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MUD DESIGN MODELS FOR UNDERBALANCED DRILLING WELLS IN SHALE

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ABSTRACT

Mud design for underbalanced drilled (UBD) wells in shale needs accurate rock strength to avoid borehole collapse. Understanding borehole collapse mechanisms during UBD in shale is becoming increasingly important for the petroleum industry, especially due to implementation of the UBD technique in operational practices. It is a well accepted statement that shale comprises three quarters of the sediments and rocks in siliclastic environments and most of the downhole problems occur during drilling in shale. Drilling underbalanced (UB) in shale could avoid chemical instability but brings risks of sloughing shale and stuck pipes problems. It is seen that models for proper mud design, derived from the geomechanical analysis, could help as decision support tool for UBD wells. In this work, we will therefore focus on the accuracy of material models that can predict minimum mud weight to avoid collapse. Aspects of eomechanical and thermal effects on mud design were also discussed.

The main contribution of this study is to improve confidence and reduce confusion when choosing an appropriate material model to predict mud weight, with the ultimate goal of minimizing wellbore stability problems experienced by drilling communities during UBD operations.

Keywords: Shale, UBD, OBD, Borehole Instability, Collapse Pressure, Rock Strength, Material Model, Calibration.

1.0 INTRODUCTION

A main aspect of wellbore stability analysis is the selection of an appropriate rock failure criterion. Several linear elastic methods have been used to predict or describe at which stress or stress conditions failure occurs. The most popular models that have been used are Mohr-Coulomb (M-C), Mogi-Coulomb, modified Cam-Clay, modified Lade and Drucker–Prager. The principle used to predict borehole failures through these models are quite similar, but the involvement of principal stresses in the material failure process is different from model to model. For example, M-C does not consider the effect of intermediate principal stress while Mogi-Coulomb and Modified Lade do. In contrast , the modified Cam-Clay model can evaluate material hardening and softening effects in conjunction with borehole collapse problems in shale. Several authors studied the performance of each constitutive model and discussed their goodness and limitations [2, 9-14]. It is seen that any conventional elastic material model generally used in borehole stability analysis in shale eventually have compromised with model simplicity & accuracy, mainly due to neglectance of anisotropy behavior in the mechanical and strength properties. While adapting 3-D shale anisotropy material model (i.e., modified Cam-Clay) is considering a preferable option to capture the true borehole environment particularly when drilling in shale. But3-D shale anisotropy models that contain numerous parameters, or which require numerical evaluation, are difficult to implement [2, 7, and 9]. For borehole stability assessment through shale anisotropy models, directional properties and matrix anisotropic parameters are required, consisting of 22 attributes. An extensive laboratory work is essential to supply a consistent model input data set. The most potential challenge to handle for any shale anisotropy model is to organize model input parameters together with advanced computing codes.

UBD and mechanical borehole stability has been studied by many researchers in recent years [2-7]. It is seen that a certain limit of underbalance (i.e., up to 3 MPa) may be possible in soft shale. It has suggested that should underbalanced drilling in shale be required, it is recommended to do separate and more in-depth studies of the zones where this is planned. Several issues are needed to consider to avoid borehole collapse in shale. These could be estimating true pore pressure, true rock strength and accurate mud design. In addition, shale heterogeneity and anisotropy, different bedding planes and in-situ stress regimes are crucial issues to be considered in well design.

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 [2, 7, 10-11, 13]. 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 the 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 whole 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 worldwide [13, 14].

The aim of this study was adaptation of an acceptable material model to define UBD related borehole collapse risk. Several models, including M-C, Mogi-Coulomb, Mohr-Coulomb elasto-plastic, Modified Cam-Clay and Drucker-Prager, were studied to check the model performance, and how to handle shale instability based on the pre-determined standard criteria, including:

- Simple model vs. complex model
- Model accuracy
- Discrepancy of the predictive results
- Model structure, design and computing environment

Both material plasticity and thermal effects on the stable mud weight window were subsequently quantified with the calibrated borehole model while using an extensive laboratory data set obtained from Pierre-1 outcrop shale as a calibration input. Moreover, this study represents compiled methodology of borehole collapse from published works [2 -12]. A systematic approach is applied while Matlab codes were developed to simulate the borehole collapse models dynamically.

2. BASIS - COLLAPSE PRESSURE PREDICTION (CPP)

Fig. 1 presents the shear - principal stress space to describe material failure criteria. The shear stress and the principal stresses are denoted by the Y-axis and the X- axis respectively. The shear failure line and the yielding curve were constructed based on the triaxial experimental results. Usually, several triaxial compressional tests are required to estimate the material failure parameters specifically for shale [1, 2, 7, 9, 13]. The failure parameters consist of friction angle (α), failure angle (β) cohesion (C_0) and tensile strength (T_0). In addition to mud weight design, we need the elastic parameters including Young modulus, Poisson's ratio, dilatency, etc. Islam et al (2011) worked on estimation of material failure parameters through triaxial tests for laminated bedded shale. The most interesting findings were published [1, 2]. This study has utilized necessary model input data from the published work conducted by Islam et al (2011). A complete set of model input parameter to simulate MW is presented in Table 1.

In general, the classical analytical models of the M-C, Mogi-Coulomb, Drucker-Prager and Modified Lade are based on the linear failure principle. The influence of the intermediate principal stress were not accounted for in these models for the calculation of the material failure state [11, 14]. This could lead to model in-accuracy and simplicity to predict MW. In Fig. 1, the Mohr circle (red color) is shown corresponding to a critical stress state when Mohr circles touch the failure line. Under such condition materials are reaching yielding. But, due to plasticity behavior of shale, in reality, the yielding surface is not linear. Depending on hardening effects (expanding pore volume) the yield surface can be expanded while due to softening (reduced pore volume) effect it is contracted. The impact of material plasticity on MW has been reported in several published work [3, 4, 7, 12-14]. A non-linear material model (i.e., M-C elasto - plastic or modified Cam- Clay) can be more suited models to capture the impact of plasticity on calculation of MW. From these studies it is seen that material plasticity improved stability by 3-5 %.

In order to model and for understanding of the elasto-plastic behavior of shale, a yield surface is introduced in Fig. 1 (yellow curve) and by Fig. 2. Inside the yield surface (Fig. 2), the material response is fully elastic. Once the yield stresses 'touch' the yield surface the material will start to plastify and produce plastic strains. During loading the yield surface expands until failure is reached.

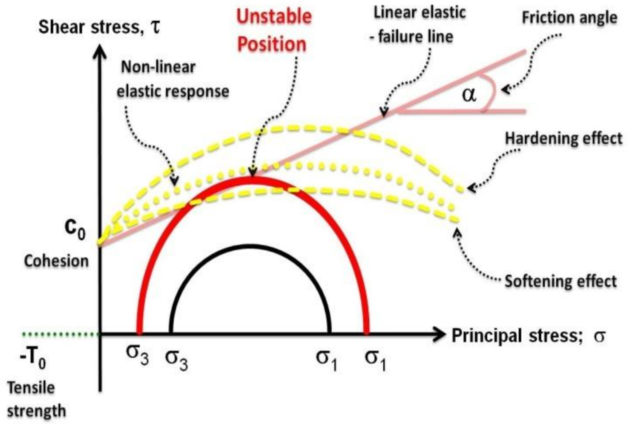


Fig 1. Illustration of material failure parameters and response for both linear and non-linear failure behavior.

In Fig. 2, the critical state line was drawn based on the stress path trend obtained from the triaxial test under drained mechanism. Both the associated and the non-associated flow influence the yield surface. As mentioned before both hardening and softening behavior of the material influenced the definition of the yield surface. Usually the potential surface (not shown in Fig. 2) should show similar trend as the yield surface under associated flow. But this potential surface will be differing from the yield surface when the strain rate followed by non-associated flow rules. Our study was based on an assumption that the strain rate followed associated flow rules (strain rate normal to yield surface). The yield or failure surface was calibrated against lab tests. A detail of this calibration procedure with necessary experimental data was found in published work done by others researcher [2, 7, and 9]. This study is beyond the scope to report the model construction and boundary condition for borehole simulation models. In fact, the models used in this study are explicitly addressed through previous work conducted by Islam et al. and Søreide et al., [2, 7, 11, and 12]. This study demonstrate?? sets of simulation and analyzed results.

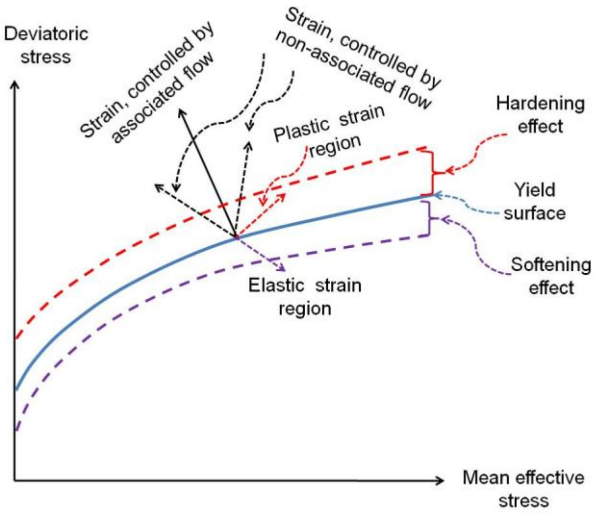


Fig 2. Illustration of material responses to show both hardening and softening behavior. The yield surface is controlled by associated and non-associated flow rules. On the yield surface, the yield function, F = 0, [2].

3. RESULTS AND DISCUSSION

A summary of the results to calculate minimum MW to prevent borehole collapse is presented in Fig. 3. It is shown how MW to prevent borehole collapse vary with respect to well inclination**.** It is a well-accepted statement that the Mohr- Coulomb model under-estimate the rock strength while this is opposite in the Drucker Prager model. By considering the above statement as a reference, it is seen from Fig. 3 that the Mohr-Coulomb elasto-plastic model (curve E) can be the best option for mud weight design in UBD wells. Because it neither over or under estimate the rock strength. In addition, this model can capture plasticity effects into MW design. The Mohr-Coulomb (curve A) or the Mogi-Coulomb (curve B) elastic models predicted 3-7 % higher mud weight than the elasto-plastic models did. A firm conclusion can first be made on the performance among the models after having conducted a real field case study of UBD wells. In general, plasticity improves wellbore stability. The effect on the rock, which is behaving plastically rather than elastically during post-failure, made failures more ductile than brittle. With respect to stability, the phase behavior lead to a "delayed" collapse of the borehole, and to reduction in mud weight, compared to a situation described by linear elastic behavior followed by brittle failure, since the plastic properties of the rock allowed it to deform permanently without causing collapse of the wellbore. The 'delayed' effect was also observed in investigations with respect to time dependency. Increased plasticity lead to fewer time-delayed instability problems, because of the stabilizing effect of the plastic behavior followed by ductile failure, compared to elastic behavior followed by brittle failure. It is seen that the stability margin increased by 1.6 % after adding the mud cooling effects (curve C) and for 27 hours of exposure (curve D). Thus, time exposure and mud cooling effects may also be noticed since they are counted as positive impacts on stability. Avoiding these effects will eventually increase the fracture risk. It will be interesting to see a range of temperature effects on MW design. A separate study can investigate this issue.

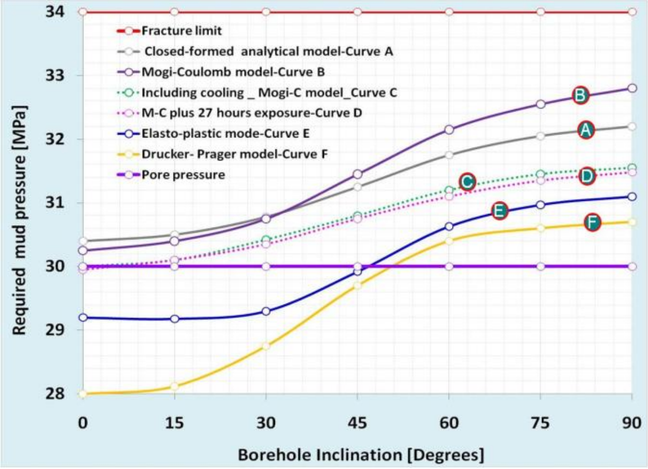


Fig 3. A summary of the results from a comparative study based on different popular models used for prediction of required mud pressure to prevent borehole collapse. This figure also presents the fracture limits together with mud cooling and time exposure effects. A fixed azimuth of 45^0 together with normal stress regimes condition was used in this study. Data are taken from Table 1.

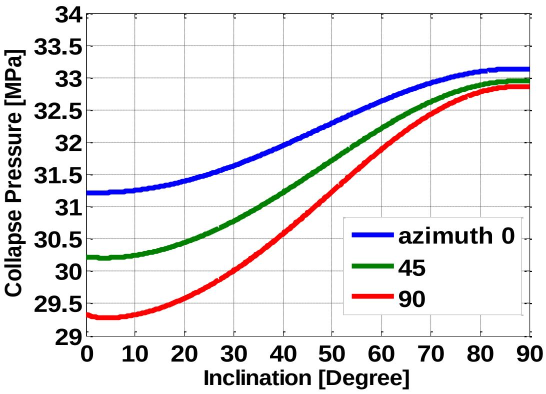
Regarding failure criteria and degree of conservativeness for such trends given from literature studies are recognized in the results obtained through the study. It is evident that Mohr-Coulomb gives the most conservative predictions of rock strength and so also of borehole stability and mud weight predictions, while Drucker-Prager (curve F) predicts the least conservative conditions.

In general, the Mohr-Coulomb criterion predicts only the lower limit of the rock strength, while the Drucker-Prager criterion predicts the upper limit of the rock strength. On the other hand, under normal fault (NF) conditions ($\sigma_V > \sigma_H > \sigma_h$) together with lower borehole inclination (i.e., vertical wells), Mogi-Coulomb predicts mud weight lower than the Mohr-Coulomb, as expected. With progressing higher inclination (i.e., high deviated wells); Mogi-Coulomb predicted MW a little bit higher than the Mohr-Coulomb. It seems that borehole trajectory, magnitude of the intermediate horizontal stress and its direction plays a role in MW – determination . Adel-Al-Ajmi et al., [11] noticed that in NF stress regime, the effect of horizontal well orientation on borehole stability is insignificant, according to the Mogi-Coulomb criterion. He also concluded that in all the stress regimes, changing the orientation of the borehole in a plane perpendicular to the maximum principal in situ stress (i.e., the σ_2-σ_3 plane) will not influence the collapse pressure predicted by the Mohr-Coulomb criterion significantly. The rate of change of the collapse pressure with respect to well orientation in the σ_2-σ_3 plane, using the Mohr-Coulomb criterion, is at least twice the one predicted by applying the Mogi-Coulomb criterion. Utilization of the Mohr-Coulomb criterion in horizontal stress evaluation may result in misleading predictions, particularly in NF stress regimes. However, Mogi-Coulomb always predicted lower MW than Mohr-Coulomb at Strike-Slipe ($\sigma_H > \sigma_V > \sigma_h$) and Reverse faults ($\sigma_H > \sigma_h > \sigma_V$) conditions.

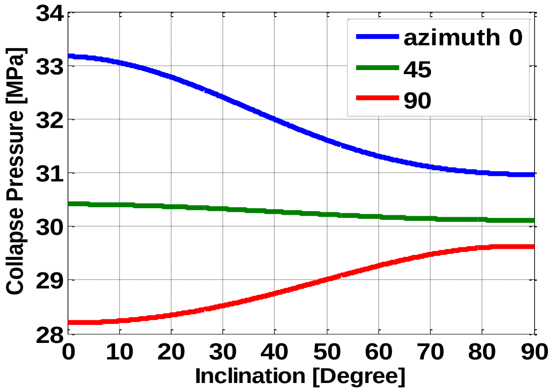
Fig. 4 presents the MW results predicted by the Mogi - Coulomb model for wells drilled through different faults conditions [5, 11]. This solution is indicating that for NF, vertical drilled wells are more favorable (stable) than deviated wells subjected to minimum mud weight to prevent borehole collapse. The CP solution under SSF stated that highly inclined wells are more favorable (showing lower CP required to prevent borehole collapse) than vertical wells. The CP indicates that horizontal drilled wells are the most favorable option when subjected to RF stress regimes. It is seen that well azimuth has a significant impact on the estimated CP to prevent borehole collapse. For this particular case, 90^0 azimuthally wells are the most stable in the context of borehole collapse. Since the Mogi-Coulomb model is simple and can include intermediate stress effects it could be used as a possible tool for mud design.

The optimum underbalanced (UB) pressure to avoid borehole collapse can be predicted from the Modified Cam Clay model [12]. This analysis shows that underbalance is possible up to 3 MPa for Pierre-1 shale.

(a)



(b)



(c)

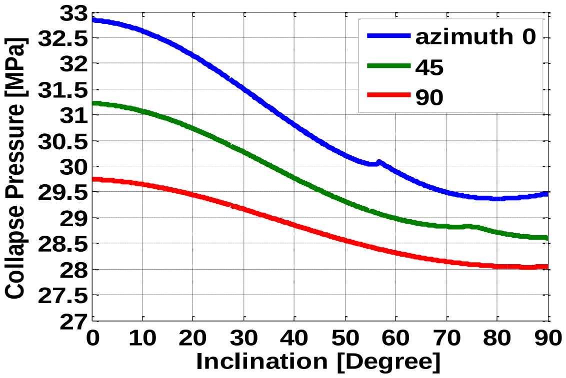


Fig 4. Prediction of borehole collapse pressure through the Mogi - Coulomb analytical model for a) NF, b) SSF, c) RF conditions. Data are taken from Table 1 [5].

This work did not study the collapse pressure influenced by the effects of WBM or drilling with OBM. It is believed and assumed that inUBD there should be no invasion into the rock and accordingly no chemical effects. The rock is particularly inert. However, it remains to validate our borehole stability models against real data and realistic environment. Some crucial factors to be addressed include mesh size effects on the numerical model accuracy, time effects such as thermal and creep effects on rock strength, true pore pressure in shale, measured rock strength based on real core specimen and capillary pressure effects on consolidation. It is agreed that UBD related field studies is a fundamental requirement to test our developed models and results.

4. CONCLUSIONS

The study of mud design for UBD wells indicated that the Mohr-Coulomb elasto-plastic or the Modified Cam-Clay model are the two best models for borehole stability analysis in shale, provided the models are supplied with significant rock mechanical data to run borehole simulations. These two models can capture the shale heterogeneity effects on MW design sufficiently accurately. Obtained results seemed more realistic than through the other models. Another observation was that the stability analysis is considerably dependent on the intermediate principal stress, plasticity and mud cooling effects, non of which should be ignored in any field applications, especially for UBD wells.

Time delayed effects are favorable for UBD. However, the plasticity effect should include developing recommended mud weights for UBD operations with respect to time of exposure. Time delayed effects durng OBD are increasing fracturing and lost circulation uncertainities.

Shale is a most heterogeneous substance. Never expect 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.

The findings of this paper will help the operator to make better drilling plans by avoiding or minimizing borehole instability problems. In the same way it may also help in increasing the confidence levels, explore in-depth knowledge about the subjects and to reduce confusion in selecting the correct model in the workflow.

This study gives confidence to optimize MW for balanced drilling also.

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7. NOMENCLATURE

Symbols	Meaning
σ_V	Vertical stress
σ_h	Min. horizontal stress
σ_H	Max. horizontal stress
P_f	Pore pressure
P_{fh}	Hydrostatic pressure
P_w	Wellbore pressure
υ	Poisons ratios
υ_{tp}	Poisons ratios for transverse to bedding
C_o	Cohesion strength
To	Tensile strength; Pa
τ	Shear stress
β	Orientation of failure angle
α	Material friction angle
Ep	Young's modulus parallel to bedding
E_t	Young's modulus transverse to bedding
ρ_s	Formation density
ρ_w	Water density

Abbreviation:

M-C : Mohr - Coulomb Model
CPP : Collapse Pressure Prediction
CP : Collapse Pressure
UBD : Underbalanced drilling
OBD : Over Balanced Drilling
OP : Over Pressure
MW : Mud Weight
UB : Underbalanced pressure
CPM : Collapse Pressure Model
NF : Normal Fault
SSF : Strike-Slip Fault
RF : Reverse Fault

Table 1: Model input parameters for prediction of borehole collapse pressure

Symbol	Meaning	Unit
σ_V	40	MPa
σ_h	35	MPa
σ_H	37	MPa
P_f	30	MPa
υ	0.32 (undrained)	-
υ_{fr}	0.14 (drained)	-
υ_{tp}	0.1	-
C_o	3.2	MPa
UCS	9.72	MPa
To	1	MPa
β	58	Degrees
ϕ	25	Degrees
ψ	9	Degrees
E_p	2.5 (undrained)	GPa
E_t	0.9	GPa
E_{fr}	1.1 (drained)	GPa
σ_{yield}	29	MPa
T_f	80	^0C
T_m	30	^0C
α_T	10^{-5}	$^0C^{-1}$
a	2.63	MPa
b	0.40	-

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Note: In the case of a short-time borehole simulation, undrained rock properties can be used, while, for long simulations, the drained rock properties are applied.