine minimum mud weight to prevent borehole collapse are presented in **Table A3.**

4. RESULTS AND DISCUSSION
4.1 Assessment of near borehole stresses
I. Anisotropy stress effect:

With the assumptions of vertical hole, anisotropic horizontal stress, impermeable wall (shale), perfect mud cake in porous and permeable formation, and steady state condition, classical **Kirsch** equation for stress concentration around a circular elastic hole, the stresses at the borehole wall are [7];

$$\sigma_r = P_w$$
$$\sigma_\theta = \sigma_H + \sigma_h - 2(\sigma_H - \sigma_h)\cos 2\theta - P_w \quad [1]$$
$$\sigma_z = \sigma_V - 2\nu_{fr}(\sigma_H - \sigma_h)\cos 2\theta$$
$$\tau_{r\theta} = \tau_{\theta z} = \tau_{rz} = 0$$

Azimuth "θ" is the relative position of horizontal stresses. The tangential (σ_θ) and radial (σ_r) stress in **Eq.1** are a functions of the mud pressure (P_w). Hence, any changes in the mud pressure will only affect σ_θ and σ_r. When P_w decreases, σ_θ increases towards the compressive strength, at which σ_r should be less than or equal to P_w. This is the concern for underbalanced drilling with respect to borehole design. Thus, the lower limit of the mud pressure is associated with borehole collapse and $\sigma_\theta > \sigma_r$. It is therefore an effective and useful approach to focus on tangential stress, which incorporates borehole failure mode, regulated by the in- situ stress magnitudes & direction, mud pressure and material intrinsic properties. Investigation of **Eq. 1,** near borehole stresses were evaluated and presented in **Figs. 4 a & b.** From **Figs. 4b,** it is affirmed that horizontal strength anisotropy has significant influence on near borehole stresses to create a strong anisotropic stress environment and lead to borehole stability problems.

II. Hoop Stress and borehole instability:

It can be seen from **Fig. 5 (a, b & c)** that at $\theta = 90^0$ or 270^0, the predicted hoop stress is maximum. The larger hoop stress at $\theta = 90^0$ position together with magnitudes and direction of the anisotropy in-situ stresses turned the borehole instable. The first borehole breakout may initiate at the peak of the hoop stress. On the other hand, at $\theta = 180^0$, the borehole stresses are lower where formation fracture may initiates. However, depending of the direction of the in–situ stresses and well trajectory, breakout and fracture initiation positions may be changing. This sensitivity analysis indicates that Mode C gives unrealistic results (i.e. see **Fig. 5a**) which is only valid in the strong tectonic stress regimes. It may be noted that, horizontal wells are more vulnerable under mode B (**Fig. 5c**). In case of vertical well, both modes A and B become closer and equally dominated to lead to borehole instability. Though the axial stress is not a function of mud weight, all modes are changing with similar trend, only anisotropy intensity of the in-situ stresses are exposed to transformed axial stresses. It is recommended that for predicted shear failure at the

borehole wall, "θ" should be equal to 90^0 while equal to 180^0 for fracturing of the formation.
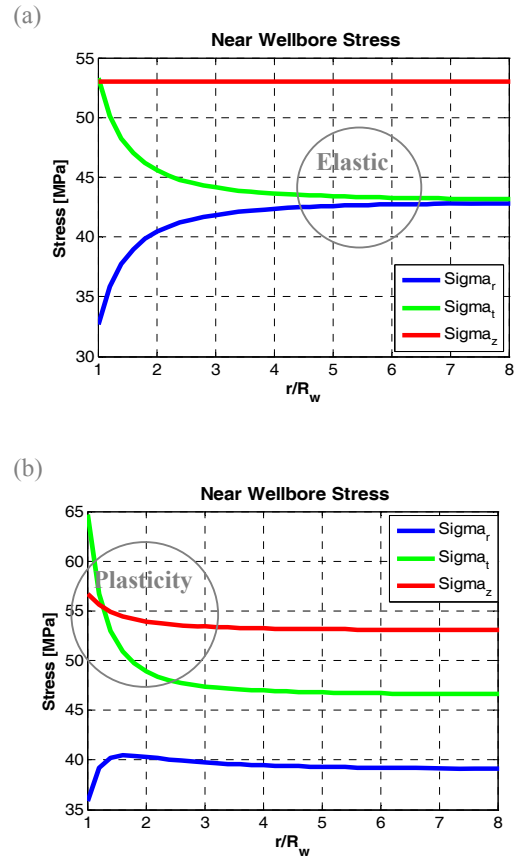
(a)

(b)

Fig 4a &b. Evaluation of the near wellbore stresses based on Kirsch solution. a) Isotropic b) Anisotropic in-situ stress state. Data from **Table A2** (case III).

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4.2. Prediction of Borehole Collapse:

From **Fig. 6 a, b & c,** it is found that predicted borehole collapse pressure through various formation under modes A & B is quantifying borehole collapse pressure (CP) and optimized MW. The predictive observations indicated; CP is determined by the largest in-situ stresses and the material intrinsic properties. In a later sensitivity analysis of this study, it is shown how in-situ stress and material intrinsic properties influences CP. This study results does not concern mud design of UBD, because UBD is a critical issue in shale, which knowledge is necessary for further investigation to capture shale heterogeneity. A 3-D orthotropic shale model is essential, and a separate study is going on within this research project to focus on shale hardening and softening effects. The complete research results on shale instability collectively may give recommendation for UBD. It is observed from the **Fig. 6** that a higher mud weight is required to prevent collapse in mode A. That means tangential stress under mode A is more dominant for determination of MW. Other observations; the rock may be relatively weak or may clay with HC in over pressure zone (@ 1500-2000 m). The estimation of minimum MW becomes equal to formation strength (mode A). It's

indicates an unconsolidated formations with hydrocarbon or the model assumption may not valid in this zones. Mondol et al. [17] is supported our observation. They were seen that in such geological formation in North Sea, formation may with overpressure with mostly quartz formation. The efficient integrated approach (GMM through CPM) in this study may therefore be useful in design of OBD wells.
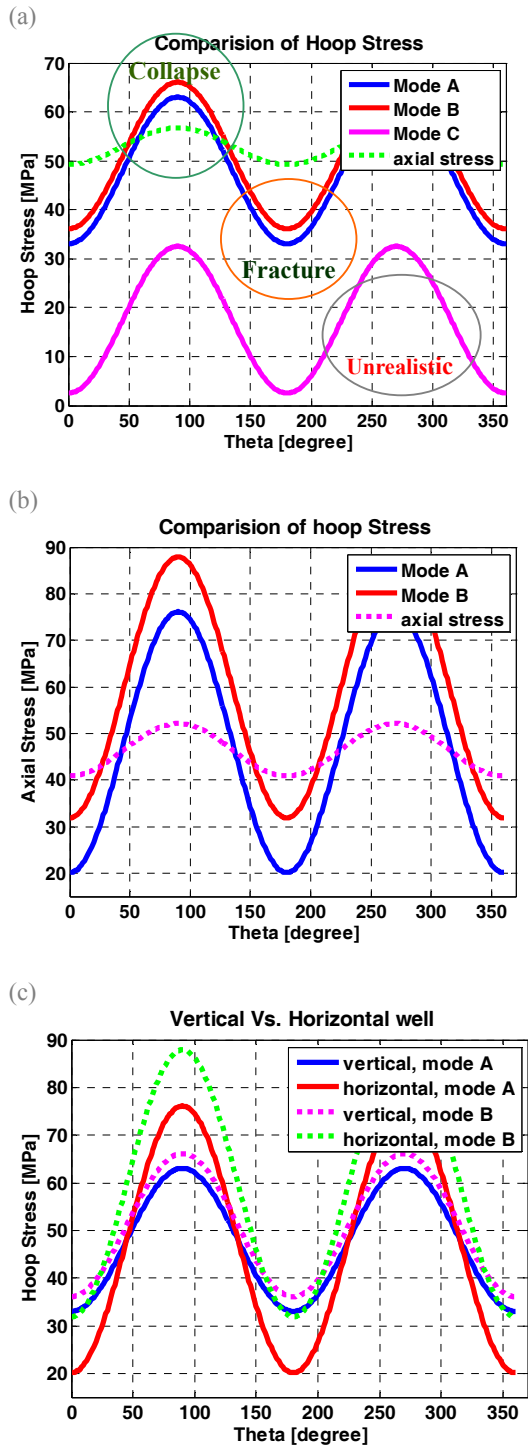
(a)

(b)

(c)

Fig. 5 a, b & c: Evaluation of hoop stresses for vertical & horizontal wells based on Kirsch solution. a) Vertical well

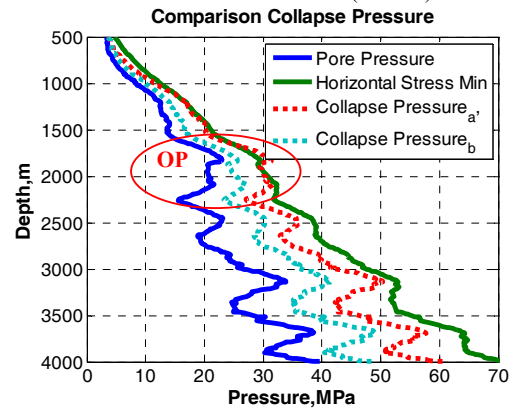b) horizontal well c) comparison between vertical and horizontal wells. Data from **Table A2** (case III).

Fig 6. Prediction of the borehole collapse pressure into vertical well through an integrated approach by using GMM & CPM. Data from Gullfaks field (well #34/10-16)

4.3 Factors associated with Collapse Pressure

Material intrinsic properties have a significant influence on the M-C failure state. The impacts of the following sensible parameters on the borehole collapse model are:
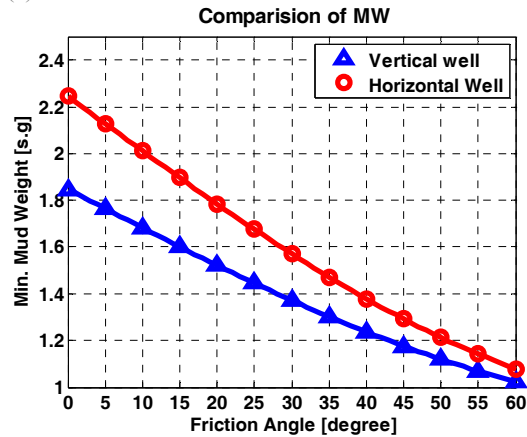
I. Effect of Friction angle and Cohesion on CPM
It is seen that material friction angle and cohesion have remarkable influence on the shear failure modes **(Fig. 7 a & b).** The required minimum MW to prevent borehole collapse is decreasing considerably with increasing material strength & its internal friction. These results indicate that the accuracy of the borehole instability model to obtain minimum MW strongly depends on the rock strength and material friction. The particular field case study shows that horizontal wells require higher mud weight in normal stress regimes (**Fig. 7 a**). It is also seen that in lower rock strength (α = 1 degree), the minimum MW difference between horizontal and vertical wells is maximum (Δ MW 0.40 s.g). The MW difference is reducing with increasing rock strength (i.e, @ α = 30 degree, Δ MW = 0.2 s.g). In ultra deep and strong tectonic geological region, horizontal stress anisotropy required relatively higher collapse pressure than vertical [9, 11, 13 & 15]. Mode C gives unrealistic result in normal stress field **[Fig. A1].** Material friction angle and cohesion play a major role to estimate MW under different shear failure modes **(Fig. A2).**

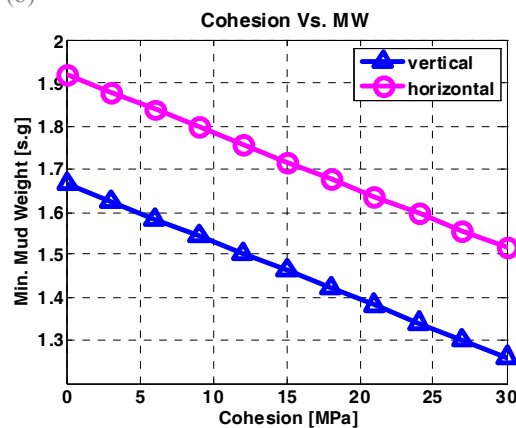**II. Effect of Pore Pressure on CPM**
Pore pressure prediction in shale, serve as an input to CPM, and produce biggest uncertainties of the model together with determining appropriate mud design to avoid collapse. This is the most unpredictable parameter that was used in GMM. However, its influence on the mud design is vital. **Fig. 7c** is indicating that MW needs to increase significantly with increasing pore pressure to avoid instability. The horizontal well under mode A and the normal in-situ stress condition is identified as critical

to require beigest mud weight to prevent borehole collapse. But under in strong tectonic stress regimes, vertical wells or drilled well through σ_H are considered as critical borehole instability [9, 15]. The borehole trajectory has trivial impact on mud design while drilling through strong tectonic geological regions, horizontal stress anisotropy determine the collapse risk [9-15].
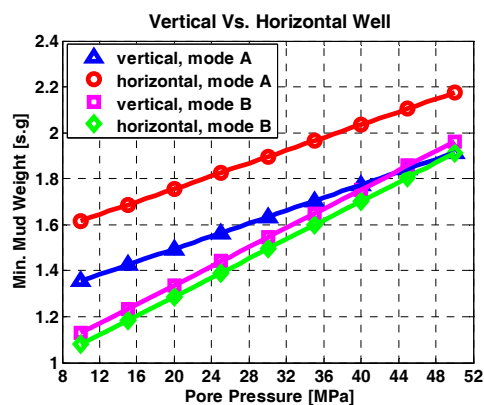
(a)

(b)

(c)

Fig 7. Prediction of the borehole collapse pressure. An integrated approach by using GMM though CPM. a) effect of friction angle , b) effect of cohesion and c) effect of pore pressure on CP. Data from **Table A2** (case III)

5. CONCLUSIONS

- A geomechanical model is under development and has reached a certain level of quality. Predicted in-situ stresses were used as input to the borehole shear failure model to quantify failure risks. The developed model can be revised and updated by using calibrated lab test data, or best fit drilling data.
- Eaton's empirical correlation can be used to predict pore pressure in North Sea wells with n greater than 3 as the best fit of exponent.
- M-C shear failure criterion can be used for minimum MW design to prevent borehole collapse under the modes A and B but not for mode C. Mode C gives unrealistic results which may only be applicable in strong tectonic geological regions. Under mode A which is the common situation, horizontal wells are most risk to instability (for lower friction angle).
- Failure modes vary with respect to material friction angle and cohesion. Mode A is dominating within friction angle $0-35^0$ while for mode B it is greater than 35^0.
- Hoop stress, mud weight and rock strength are the most influential elements in borehole collapse modeling. This study could not recommend UBD in shale. The fact that most horizontal UBD wells are completed open hole may cause a stricter requirement in quantifying rock strength. UBD in shale is risky operation where a separate in-depth study is required.
- Shale is a most heterogeneous substance never expects much accuracy of predictive results through any borehole collapse model. It is impossible to capture the total characteristics of shale behaviour into one stability analysis model.
- This study gives confidence to optimize MW for balanced drilling. The techniques used in this study may apply equally to others wells to optimize model verification.

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7. NOMENCLATURE

Symbol	Meaning	Unit
σ_V	Vertical stress	MPa
σ_h	Min. horizontal stress	MPa
σ_H	Max. horizontal stress	MPa
σ_θ	Tangential or hoop stress	MPa
σ_z	Axial stress	MPa
σ_r	Radial stress	MPa
P_f	Pore pressure	MPa
P_{fh}	Hydrostatic pressure	MPa
P_w	Wellbore pressure	MPa
υ	Poisons ratios	

C_o	Cohesion strength	MPa
To	Tensile strength; Pa	MPa
τ	Shear stress	MPa
β	Orientation of failure angle	Degrees
α	Material friction angle	Degrees
Δt_s	Shear sonic travel time	μs/m
Δt_c	Compressional sonic travel time	μs/m
D or h	Depth	m
E	Young's modulus	GPa
ρ_s	Formation density	gm/cm^3
ρ_w	Water density	gm/cm^3
O	Overburden gradient	KPa/m
H	Hydrostatic gradient	KPa/m
r	Radial distance	m
R_w	Borehole radius	m
V_P	P- wave velocity	m/s

Abbreviation:

GMM	:	Geomechanical Model
CPP	:	Collapse Pressure Prediction
CP	:	Collapse Pressure
UBD	:	underbalanced drilling
OBD	:	Over Balanced Drilling
OP	:	Over Pressure
HC	:	Hydrocarbon
CPM	:	Collapse Pressure Model

8. ACKNOWLEDGEMENTS

Appendix A:

Table A1: Main parameter and sources of information used to build the geomechanical model [3,4, 8, 11, 12].

Parameter	source	Correlation used in this study
σ_v	Density log	$\sigma_v = \int_0^h \rho_b g h$
σ_H	Best gauge	$\sigma_{H} = 1.2 * \sigma_{h \ (\text{best guess})}$
σ_h	Breckels, 1982	$\sigma_h = 0.0053 D^{1.145} + 0.46(P_f - P_{fn})$; D < 3000 m $\sigma_h = 0.0264 D - 31.7 + 0.46(P_f - P_{fn})$; D > 3000 m
P_f	Eaton, 1975	$P_f = O - (O - H)\left(\dfrac{\Delta t_{\text{normal}}}{\Delta t_{\text{observed}}}\right)^{3.0}$
C_0	Horsrud, 98	$C_0 = 0.77 * V_p^{2.93}$
ν	DSI tool	$\nu_{dy} = 1/2((\Delta t_s/\Delta t_c)^2 - 1)/(\Delta t_s/\Delta t_c)^2 - 1$ $\nu_s = 0.7\nu_{dy}$
E	DSI tool & Wang, 98	$E_{dy} = \rho_b(4\Delta t_s^2 - 3\Delta t_c^2)\Big/ 1 - \Delta t_c^2/\Delta t_s^2$ $E_s = 0.41 E_{dy} - 1.059$

Table A2: Stress field data used in borehole analytical model to predict CP through a sensitivity analysis

Case #	Stress Criteria, MPa	Others parameters
Case-1; Shallow depth (1200 m) (manipulated)	$\sigma_H > \sigma_h > \sigma_V$ 22 > 19 > 18	$P_f = 13$ MPa, $C_0 = 8$, MPa, $T_o = 1$ MPa, $\upsilon = 0.20$, $\alpha = 30^0$, $\theta = 90^0$
Case-II; Intermediate depth (2000 m)	$\sigma_H > \sigma_V > \sigma_h$ 40 > 36 > 33	$P_f = 25.5$ MPa, $C_0 = 10$ MPa, $T_o = 1$ MPa, $\upsilon = 0.25$, $\alpha = 30^0$, $\theta = 90^0$
Case-III; Deep (2500 m)	$\sigma_V > \sigma_H > \sigma_h$ 53 > 46.5 > 39	$P_f = 23$ MPa, $C_0 = 10$ MPa, $T_o = 1$ MPa, $\upsilon = 0.25$, $\alpha = 30^0$, $\theta = 90^0$

A3: M-C Borehole collapse Model

For borehole collapse it is assumed a M- C shear failure model. This is governed by the maximum and minimum principle stresses. The failure model is:

Mode A: Considering the situation where, $\sigma_\theta \geq \sigma_z \geq \sigma_r$
According to the M- C criterion, failure will occur when;

$$\sigma_1' = \sigma_\theta' = C_0 + \sigma_r' \tan^2\beta$$
$$\sigma_1' = \sigma_H + \sigma_h - 2(\sigma_H - \sigma_h)\cos 2\theta - P_w - P_f$$
and $\sigma_3' = \sigma_r' = P_w - P_f$;

By applying for minimum borehole pressure to prevent borehole collapse, above equations becomes:

$$\sigma_H + \sigma_h - 2(\sigma_H - \sigma_h)\cos 2\theta - P_w - P_f - C_0 - (P_w - P_f)\tan^2\beta \leq 0$$
and resulting;

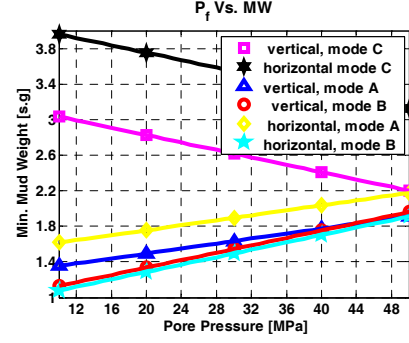$$P^a_{w,min} \leq \frac{3\sigma_H - \sigma_h - C_0 + P_f(\tan^2\beta - 1)}{1 + \tan^2\beta}$$

Similarly for mode B and C, collapse pressure equations can be derived. A set of analytical solutions for shear failures is included in **Table A3**.

Table A3: An analytical solution of borehole collapse model with the assumption of vertical well, impermeable borehole,
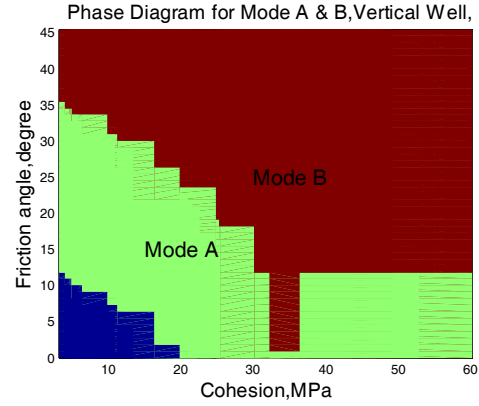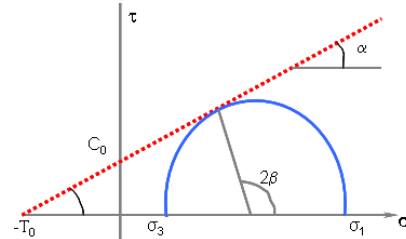
be greater than σ_θ and σ_H or σ_h also greater than σ_v.

Fig A1. Unrealistic results from mode C. data from Table A2 (case III).

Fig A2. effect of material cohesion and friction angle on CP

Fig A3. M-C failure criterion model

M	Condition	Borehole Failure occurs if	Satisfy the condition
A	$\sigma_\theta \geq \sigma_z \geq \sigma_r$	$P^{(a)}_{w,min} \leq \dfrac{3\sigma_H - \sigma_h - C_0 + P_f\left(\tan^2\beta - 1\right)}{1 + \tan^2\beta}$	$\sigma_r = P^{(a)}_{w,min}$ $\sigma_\theta = \sigma_H + \sigma_h - 2(\sigma_H - \sigma_h)\cos(2\theta) - P^{(a)}_{w,min}$ $\sigma_z = \sigma_V - 2v_{fr}(\sigma_H - \sigma_h)\cos(2\theta)$
B	$\sigma_z \geq \sigma_\theta \geq \sigma_r$	$P^{(b)}_{w,min} = P_f + \dfrac{\sigma_V + 2\left|v_{fr}\right|(\sigma_H - \sigma_h) - C_0 - P_f}{\tan^2\beta}$	$\sigma_r = P^{(b)}_{w,min}$ $\sigma_\theta = \sigma_H + \sigma_h - 2(\sigma_H - \sigma_h)\cos(2\theta) - P^{(b)}_{w,min}$ $\sigma_z = \sigma_V - 2v_{fr}(\sigma_H - \sigma_h)\cos(2\theta)$
C	$\sigma_z \geq \sigma_r \geq \sigma_\theta$	$P^{(c)}_{w,min} = 3\sigma_H - \sigma_h - P_f - \dfrac{\sigma_V - C_0 - P_f}{\tan^2\beta}$	$\sigma_r = P^{(c)}_{w,min}$ $\sigma_\theta = \sigma_H + \sigma_h - 2(\sigma_H - \sigma_h)\cos(2\theta) - P^{(c)}_{w,min}$ $\sigma_z = \sigma_V - 2v_{fr}(\sigma_H - \sigma_h)\cos(2\theta)$

For horizontal well σ_v change to σ_H and σ_H change to σ_v. Mode C is only applicable in strong tectonic stress area where σ_r will