Borehole Collapse Modelling with Sensitivity Analysis in a North East India

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Keywords

Wellbore stability, poroelastic stress modelling, North East India

Summary

Distribution of stress around a borehole are the primary cause of deformation of well. Pore pressure, rock mechanical characteristics and trajectory of the wellbore also have significant contribution. A deformed wellbore, if unchecked, may, lead to instability amounting to loss of time and increase in cost thus adversely affecting drilling and production operations. Density of drilling fluid, which plays the primary role to maintain wellbore stability that is the mud-weight should be predicted with confidence. Proper mitigation of the issue is addressed in the study by analysis of rock failure criteria through borehole collapse model. Minimum mud weight has been predicted using Mohr- Coulomb and Mogi-Coulomb failure criteria. Due to inherent uncertainties in the input parameters sensitivity analysis is carried out to define the most critical parameters affecting the rock failure criteria derived mud weight.

Introduction

The North East India is characterized by complex evolutionary history. The high seismicity of the region is attributed to the presence of two major subduction boundary in the region, one between Indian plate and Eurasian and another between Indian plate and Myanmar plate. Crustal shortening, caused by collision between Indian plate beneath Eurasian plate is marked by the rising Eastern Himalayas. Main boundary thrust (MBT), Main Central thrust (MCT) and Main Frontal Thrust (MFT) and several other smaller north heading thrust are characteristics of this region. Though dominated by myriad thrust systems a section of Upper Assam, in North eastern India remains aseismic in nature. This region is termed as Assam Gap which is known to be influenced by normal faulting mechanism. This region which lies along the Bramhaputra valley is bordered by the Mikir Hills, MBT, Mishmi Thrust and the Naga-Disang Thrust on all four sides as shown in Figure 1. The entire province of Upper Assam is one of the oldest producing basin of India, rich in hydrocarbon reserves. Two wells, M1 and M3 in this extensional region of Assam Gap has been chosen to study well stability using borehole collapse modelling.

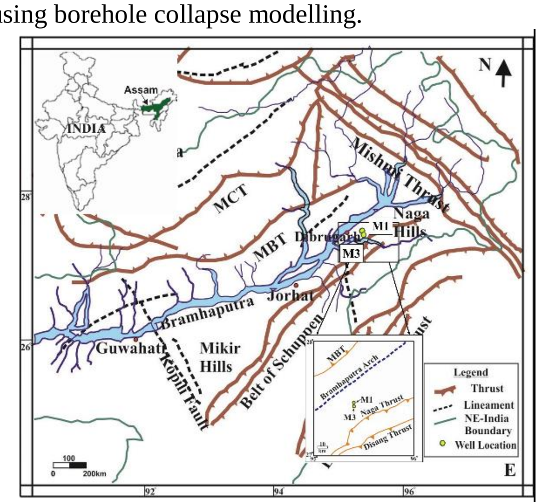


Figure 1**:** Illustrates major geotectonic setting of the study area along with well locations. Inset marking the wells in the Assam Gap has been added.

Theory and Method

Extensive knowledge of pore pressure, in situ stress magnitudes and orientation is essential for detailed wellbore stability analysis. Alam et al., 2019 in her paper discusses in details the method of determining pore pressure (PP) from conventional well log data using Eaton's sonic equation. The PP calculated has been further used by Alam et al. to calculate maximum and minimum in-situ horizontal stresses (S_H and S_h respectively) using poroelastic modelling for M1 and M2. The poroelastic equations are as follows:

$$S_h = \frac{\nu_s}{1-\nu_s}(S_V - PP) + PP + \frac{\nu_s Y_s}{1-{\nu_s}^2}\varepsilon_x + \frac{Y_s}{1-{\nu_s}^2}\varepsilon_y \quad (1)$$

$$S_H = \frac{\nu_s}{1-\nu_s}(S_V - PP) + PP + \frac{\nu_s Y_s}{1-{\nu_s}^2}\varepsilon_y + \frac{Y_s}{1-{\nu_s}^2}\varepsilon_x \quad (2)$$

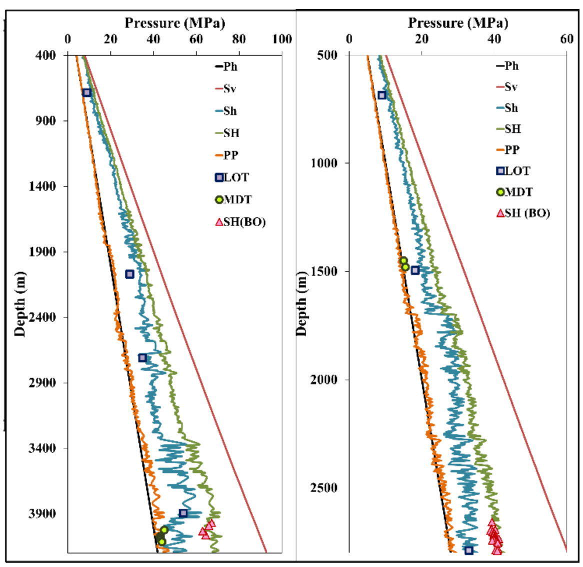
Here S_v is the overburden stress, PP is pore pressure from Eaton's sonic equation (Equation 3), Y_s is static Young's modulus and ε_x and ε_y are the maximum and minimum tectonic strains along NE-SW and NW-SE directions respectively. Uniaxial Compressive Strength (UCS) and Y_s have been calculated using established empirical relations appropriate for corresponding lithology.

$$PP = S_V - (S_V - P_h) * (\Delta t_n/\Delta t)^n \quad (3)$$

Δt_n is the Δt = compressional sonic travel time, Δt_n = travel time computed from normal compaction trend (NCT) and n = Eaton's exponent which has been determined using best fit method to be 1 for M1 and M3.

Well name	ε_x Maximum Tectonic Strain	ε_y Minimum Tectonic Strain
M1	0.00077	-0.001
M3	0.000099	-0.0019

Table 1: Displays maximum and minimum tectonic strain directed along NE-SW and NW-SW directions respectively calculated using poroelastic model for M1 and M3



(a) (b)

Figure 2: (a) and (b) hydrostatic stress (Ph), vertical stress (S_V), minimum (S_h) and maximum (S_H) horizontal stress , pore pressure (PP), leak off test data (LOT), modular tester data (MDT), and breakout derived maximum horizontal stress (S_H(BO)) have been plotted against depth for wells M1 and M3.

ε_x and ε_y have been calculated from equations 1 and 2 at depths where S_h and S_H values can be approximated from known leak off test data (LOT) and breakout (BO) out respectively. Tectonic strains used for wells M1 and M3 have been tabulated in Table 1. Stress magnitude against depth as well as pore pressure have been plotted in Figure 2 (a) and (b). Modular Dynamic Test (MDT), LOT and BO derived S_H has been used for validation of results and found to match satisfactorily with calculated. Comparing the magnitude of S_V, S_H, S_h we can construe from the figure that a stress regime $S_V>S_H>S_h$ is prevalent throughout the well which corresponds to a normal faulted system.

Rock Failure Analysis

In a vertical wellbore, the impact of stresses on the wall of borehole can be resolved into three components of tangential (σ_θ), axial (σ_z) and radial (σ_r) component. These are calculated using Kirsch's simplified equation (4), (5) and (6)

$$\sigma_\theta = (\sigma_H - \sigma_h) - 2(\sigma_H - \sigma_h)\cos 2\theta - PP \quad (4)$$

$$\sigma_r = PP \quad (5)$$

$$\sigma_z = \sigma_V - 2\nu(\sigma_H - \sigma_h)\cos 2\theta \quad (6)$$

σ_θ and σ_z are a function of θ and hence vary sinusoidally along borehole circumference. Breakout or shear failure is observed at maximum σ_θ at $\theta = \pm\pi/2$, whereas, σ_θ is minimum at θ = 0 and π. It is found that the dominating order $\sigma_\theta \geq \sigma_z \geq \sigma_r$ is followed in MI and M2, hence minimum permissible mud weight (MW) is estimated using Mohr Coulomb (MC) and Mogi Coulomb (MG) failure criteria considering the above situation for M1and M3.

The minimum mud weight following the MC criteria is given by

$$P_{MC} \leq \frac{3\sigma_H - \sigma_h - UCS + PP\,(q-1)}{1+q} \quad (7)$$

$$q = \frac{1+sin\varphi}{1-sin\varphi} \quad (8)$$

ϕ is the internal frictional angle calculated using equation 9.

The MG failure criteria has been proposed by Al-Ajmi and Zimmerman (2006). It is given by

$$P_{w_{MG}} = \frac{A}{2} - \frac{1}{6}\sqrt{12[a' + b'(A - 2PP)]^2 - 3(A - 2B)^2} \quad (9)$$

Where, $a' = 2c\cos\varphi = \frac{2UCS}{q+1}$

$b' = \frac{q-1}{q+1}$

$A = 3\sigma_H - \sigma_h$ and $B = \sigma_V + 2\nu\ (\sigma_H - \sigma_h)$

Figure 3 (a,b) and figure 4 (a,b) illustrates predicted MW using MC and MG criteria, actual MWs, along with bit size/caliper M1, and M3, for specific depth intervals. Bit Size-Caliper plots for corresponding depths are also displayed. Available FMI for specific depths displayed for M1. MG predicted mud weight reveals a more suitable match with actual MW for wells (M1, M3) in normal faulted region. Little to none deviation of caliper log from bit-size and shows that well bore has not undergone collapse and is stable using MG derived MW. We can infer from this result that minimum MW estimated using MC rock failure criteria overestimates the predicted MW for the study area.

A numerical model is devised using MATLAB programming software to evaluate the critical mud weights to prevent breakouts M1, and M3. As MG failure criteria observed to hold stable wellbore condition for M1and M3 the MATLAB softcode is used to model the collapse limit for this. In figure 3 © and 4 (c) the centre of the plot represents the location of vertical well while the edges give positions of horiaontal ones. Blue signifies stable well bore conditions while red defines unstable conditions. For both M1 as well as M3 we can decipher that MG derived criteria gives stability for vertical wellbores.

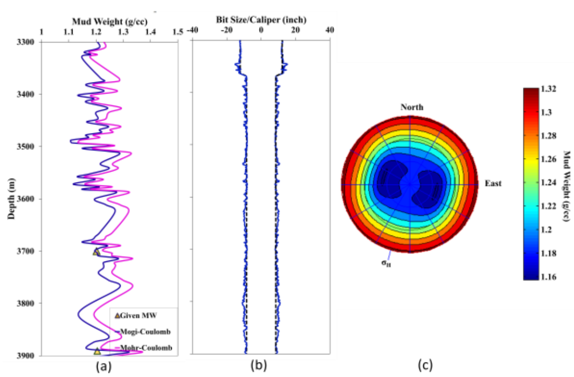


Figure 3- *(a)Minimum MW for MG and MC derived rock failure criteria along with actual MW used while drilling well M1 for interval3300-3900m (b) Bit/Size and Caliper against depth for the same interval. (c) Borehole collapse model at 3500m displaying minimum MW required to prevent breakout using MG criteria. Colour bar shows required MW in specific gravity units. Direction of S_H has also been marked*

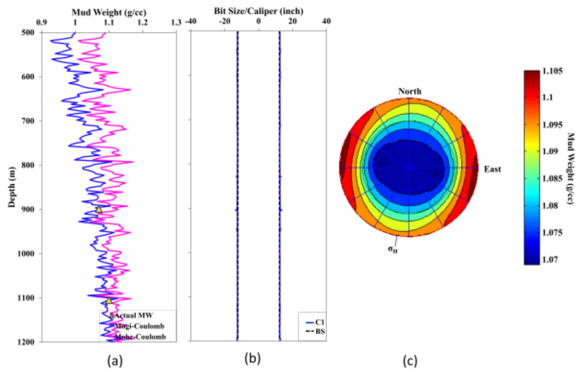


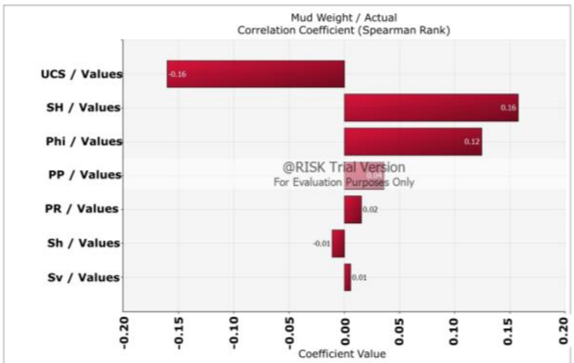
Figure 4: (a)Minimum MW for MG and MC derived rock failure criteria along with actual MW used while drilling well M3 for interval500-1200m (b) Bit/Size and Caliper against depth for the same interval. (c) Borehole collapse model at 899m displaying minimum MW required to prevent breakout using MG criteria. Colour bar shows required MW in specific gravity units. Direction of S_H has also been marked.

Sensitivity Analysis

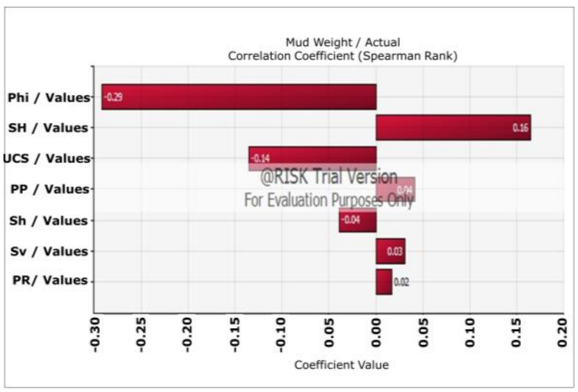
Well logs, in absence of core data, which serve as input for the crustal stress determination and rock failure analysis have a degree of uncertainty infused in it. Thus, identifying the influence of S_V, S_h, S_H, PP, UCS, ν, on modeled MG rock failure criteria for minimum MW calculation help us approach the wellbore instability challenge in a more stochastic manner. @RISK Excel software has been used to run sensitivity analysis on M1 and M3. Probability density function (PDF) are generated for each input parameter of S_V, S_h, S_H, PP, UCS, ν for wells M1 (400-4100m), M3 (500-2700m), using best fit distribution. The PDFs defines the minimum, maximum and most likely values for every distribution. Monte Carlo Simulation (MCS) is run with 5000 iterations building possible models for each PDF with their intrinsic uncertainity corresponding to input parameters. Sensitivity of each input parameter is carried out on the basis of regression coefficient and displayed in the form of tornado chart (Figure 5a and b).

The tornado chart in Figure 5 displays the influence of input parameters affecting the required minimum MW to prevent BO. The input parameters; UCS, friction angle and SH are observed to affect the MG derived MW mostly for wells M1 and M3 in normal faulted regions of Upper Assam (Figure 5a and b) while Sv, Sh and Poisson’s ratio are seen to affect the MW minimally.

Borehole Collapse Modelling with Sensitivity Analysis



(a)



(b)

Figure 5: Sensitivity analysis for modelled MG derived MW using @RISK Excel software for (a)M1 and (b)M3.

Results and Discussion

Crustal stress magnitude estimation using poroelastic modelling illustrates the order of stress to be $S_V>S_H>S_h$. We can conclude that a normal faulting regime prevails throughout the length of the wells in Assam Gap. Predicting minimum MW from analysis of MC and MG rock failure criteria and comparing with actual MW we find that for stable borehole intervals MG derived MW fits better whereas MC derived MW overestimates the minimum MW by a small degree. Borehole Collapse modelling carried out using MG derived minimum MW condition displays that for M1 and M3 in the normal faulted region a vertical well ensures much more stability in comparison to a horizontal one. It is evident from the borehole collapse model that a trajectory parallel to S_h may be considered as optimal well path to ensure stability. From sensitivity analysis of MG derived minimum MW for M1 and M3 we may surmise that UCS, SH and ϕ are the components to which the predicted MW is most sensitive, hence care must be taken while estimating these parameters to diminish errors in the final results (Figure 5(a) and b). Rock failure analysis discussed here approaches the well bore stability issue in a deterministic way, however quantifying the uncertainties associated with the most critical parameters affecting the minimum MW can guide the drilling of stable borehole in a with a stochastic approach which would be free from inherent uncertainties in input parameters.

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