

Addressing Type-II Overpressure and Comprehensive 1-D Mechanical Earth Modeling in a Tectonically Active Area in Tripura Fold Belt of India: A Case Study

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Keywords

Unloading, Modified Bowers' Method, Safe Mud Weight Window, MEM, Triaxial Data

Summary

The main objective of this study was to prepare a comprehensive Mechanical Earth Model considering all the data acquired in Khubal field till date. The aim was to provide optimum mud weight windows in overpressured Middle Bhuban and Lower Bhuban formations, preferential direction for smooth drilling of inclined wells, realistic idea of prevailing pore pressure and its causatives and inputs for any hydrofracturing jobs planned in future.

Introduction

Tripura fold belt constitutes the southern part of frontal fold belt of Assam-Arakan basin and is characterized by a series of sub-parallel, doubly plunging, elongated, narrow anticlines which are trending roughly north-south. Khubal structure is a doubly plunging anticline, trending NNE-SSW (Fig.1).

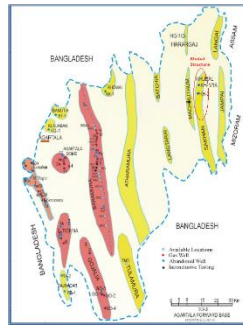


Figure 1: Study Area

The study area is tectonically active with complex folding and faulting. Target formations are in excess of 3,000 m through these complex structures. At several places, we experience high formation dips (>60 deg). The main challenges faced during drilling have been various well control and instability events: kicks, tight hole, stuck pipe, lost in hole BHAs, short TD and thereby increasing NPT and cost of the well. The causes of this instability were difficult to isolate. Due to poor hole condition in these formations, logging was limited and recorded logs were of poor quality in many wells. Unavailability of advance logs and formation pressure measurements in initial wells in Middle Bhuban Formation gave rise to poor

understanding of the formations and led to uncertainty in past predictions.

Experience from past wells also indicated the existence of overpressure in the Middle Bhuban and Lower Bhuban Formation, which could not be accurately predicted by surface seismic data. Hence, drilling through these highly stressed and overpressured formations led to excessive NPT and cost. In addition, severe hole enlargement and rugosity through eventual reservoir sections resulted in poor logging conditions and uncertain reservoir evaluation. As a result, access and interpretation of the reservoirs, to prove and produce reserves, has been a major challenge in this region.

Methodology Adopted

The basis for predicting stress induced wellbore failure successfully and accurately lies in understanding of a comprehensive Geomechanical Earth model. It helps to understand and predict stress induced failures in an area/well. The principal constituents of the Geomechanical model are three principal stresses namely vertical stress (S_v), maximum principal horizontal stress (S_{Hmax}) and minimum principal horizontal stress (S_{Hmin}), pore pressure (P_p) and the rock strength (UCS). Methodology Adopted in this study is as follows.

- Data availability and QC
- Shear slowness data generation in older wells.
- Mechanical Stratigraphy determination using basic logs & master log.
- Computation of Overburden stress by integrating density log.
- Estimation of overpressure generation mechanism by Hoseni's density-velocity cross-plots.
- Pore pressure prediction using Eaton's trend line method (using both sonic and resistivity) and Modified Bowers' method.

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- Calibration of estimated pore pressure with wireline formation pressure data.
- Dynamic Elastic properties computation using dipole sonic and density data.
- Static Elastic properties computation using lab derived correlations on cores.
- Estimation of Rock Strength (UCS, Tensile Strength & Static Young's modulus) using already established correlations.
- Horizontal Stress Direction determination by identifying drilling induced fractures and breakouts on Resistivity Image log / 4-arm caliper or by using sonic anisotropy data.
- Horizontal Stress magnitude computation using poro-elastic horizontal strain model and calibration of Minimum Horizontal Stress magnitude with Leak-off test data.
- Calibration & Validation of results with drilling events, Image log, 4-arm Caliper, LOT & formation pressure tests for Maximum Horizontal Stress magnitude and Wellbore stability Analysis.
- Shear failure mud weight and breakdown mud weight sensitivity analysis for different well inclinations and azimuths.

S_v = Vertical/overburden stress (Pa),
 ρ = Formation bulk density (kg/m³),
 g = Gravitational acceleration (m/s²),
 z = Depth (m)

Bulk density log data were available for all the studied wells. However, in some cases the bulk density data were affected by borehole condition. So, wherever necessary, a pseudo-density profile was created from acoustic data using the Gardner equation:

$$\rho = A \left(\frac{10^6}{DT} \right)^B$$

Where ρ = density (g/cc)
 A = coefficient
 B = exponent
 DT = acoustic slowness (μ s/ft)

Shallow bulk density trend was constructed using extrapolation and this trend was composited with the bulk density and/or pseudo-density data till the top of first reliable logs. The density data was integrated with the respective density trend to obtain a continuous vertical stress (overburden) profile for each well. For QC, density from RHOZ and Gardner were matched in the top interval of RHOZ.

Case Study

Shear Slowness Data Prediction: Shear slowness data was not available for a number of wells. For any Geomechanical analysis to carry out, compressional sonic, shear sonic and bulk density data are the most important inputs.

“FACIMAGE” module of GEOLOG was used for prediction of shear slowness (DTSM). Well KH-A was chosen as the model well as it had all the required data. In this well, GR, NPHI, RHOB and DTCO curves were taken as inputs for facies generation using MRGC model and DTSM log was predicted. Excellent match was observed between predicted and recorded DTSM data. The same model was propagated to other wells for DTSM prediction.

Overburden Stress Estimation: The vertical component of the overburden stress at depth z , is calculated by integrating the weight above the point z using the following equation (Fjaer et al, 1992):

$$S_v = \int_0^z \rho g dz$$

Where,

Pore Pressure Estimation: Most common log based method for pore pressure estimation is Eaton's trend line method, wherein deviation of porosities from a normal compaction trend for the field is seen. For porosity computation, Resistivity, Density, Neutron or Sonic log can be used. However, sonic porosities are considered to be the least affected by the presence of fluids or specific minerals in the rock.

$$P_p = \sigma_v - (\sigma_v - P_{pnorm}) \times a \times \left(\frac{DT}{DT_{norm}} \right)^n$$

In semi-log trend line: $\log(DT_{norm}) = DT_0 + KZ$

Where, Z is the depth measured from the mudline, DT is the measurement value, DT_0 is the measurement of sediments at the mudline, DT_{norm} is the measurement value if the formation was normally pressured, P_{pnorm} is the normal pore pressure, a and n are fitting parameters named Eaton factor and Eaton exponent respectively. The values used for Eaton's method using compressional slowness are: $a=1$ and $n=3$.

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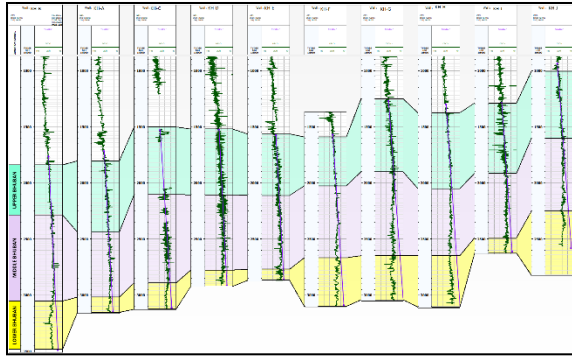


Figure 2: Overpressure indicated by deviation from normal compaction trend

Displayed above wells in Fig.2 are those, which have gone up to the Lower Bhuban formation. We can see that in the first five wells (KH-B, KH-A, KH-C, KH-D, KH-E), onset of overpressure starts in deeper part of Middle Bhuban and continues in Lower Bhuban, while in last five wells (KH-F, KH-G, KH-H, KH-I, KH-J), almost entire Middle Bhuban is overpressured along with Lower Bhuban.

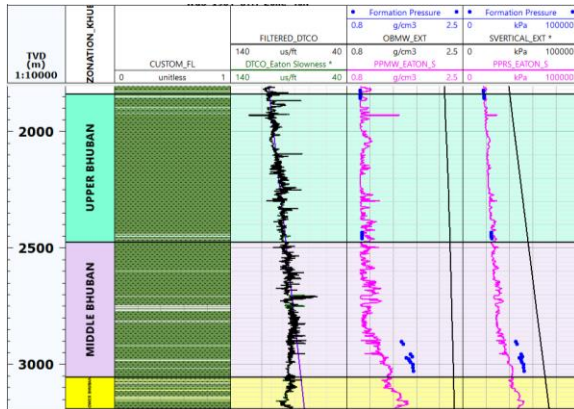


Figure 3: Eaton's sonic method underestimating overpressure

Fig.3 shows Pore pressure estimation using Eaton's sonic method in KH-A. The available formation pressure data in deeper part of Middle Bhuban formation suggests that the pore pressure remains drastically under-estimated by Eaton's sonic method.

Log-based methods like Eaton's generally see the compaction behaviour of shales and rely on assumption that porosity is intrinsically linked to compaction state, which itself is controlled by the effective stress. Eaton's method is such an equivalent

depth method, which fails when velocity-effective stress from a reversal diverge from the compaction trend defined by shallower formations. It will significantly underestimate pore pressure in such cases. The same will hold true for any pore pressure estimation method that relies upon a single velocity-effective stress relation. The conventional approach of fitting trend line on porosity logs does not work here as the pressure generation mechanism is altogether different from under-compaction (Zoback, 2007).

This type of overpressure is termed as type-2 overpressure and can arise due to unloading (upthrust), Clay diagenesis (smectite to illite conversion), thermal cracking of kerogen (fluid expansion) etc.

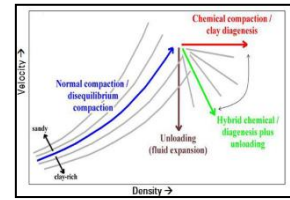


Figure 4: Hoseni Curve

Overpressure generation mechanism can be found out by a cross-plot between compressional slowness and density, which is called a Hoseni curve (Fig.4). It differentiates between different mechanisms of overpressure generation. Under compaction follows the normal curve while any significant deviation from the normal trend reflects a different overpressure mechanism (type-2 overpressure).

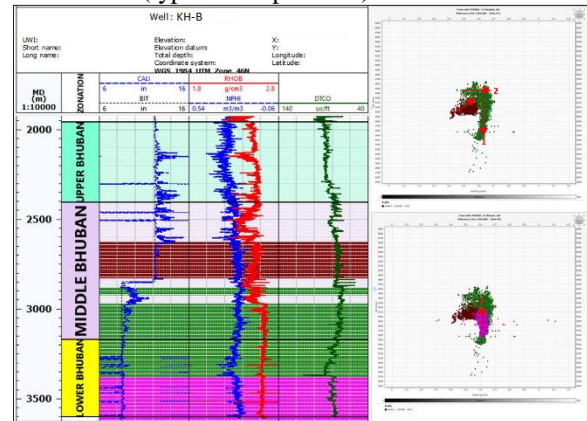


Figure 5: Density-Velocity plot in well KH-B

In well KH-B, the cleanest available shale data from inside and outside the reversal was picked. In the deeper section of Middle Bhuban Formation and top of Lower Bhuban (shaded with green), we can see a distinct unloading trend (trend 1) associated with tectonic activity and uplifting, which is the prime cause of overpressure generation in this tectonically

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complex, thrust and folded area. Clay diagenesis trends were also observed (trend 2) which can be attributed to transformation of smectite to Illite. XRD studies have reported Illite to be present in Middle Bhuban formation as well as Lower Bhuban (less than Middle Bhuban). Lower Bhuban formation at a depth is showing overpressure due to undercompaction mainly, as velocities start increasing (shaded with magenta). This trend (trend 3) can easily be confused with unloading trend 1, if not plotted separately.

Bowers discussed ways to account for type-2 overpressure situations. For Modified Bowers' method to be used, reliable formation pressure measurements in permeable sands have to be made with good quality sonic and density measurements. To account for high pressure situations, Bowers introduced a second velocity-effective stress relation (Bowers, 2001). He defined a virgin curve/loading curve and an unloading curve (Fig.6).

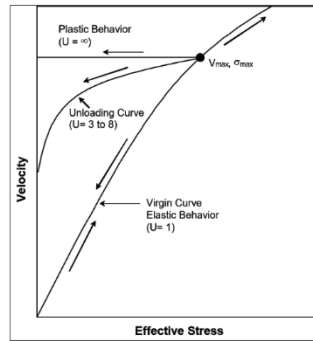


Figure 6: Loading & Unloading Curves

Loading curve can be represented by the following equation

$$V = 5000 + A\sigma^B$$

The unloading curve is defined by the empirical relation

$$V = 5000 + A [\sigma_{max} (\sigma/\sigma_{max})^{(1/U)}]^B$$

Where, A & B are as before, U is the unloading parameter

$$\sigma_{max} = ((V_{max} - 5000)/A)^{1/B}$$

Where, σ_{max} and V_{max} are estimates of the effective stress and velocity at the onset of unloading. Unloading parameter U is a measure of plastic behaviour of the sediments. Using the formation pressure data in deeper part of Middle Bhuban formation in well KH-A, two different velocity-effective stress relationships were developed for loading and unloading episodes (Fig.7).

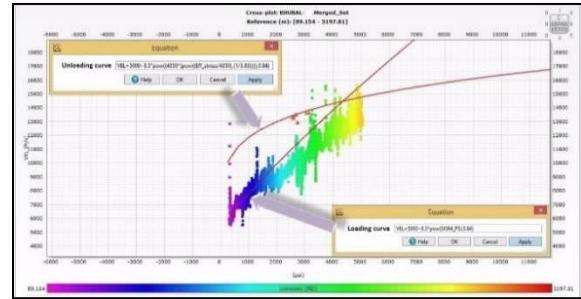


Figure 7: Velocity-Effective Stress Relationship

Once effective stress has been finalised, one can use Terzaghi's effective stress principle to derive pore pressure.

$$P_p = \sigma_v - \sigma_E$$

Where: P_p = pore pressure, σ_v = vertical stress, σ_E = effective (matrix) stress

Fig. 8 shows estimated pore pressure in deeper part of Middle Bhuban in well KH-A using Modified Bowers' relationship, which is now giving a realistic picture as compared to before.

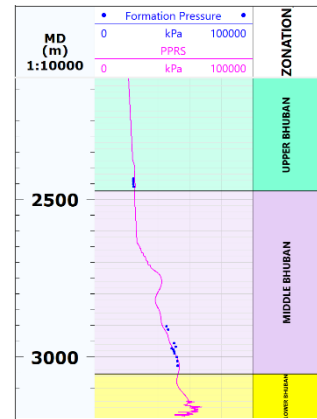


Figure 8: Pore Pressure by Modified Bowers' Method

Estimation of Rock Elastic Properties:

Rock elastic properties such as compressive strength, internal friction coefficients, Poisson's ratio and more can be computed using correlations of Bulk density, Compressional and Shear slowness log data. Elastic properties computed using logs are termed as dynamic as these measurements involve propagation of an elastic wave at very high frequencies. The rock under such conditions exhibits a stiffer response than under static loading in a laboratory test or in situ. Hence calibration with static data is required for geomechanical analyses.

On core samples of three wells, Triaxial lab studies were carried out. Using these lab derived static values of Young's Modulus and Poisson's Ratio, field specific correlations were developed to derive Static elastic properties from Dynamic values. Also,

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computed values of UCS, Cohesion and Friction Angle were calibrated with lab data.

$$YM_{static} = 0.0006 * (YM_{dynamic})^{2.8977}$$

$$PR_{static} = PR_{dynamic} * 0.65$$

$$UCS = 4.242 * YM_{static}$$

$$TSTR = 0.1 * UCS$$

$$FANG = 19 + 31.172 (1 - \Phi - V_{clay})^2$$

$$COH = \frac{UCS}{2[\sqrt{(1 + (\tan FANG)^2)} + \tan FANG]}$$

Horizontal Stresses: The knowledge of the magnitude of these stresses enables us to estimate the hoop stress acting on the periphery of the wellbore so that one can predict whether the rock with a given strength and given mud weight will fail or not. Besides magnitude, the direction of horizontal stresses becomes all the more important when we plan to drill deviated and horizontal wells. In a normally faulted basin, the preferred well azimuth is the orientation of Shmin whereas in strike-slip or thrust fault basin the preferred direction is that of SHmax.

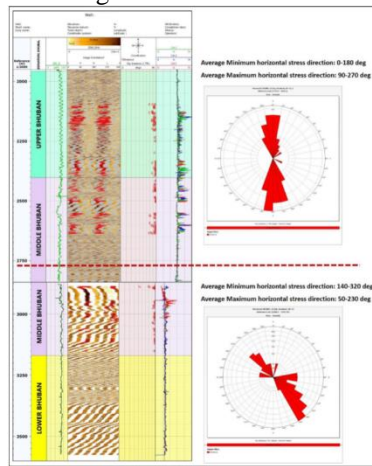


Figure 9: Minimum Horizontal Stress Direction in KH-B

Direction of Horizontal Stresses: KH-A, KH-B, KH-D & KH-F have resistivity image data recorded, which has been studied thoroughly for prevailing principal stress directions in study area. By analyzing borehole image data in well KH-B, it is observed that in the middle part of Middle Bhuban Formation, there is a distinct change in dips orientation and magnitude, and change in stress direction as inferred from breakout analysis (Fig.9). This indicates presence of thrust in the vicinity. Direction of maximum horizontal stress in Upper Bhuban and upper part of Middle Bhuban is

90° N. It changes to 50° N in lower part of Middle Bhuban and Lower Bhuban formation.

Stress magnitude estimation: In this study, a poro-elastic horizontal strain model (Fjaer et al., 1992) is used to estimate the magnitudes of the minimum and maximum horizontal stresses.

$$\sigma_h = \frac{\nu}{1-\nu} \sigma_v - \frac{\nu}{1-\nu} \alpha P_p + \alpha P_p + \frac{E}{1-\nu^2} \epsilon_x + \frac{\nu E}{1-\nu^2} \epsilon_y$$

$$\sigma_H = \frac{\nu}{1-\nu} \sigma_v - \frac{\nu}{1-\nu} \alpha P_p + \alpha P_p + \frac{E}{1-\nu^2} \epsilon_y + \frac{\nu E}{1-\nu^2} \epsilon_x$$

Where σ_h = minimum horizontal stress, σ_H = maximum horizontal stress, σ_v = overburden stress, α = Biot's elastic coefficient, P_p = pore pressure, ϵ_x = strain in the minimum horizontal stress direction, ϵ_y = strain in the maximum horizontal stress direction respectively.

Calibration of the Minimum Horizontal Stress Magnitude (Shmin): The most reliable measurements of in-situ least principal horizontal stress are those provided by analysis of minifrac and/or extended leak-off test (XLOT). Leak-off test data available for studied wells was used to calibrate Shmin (Zoback, 2007).

Calibration of the Maximum Horizontal Stress Magnitude (Shmax): Hottman, Smith et al. (1979) used variations of the occurrence of breakouts (as indicated by wellbore spalling) or drilling induced tensile fractures with changes in mud weight to make an estimate of the maximum horizontal stress, after first constraining the other parameters associated with wellbore failure (Zoback, 2007).

Wellbore stability analysis and 1D Geomechanical Model Calibration: Using the computed rock properties and horizontal stresses, wellbore stability analysis tells us how good the MEM is by comparing the predicted wellbore stability with the drilling events observations, breakouts or drilling induced tensile fractures observed on image or caliper logs. Generally, the model can be verified against these compressive and tensile failure occurrences as observed in image logs or caliper logs, if coverage is good (Fig. 10). Table-1 gives optimum mud weight window for smooth drilling in 12.25" and 8.5" sections:

Borehole size	Minimum Mud Weight	Maximum Mud Weight
12.25"	11 ppg	13.5 ppg
8.5"	16.8 ppg	19.5 ppg

Table 1: Optimum Mud Weight Windows in KH-A

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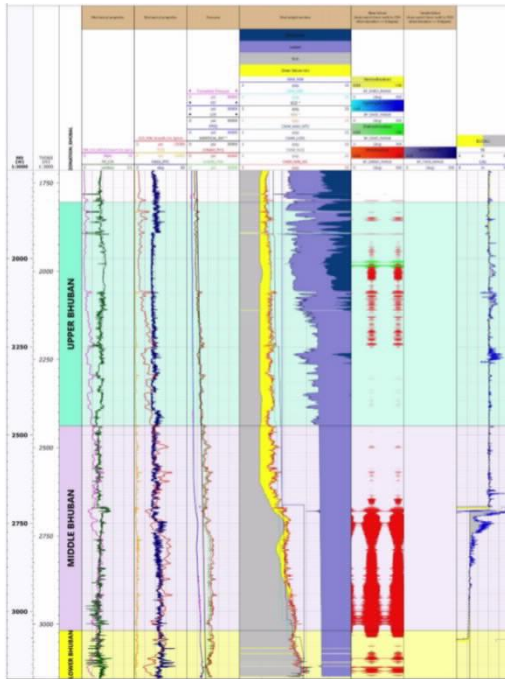


Figure 10: Wellbore Stability Analysis in KH-A

Sensitivity Analysis: Sensitivity analysis uses wellbore information (azimuth and deviation), WBS parameters (mud weight, mudcake coefficient), and MEM data (elastic properties, rock strength, pore pressure, stress) as input and perform WBS analysis with respect to a given depth and sensitivity analysis with respect to a specific input parameter. The Shear

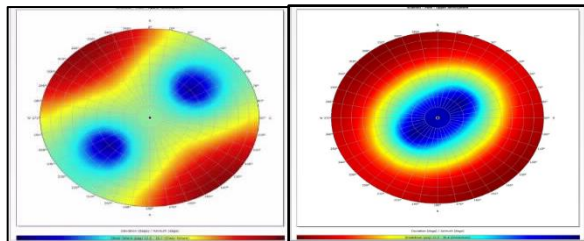


Figure 11: Sensitivity Analysis for shear failure (left) and breakdown (right) in KH-A

Failure Minimum Mud Weight (Breakout) Vs. Borehole Orientation plot shows breakout as a function of borehole orientation (azimuth and deviation), and the color shading indicates the wellbore damage mud weight. Plot in Fig.11 shows sensitivity analysis at the top of Lower Bhuban in KH-

A. It depicts that minimum mud weight (13.5 ppg) will be required to avoid shear failure at top of Lower Bhuban, if well deviation is 40° and well azimuth is 50°N. Similar exercise can be carried out for Breakdown Mud Weight.

Conclusions

- Deeper part of Middle Bhuban and shallower part of Lower Bhuban are primarily overpressured because of uplifting and partly because of clay diagenesis (unloading mechanisms). Other overpressured zones are because of compaction disequilibrium. Modified Bowers method has been used to estimate type-2 overpressure.
- Using wireline pressure data, Velocity-effective stress relations have been developed for loading and unloading cases and parameters A, B and U determined.
- Estimated Pore pressure is fairly matching with recorded formation pressure data.
- Field specific correlations have been developed for static elastic parameters using triaxial lab data.
- The average direction of SH_{max} is 90° N in Upper Bhuban and Upper part of Middle Bhuban formation. It rotates to 50° N in Lower part of Middle Bhuban and Lower Bhuban formation.
- The MEMs have been subjected to well failure predictions in all the studied wells and the predicted failures have been matched with actual failures.
- Optimum mud weight windows and preferential azimuth to avoid shear failures have been provided in overpressured Middle Bhuban and Lower Bhuban formations.

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