P 046

Predrill wellbore stability analysis using rock physical parameters for a deepwater high angle well: A case study

Samit Mondal *, Karthikeyan G & B K Patel

Summary

Drilling horizontal or high angle wells in relaxed basin (S_V>S_H>S_h) is more difficult due to compressive or shear failure (breakouts, cavings, stuck pipe etc.) of the wellbore. These events are very extensive for those kinds of wells as the wellbore stress difference reaches at maximum with increase in inclination. Proper planning of the well trajectory and mud weights are crucial to avoid such complexity which causes huge rig downtime and cost. With the aid of in-situ stress, pore pressure and rock strength analysis the wellbore stability can be assured with suggested optimum deviation profile and mud weights for different inclinations and azimuths.

An attempt has been made to perform the wellbore stability analysis for a high angle (horizontal section of ~1000 m within the reservoir) development well in deepwater Krishna-Godavari Basin which is planned for production in near future. In our workflow, the seismic data and offset well information have been incorporated to generate pore, fracture pressure and shear failure gradient. Rock physical parameters have been calculated from the offset well's logs and calibrated with laboratory tested dataset to use in the stability analysis.

As the outcome of our study, the well trajectory has been optimised on the basis of the in-situ stress analysis (orientation, magnitude) and the reservoir polygon. The mud weights have been recommended for the sections and been plotted in the safe mud weight window analyzer which ascertain a stable wellbore and added values in our understanding of pre-drill geomechanical model in this area. The study is relevant in terms of safe completion of high angle well and cost effectiveness and being implemented in the well planning process flow.

Keywords: *Wellbore Stability, Horizontal Well, Rock Strength, Stress Orientation*

Introduction

Wellbore stability problems are common when drilling high angles wells in deep and ultra-deep water basins. Conditions for wellbore failure depends on various parameters such as the in-situ stresses, pore pressure, rock properties, formation strength, mud weights, well profile etc. According to the theory of rock mechanics, drilling results changes in the stress field when supporting rock mass fails. Hence, circumferential and radial stresses are generated which produce an additional shear stresses. When the magnitude of shear stress exceeds the rock strength, failure takes place in the borehole. To avoid wellbore failures, appropriate understanding of rock mechanical properties is crucial for designing optimally-stable borehole trajectories and mud weight values (After Jimenez et al., 2007). Generally, in the Passive margin basin setting, S_v remains dominant stress and S_{Hmax} and S_{hmin} are close to each other, hence different tangential stress acting on the well bore is less. However in the case of highly inclined and/or horizontal well, the stress acting on the wellbore (differential tangential stress) is increasing with inclination of the well which significantly affect mud weight selection for stable well bore planning.

In the study area, the high angle wells have been planned to appraise the Miocene sandstone reservoir. An integrated approach has been adopted in this study to do a

Reliance Industries Ltd, Navi Mumbai, Maharastra 400701, India.
e.mail: samit.mondal@ril.com

geomechanical modelling using seismic velocity and offset well information. The stress field orientations have been mapped and optimised the well trajectory accordingly. The rock physical parameters have been derived and incorporated in wellbore stability analysis. The mud weights have been recommended to ascertain safe wellbore in different depths with different azimuths and inclinations.

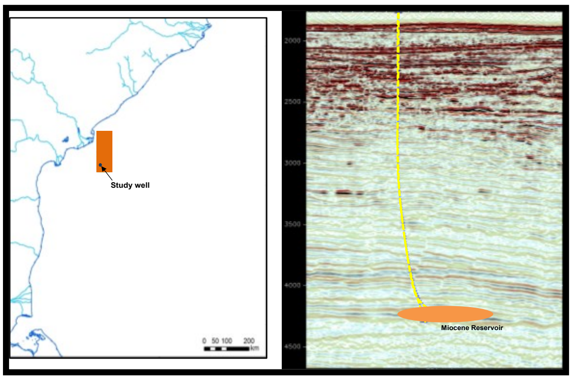

Figure 1. (a) Study area with the well shown in black dot. (b) Seismic section showing the well trajectories of pilot and drain holes.

Geology of the study area

The study area (Figure 1) is located in the deepwater basin of the East Coast India. Sediment distribution in the basin is controlled by Krishna and Godavari river systems, along with numerous tributaries and represents a depositional setting of a well-defined shelf, slope and deepwater system. The basin contains thick sequences of sediments with several cycles of older sequence ranging in age from Late Carboniferous to Holocene (G N Rao, 2001). Paleogene clastics in the coastal basins were sourced predominantly from the Indian craton. In the offshore area, particularly in deep water, the Neogene sequences are significantly thicker. The successive changing of the depocenter had taken place in the Eocene at a shallow hinterland whereas Pliocene/Pleistocene in deep water offshore. The shifting of the depocenter through geological time from onshore to offshore may envisaged Cretaceous depocentres in deeper offshore.

The offshore portion of the Tertiary sequence includes depositional systems ranging from shore-face through to deep-water submarine channels, levee and overbank facies. The primary targets in this area are Miocene to Pleistocene submarine meandering river channels and submarine fan complexes. These sandstones were sourced from the Godavari River system, and deposited on the upper to lower slope regime and further deepwater system. Discoveries have been reported from above mentioned Neogene stratigraphic units.

In offshore Krishna-Godavari basin, during Miocene period the sediments were deposited rapidly with relatively lower expulsion of fluid which resulted moderate to high pore pressure generation in these sequences.

Methodology

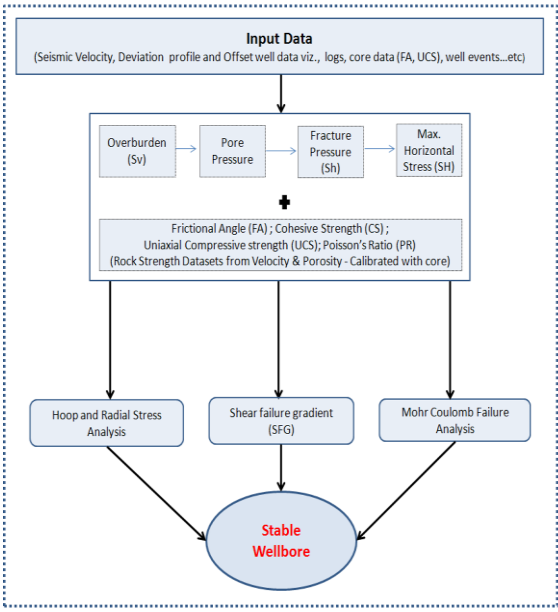

Figure 2. Workflow carried out for wellbore stability analysis.

Figure 2 shows the work flow of the wellbore stability analysis. There is a series of data that provide information about the in situ stresses, pore pressure and the rock strength. The vertical stress can be estimated from overburden pressure which is computed from offset well density logs and pseudo density from seismic velocity. The pore pressure in shales can be estimated from compaction analysis using seismic velocity and offset well log data includes formation tester data for sandstone reservoirs as an input. The least principal stress can be obtained from available leak-off test data. The maximum horizontal stress can be estimated from indirect methods such as analysis of tensile fractures and breakouts from image logs or caliper logs. Empirical formula of wellbore stress analysis can be applied using these data to constrain the magnitude of the same. Rock strength can be estimated from velocity, porosity data and calibrated from core data. However, the quality core plugs of the non-reservoir formation (e.g., mudstones and shales), are rarely available for laboratory testing. So the analysis of the calibrated rock strength parameters in shale based on the well log depends solely on the formulation, type and resolution of the log data.

The methodology has been adopted in this study has been shown in figure 2. Seismic velocity, offset well information and laboratory reports have been used as input dataset to analyze the pore pressure and principal stresses. The rock physical parameters have been calculated and integrated to the stress field analysis output to do the safe wellbore analysis. The analysis was carried out in Drillworks® Geostress module (Halliburton Software) at different depths for the pilot and drain hole, giving corresponding recommended mud weight values as output. With those recommended mud weights, the magnitude of circumferential stress and the radial stress distribution have been shown for those corresponding depths.

Predrill Pore Pressure Analysis in study well

In the study area pore pressure was estimated using Miller and Eaton normal compaction trend analysis from the seismic velocity incorporating offset well logs (Gr, Resistivity and sonic logs), measured pressure data and well events. Fracture pressure had been taken as minimum horizontal stress (S_{hmin}) and overburden pressure as vertical stress (S_V). The intermediate stress i.e., maximum horizontal stress was calculated using empirical formula (Appendix 1). The orientation of maximum horizontal stress (S_{Hmax}) is ~144° N observed from the breakout analysis, which is nearly parallel to the regional fault orientation (~140-150° N).

Wellbore Stability Analysis in study well:

Wellbore instability can results in (i)lost circulation where tensile failure occurred and in (ii) spalling and/or hole closure in case of compressive failure of the rock. In severe cases, hole instability can lead to stuck pipe, pack off and eventual loss of the open hole section (N. C. Last et al., 1996).

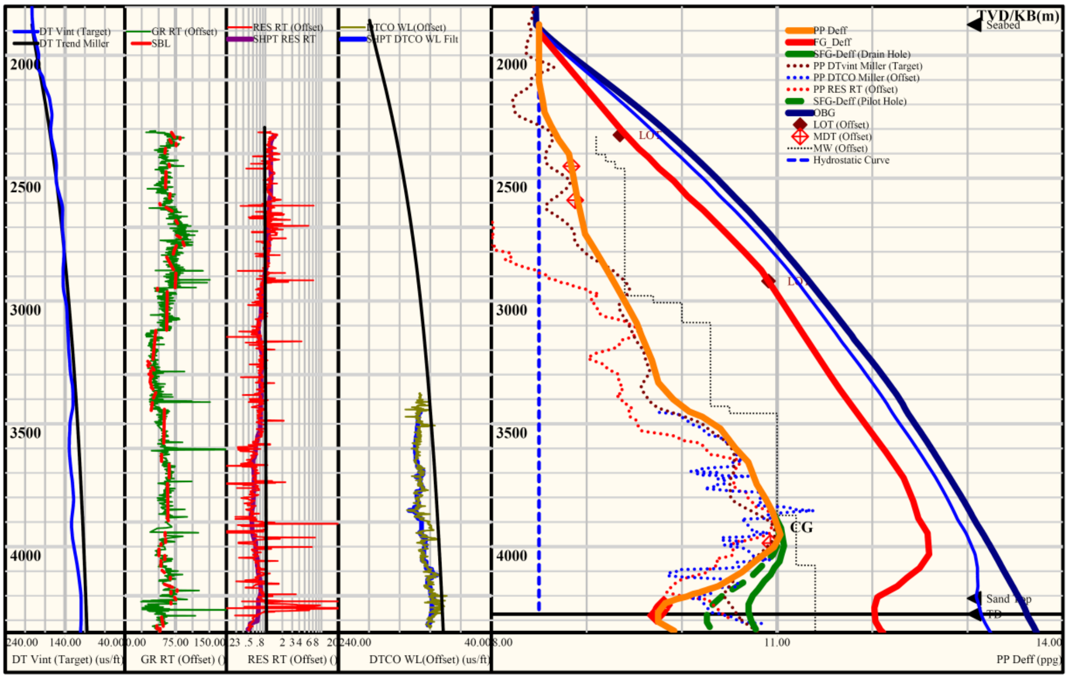

Figure 3. Predrill Geopressure analysis based on the proposed well seismic velocity (Track 1) and offset well data (Track 2-4) with final results (Track 5).

In the study area, wellbore stability analysis was carried out in both the pilot and drain hole sections. However, because of horizontal drilling plan in drain hole, differences in principal stresses in the wellbore and their physical implication on stability has been plotted and interpreted through stress concentration plot and safe MW window analyzer extensively. The stresses and the rock strength datasets input (derived using Appendix 1 and calibrated with core data) were used to derive the shear failure gradient curve (SFG) using Modified-Lade criteria (Appendix 2). The wellbore circumferential and radial stress distribution analysis has been done for different depths with the inputs from stresses and the corresponding cohesive strength (C_0) and the Frictional Angle (Ø) (Appendix 3).

With these analytical results (shown below), here we have recommended the wellbore trajectory along S_{hmin} direction and along the maximum good reservoir facies with corresponding mud weight profile required to drill the well.

Results: ***Stability analysis in Pilot hole (Inclination 38°, Azimuth 226°):***

Well is shown as red star in the stereonet projection diagram (Figure 4). In this diagram, S_{Hmax} and S_{hmin} direction is also shown.

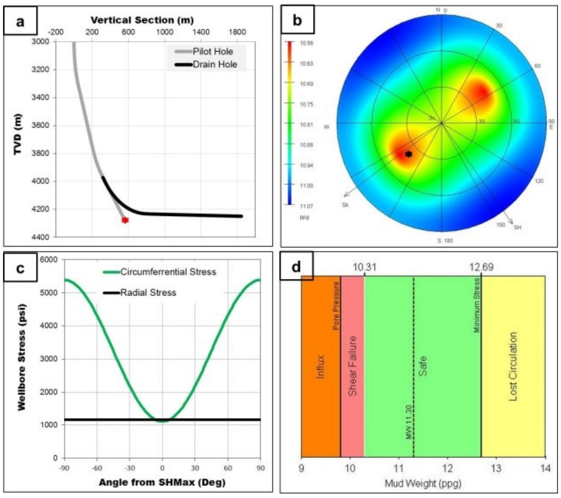

Figure 4: (a) Red dot showing the depth of study in PH (b) Stereonet diagram showing the well location as black dot. (c) Wellbore stress orientation plot. (d) Recommended MW plot in safe MW window analyzer.

The well azimuth is along the direction of S_{hmin}, i.e. the minimum stress convergence direction. At this depth, predicted SFG in the model is 10.31 ppg which is 0.4 ppg higher than predicted reservoir pressure and 2.38 ppg lower than FG.

Wellbore stress distribution analysis was carried out and the maximum stress difference is 4227 psi with this corresponding mud weight of 11.3 ppg. Safe MW window analyzer shows safe wellbore at this depth.

Stability analysis in Drain hole

For drain hole as stated earlier, safe wellbore trajectory analysis had been done at different depth level accompanied with principal stress magnitude distribution analysis and safe MW window analyzer.

(a) Sidetrack point (Inclination 38°, Azimuth 224°):

The well is shown as black star in the stereonet projection diagram (Figure 5). The diagram shows that the present well's azimuth remains same as in pilot hole, i.e., along S_{hmin} direction. At this depth, predicted SFG is 11.07 ppg and FG was 12.59 ppg. The circumferential and radial stresses were plotted in the Figure 5c, where the maximum magnitude difference between circumferential and radial stresses was 2824 psi with recommended mud weight of 11.3 ppg. Finally, safe MW window analyzer plot assured stable wellbore at this depth.

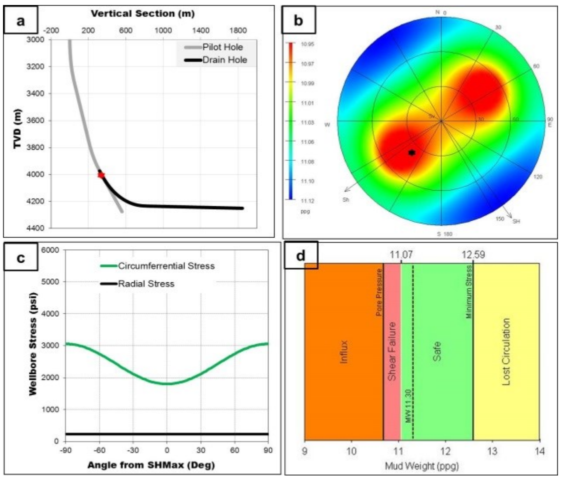

Figure 5: a) Red dot showing the depth of study in DH. (b) Stereonet diagram showing the well location as black dot. (c) Wellbore stress orientation plot. (d) Recommended MW plot in safe MW window analyzer.

(b) Point within the reservoir (Inclination 70°, Azimuth 228°):

At this depth, the well is maintaining azimuth in the direction of S_{hmin} with increased inclination of 70° (Figure 6). As the well is on the verge of achieving maximum inclination, the Sv will now contribute as maximum stress and S_{Hmax} will act as minimum stress.

The predicted SFG and FG are 10.74 ppg and 12.09 ppg respectively. The maximum magnitude difference between circumferential and radial stresses was 3766 psi with recommended mud weight of 11.3 ppg. The sinusoidal nature of the circumferential stress increased compared to the previous depth (Figure 6). Safe MW window analyzer plot shows stable wellbore with this recommended MW.

(c) Drain hole (Inclination 89°, Azimuth 228°):

The drain hole achieved maximum inclination of 89° along the direction of S_{hmin} (Figure 7). S_V is completely acting as maximum stress and S_{Hmax} contributing to the minimum stress. Predicted SFG was 10.74 ppg and FG was 12.09 ppg. The maximum magnitude difference between circumferential and radial stresses was 4289 psi with recommended mud weight of 11.3 ppg. Although the drilling window is relatively narrower than the previous depth, safe MW window analyzer shows stable wellbore at this depth.

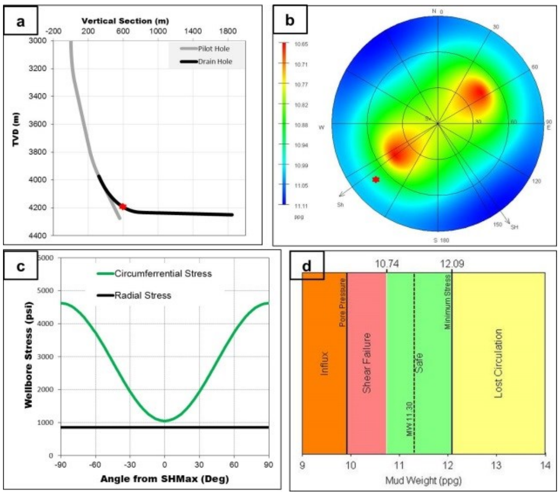

Figure 6. a) Red dot showing the depth of study in DH. (b) Stereonet diagram showing the well location. (c) Wellbore stress orientation plot. (d) Recommended MW plot in safe MW window analyzer.

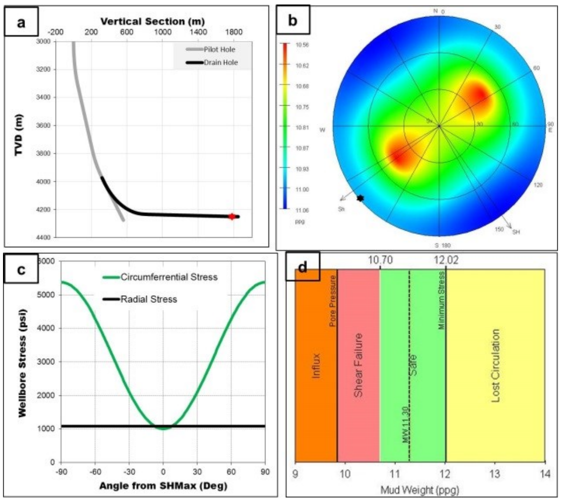

Figure 7: a) Red dot showing the depth of study in DH (b) Stereonet diagram showing the well location. (c) Wellbore stress orientation plot. (d) Recommended MW plot in safe MW window analyzer.

Conclusions

(i) The study indicates that the well should not face any wellbore failure problem with the recommended mud weights are used at different depth.

(ii) The proposed well is recommended to drill along Shmin direction on the basis of our stress field analysis to minimize wellbore instability.

(iii) Shear failure analysis based on Modified Lade method results that the maximum SFG/collapse gradient is 11.1 ppg at the top of reservoir (38° inclination) and 10.3-10.7ppg (PH and DH) within reservoir (89° inclination). Our recommended mud weight is 11.3 ppg to avoid compressive failure with further 0.7 to 0.8 ppg window to prevent tensile failure considering the ECD values as worst case scenario.

(iv) The output of the study has been incorporated for well planning speculating the wellbore instability and the cost effectiveness for the high angle/horizontal well in this area.

(v) This study neither has considered chemical interactions between drilling fluid (SOBM) and shale nor poroelasticity effects of pore fluid or thermal diffusion. However, our experiences have shown that these effects do not have significant impact on the geomechanical model building in this area.

Abbreviations:

SFG: Shear Failure Gradient
S_{Hmax}: Maximum Horizontal Stress
S_{hmin}: Minimum Horizontal Stress
MW: Mud Weight
PH: Pilot Hole
DH: Drain Hole
ECD: Equivalent Circulation Density
FG: Fracture Gradient
SOBM: Synthetic Oil Base Mud
PPG: Pounds per Gallon
FA: Friction Angle
CS: Cohesive strength
UCS: Uniaxial Compressive Strength
PR: Poisson's Ratio

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Appendix 1

The overburden pressure was calculated using density logs of the offset wells where as expected pore pressure and fracture pressure curves were calibrated with the formation pressure and the leak off test data respectively.
Maximum horizontal stress was calculated using the equation

$S_{Hmax}= S_{hmin} + tf*(S_V- S_{hmin})$…………………………..….(1)

Where tf is tectonic factor (0.5 in this study area). The direction of S_{Hmax} was measured from the existing borehole breakout data in this area (Azimuth 140°).

Rock strength inputs such as frictional angle (Ø), cohesive strength (C_0), poisson's ratio (PR) and uniaxial compressive strength (UCS) was estimated from processed sonic data of the drilled well. For the other intervals (where sonic data is not available), the same were calculated from the calibrated seismic velocity. All these log derived parameters are compared with available core data of available in the reservoir section, which shows comprehensive correlatibility with each other.

For rock strength calculations from wireline sonic data, there are lot of published empirical formulas available. In our case, it had been observed that the Lal's correlation law to derive rock strength from compressive sonic velocity gave the excellent correlation with the laboratory test data. The empirical equations for Uniaxial Compressive Strength (UCS), Angle of internal friction (Ø) and cohesive strength (C_0) as a function of sonic velocity are as follows:

UCS= 10 (304.8/Δt – 1……………...…………………(2)

Ø = Sin-1(V_P-1)/(V_P+1) ……………………...(3)

C_0 = 5(V_P-1) / (V_P) 0.5 or 10 tan Ø …………..……. (4)

Where Δt is travel time of compressive sonic wave in µs/ft, V_P is the compressive velocity derived from sonic data in km/sec, Ø is in degrees, C_0 and UCS are in MPa.

Appendix 2

Calculation of Shear Failure Gradient (SFG): SFG was calculated using Modified Lade Criteria. The formula for the Modified Lade failure criteria is as follows (according to Drillworks® manual)

SL' = Hσm +K………………………………………. (5)

Where H and K are material properties which can be related to the rock strength parameters cohesive strength (C_0) and friction angle (Ø), σm is the mean effective stress and where SL' is the modified Lade shear stress invariant.

The constants H and K are defined in terms of the rock strength parameters cohesive strength (C_0) and friction angle (Ø) as follows:

H = 4 (tan Ø)^2 (9 -7sin Ø) / 27(1 - sin Ø)..…..……..…..(6)

K = 4 C_0 tan Ø (9 – 7 sin Ø) / 27(1 - sin Ø)……….... (7)

The Modified Lade criterion has the advantage over the other methods that it considers all three principal stresses and more accurately predict the effects of the intermediate principal stress on failure so that the maximum and minimum principal stresses do not have to be known a priori.

Appendix 3

Calculation of Circumferential Stress ($\sigma_{\theta\theta}$) and Radial stress (σ_{rr}): Compressive wellbore failure is the result of stress concentration around the wellbore that arises in time of drilling of well into an already stressed rock mass. In a homogenous and isotropic elastic material in which one principal stress acts parallel to the wellbore axis, the effective circumferential and radial stress at the wall of a cylindrical, vertical wellbore is given by the following equation (After Zoback 2007)

$$\sigma_{\theta\theta} = S_{hmin}+S_{Hmax}-2(S_{Hmax}-S_{hmin})\cos 2\theta - P_P - P_{Mud} - \sigma\Delta T \quad (8)$$

$$\sigma_{rr} = P_{Mud} - P_P \quad (9)$$

Where θ is the angle measured from the azimuth of the SH_{max}, P_P is the pore pressure, P_{Mud} is the mud weight and $\sigma\Delta T$ is the thermal stress induced by the cooling of the wellbore by ΔT. At the point of minimum compression around the wellbore (i.e., at θ=0, parallel to SH_{max}), equation 8 reduces to

$$\sigma_{\theta\theta}\ min = 3S_{hmin} - S_{Hmax} - P_P - P_{Mud} - \sigma\Delta T \quad (10)$$

Whereas, at the point of maximum stress concentration around the wellbore (i.e., at $\theta=\pi/2$, parallel to Shmin)

$$\sigma_{\theta\theta}\ max = 3S_{Hmax} - S_{hmin} - P_P - P_{Mud} - \sigma\Delta T \quad (11)$$

In normal faulting regime, highly deviated / horizontal wells drilled Shmin direction are more stable as because S_V pushes down on the wellbore, but SH_{max} acts in a horizontal plane normal to the well path, resulting in a lesser stress concentration (and much less stress anisotropy) on the borehole wall. (Zoback, 2007)

Appendix 4

Construction of Linearized Mohr envelop: The Mohr envelop gives the limit of the shear stress value acting on the rock mass before it failed. The formula for the linearized Mohr envelop is as follows:

$$\tau = C_0 + \mu_i \sigma_n \quad (12)$$

Where τ is the shear stress, C_0 is the cohesive strength of the rock, μ_i is the internal friction coefficient and σ_n is the effective normal stress. C_0 has been taken from the derived logs (calibrated with core data) and μ_i has been calculated from frictional angle (Ø) as

$$\mu_i = \tan Ø \quad (13)$$

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