PaperID **ST261**

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Borehole Collapse Model for Wellbore Stability Analysis in Shale Gas Reservoir of Krishna-Godavari Basin

Abstract

Wellbore stability analysis helps in developing a reasonable plan before drilling; require identification of challenging regions and improving of drilling operation. The important part needed for wellbore stability is rock failure criteria, which are controlled by rock mechanical properties and the in-situ stresses. The vertical drilled well W-1 has penetrated through Palakollu Shale and Raghavapuram Shale in the Krishna-Godavari basin, India and these shale formations are vertically transverse isotropic in nature. The main focus of the study is to develop borehole collapse model using two different rock failure criteria such as Mohr-Coulomb and Mogi-Coulomb for transversely isotropic media. The caliper log for above mentioned wells have experienced complete to moderate failure, considered as a lower bound of onset offailure at selected depth intervals. It is observed that Mohr – Coulomb failure criteria overestimates the predicted mud weight for the safe drilling. On the contrary Mogi – Coulomb failure criteria is closer to the expected result. Here software program in MATLAB has been used to interpret the mud weight density in the form of contour plot with given azimuth and inclination of the vertical borehole.

Introduction

Wellbore instability is the adverse condition of an open hole that does not maintain its gauge size and shape referring to wellbore collapse or failure and causes huge economic loss (Aadnoy, 1987, Das and Chatterjee, 2017). Determination of minimum mud weight by rock failure analysis is a required step to control wellbore instability (Al-Ajmi and Zimmerman, 2006). Study of wellbore stability helps in developing a reasonable plan before drilling; require identification of challenging regions and improving of drilling operation. The important part needed for wellbore stability is rock failure criteria, which are controlled by the in-situ stresses (Aadnoy, 2003). When a borehole is drilled, the equilibrium of in-situ stresses is disturbed, which causes stress concentration i.e. increase of stress around the wall of the hole. In order to sustain the stress release and to prevent hydrocarbon invasion into the cavity, the borehole is filled with fluid i.e. mud pressure by building new stress pattern around the borehole wall. So to choose proper mud pressure is very important. In practice, typically overbalance pressure of 100-200 psi causing mud weight of 0.036–0.06 g/cc has been maintained over the formation pore pressure (Awal et.al., 2001).

Shale which is found in most of the sedimentary basin, are anisotropic in nature and the elastic moduli of the rock will then depend on the orientation of the layered structure which intensifies the anisotropic response in stress tests. The modulus of elasticity of sedimentary formation generally differs greatly between vertical bedding directions and parallel bedding directions, besides which, obvious differences also exist in Poisson's ratio and other intensive parameters (Das and Chatterjee, 2018a).The differences in rock mechanical parameters cause great influence in the stress of adjacent rock, thereby affecting the analysis of borehole stability (Li 1983; Aadnoy 1991; Liu and Zhu1998). Simple isotropic stress equations do not consider the anisotropic rock properties. Results obtained in this way usually lack accuracy and can lead to inaccurate conclusions when designing corresponding mud density during the well drilling process.They can thus result in serious borehole instability accidents.Therefore, the issue of rock anisotropy should not be ignored.

Mohr-Coulomb criterion is the most frequently used failure criteria for wellbore stability analysis. This criterion may not be able to determine the minimum mud pressure accurately due to not considering the effect of intermediate stress ($\sigma1>\sigma2=\sigma3$). It is found that Mohr-Coulomb criterion overestimates the minimum mud pressure for wellbore analysis. This criterion does not give reliable result and very conservative in prediction of wellbore stability analysis. To consider the effect of the intermediate principal stress, many triaxial or polyaxial rock failure criteria have been developed. Previous authors have suggested polyaxial Mogi-Coulomb failure criterion and proposed a new 3D analytical model to estimate the minimum mud weight to avoid failure for the vertical wells (Al-Ami and Zimmerman, 2006). The effect of intermediate principal stress has been considered for this criterion to avoid unrealistic solution.

This paper will investigate the effect of the rock anisotropy and the stress distribution at the wall of vertical wellbores for wellbore stability analysis in the shale reservoir of Krishna-Godavari (K-G) basin in India.

Data Used

The well W-1 has penetrated basement through Palakollu Shale (PS), Tirupati Sandstone (TS) and Raghavapuram Shale (RS) formations (Das and Chatterjee, 2018b). The well logs namely; natural gamma ray (GR), true resistivity (Rt), bulk density (ρ), compressional sonic transit time (DTCO) and dipole shear sonic transit time (DTSM) are used for computation of Young's modulus (E) and Poisson's ratio(v) in the vertical and horizontal direction of this well (Figure 1). The dynamic elastic constants such as: E_{dyn} and v_{dyn} have been estimated for the depth interval of 410-1477m from density, compressional and Dipole Shear Sonic (DSI) travel time logs using the following equations (Mohammed and Zillur, 2001; Boonen, 2003; Potter and Foltinek, 1997):

νdynh = Vp2-2Vslowerdipole22Vp2-Vslowerdipole2 ------------------------------ (1)

νdynv = Vp2-2Vsupperdipole22Vp2-Vsupperdipole2---------------------------- (2)

Edynh = ρVslowerdipole23Vp2-4Vslowerdipole2Vp2-Vslowerdipole2---------------------- (3)

Edynv = ρVsupperdipole23Vp2-4Vsupperdipole2Vp2-Vsupperdipole2-------------------- (4)

Where,νdynh,νdynv,Edynh and Edynv are the v and E in lateral and its perpendicular direction respectively. Another parameter namely; degree of anisotropy defined as the ratio between E_h and $E_v$of VTI media is shown in Figure 2.

Core samples were not available to us and as a last resort; Wang's relation (Wang, 2000) has been used to compute static elastic constants. Dynamic and static Poisson's ratio of rocks in this basin is considered equal. The equation for conversion of dynamic to static E is proposed by Wang (2000) for shale formation of Cretaceous age and the Raghavapuram Shale belongs to Cretaceous age, the authors used the same equation for estimation of static E as:

$E_{stat} = 0.4145E_{dyn} - 1.0593$ --------------------- (5)

The GR, Rt and density values in PS range from 100-140API, 2-5 ohm-m and 2000 to 2200kg/m^3 respectively. The GR, density and Rt vary from 80-180API, 1600 to 2200kg/m^3 and 8-10 ohm-m in TS. For RS, GR, density and Rt vary from 75-280 API, 2100 to 2600kg/m^3 and 2-8 ohm-m respectively. The value of v ranges from 0.29 to 0.39, 0.33 to 0.37and 0.24 to 0.32 for PS, TS and RS respectively. The value of E_{dyn} ranges from 4.5 to 8.5 GPa, 4.17 to 7.30 GPa and 9.0 to 21.0 GPa for PS, TS and RS respectively. Large separation is clearly visible between vertical v and horizontal v for anisotropic layers but less separation is observed between vertical $E_{dyn}$and horizontal E_{dyn}. Structural anisotropy exists between layered sediments in geological formations in K-G basin.

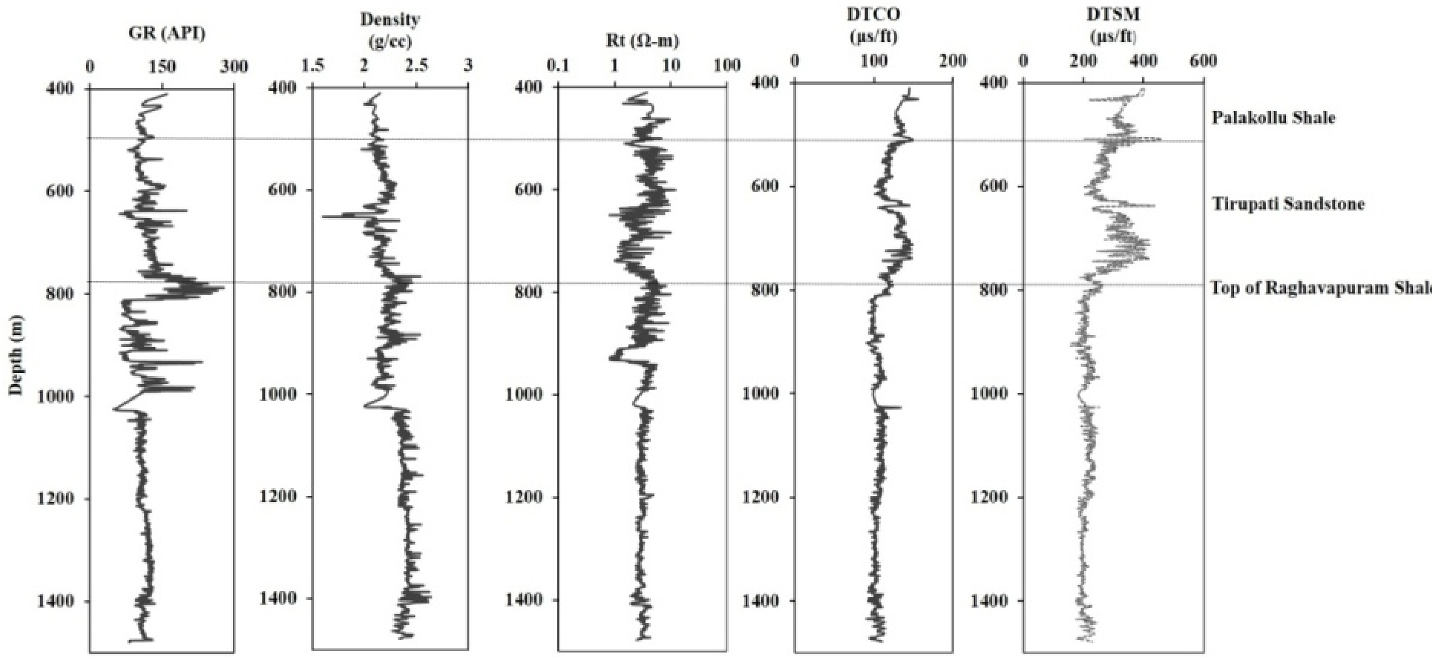


Figure 1: Well log responses of gamma ray (GR), density (ρ), resistivity (Rt), Compressional travel time (DTCO) and Dipole Shear Sonic travel time (DTSM), are displayed for well W-1,

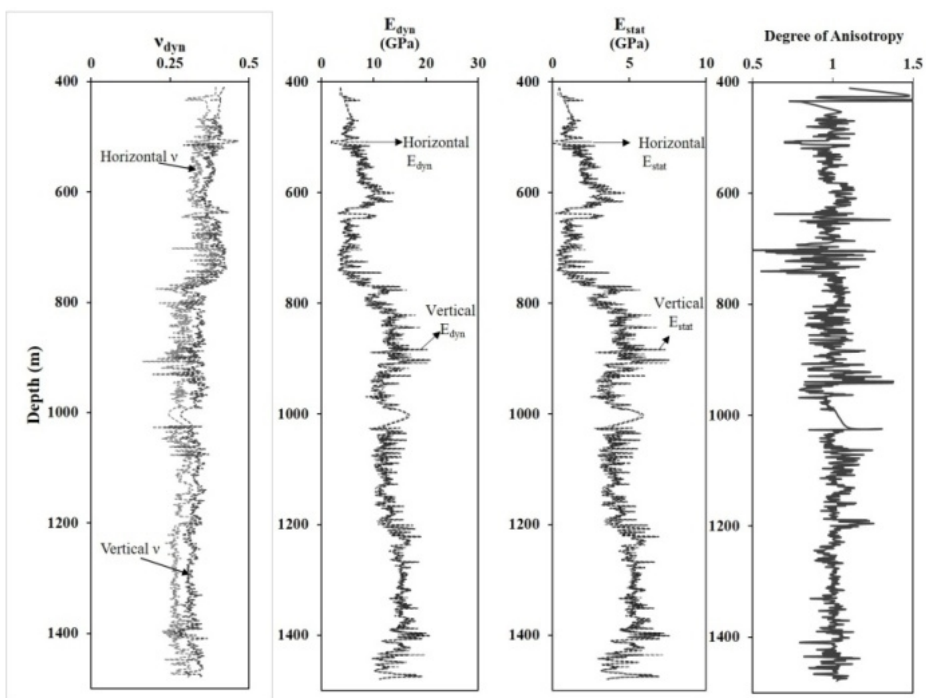


Figure 2:Displays well log responses of dynamic vertical and horizontal Poisson's ratio (vdyn), dynamic vertical and horizontal Young's Modulus (Edyn), static vertical and horizontal Young's modulus (Estat) for well W-1 for the selected depth interval 410-1477m. Log derived parameter i.e. degree of anisotropy (i.e. ratio between horizontal and vertical E) has been plotted for the available depth interval 410-1477m. Dynamic vertical and horizontal Young's Modulus are overlying with each other due to less separation.

Rock Failure Criteria

Failure criterion discusses the stress condition around the wellbore under which wellbore either collapses or induced fracture occurs. In this section three rock failure criteria: Mohr-Coulomb and Mogi-Coulomb have been discussed.

For a normal faulting stress regime as in K-G basin the first principal stress is considered to be vertical (σV), the second and third principal stresses are σHandσhrespectively (Singha and Chatterjee, 2015). The vertical stress (σV) is estimated by cumulative sum of the formation density from the surface to the depth of interest (Plumb et al 1991).

σV=0zρzgdz---------------------- (6)

Vertical stress gradient in K-G basin is noted as 22.8 MPa/km from the vertical stress profile.

Pore Pressure (PP) has been calculated as:

PPg=VSG-(VSG-Phg)DTCOnDTCO3--------------------- (7)

Where, VSG is the vertical stress gradient, Phg is the hydrostatic pressure gradient, assumed as 10MPa/km in K-G basin (Singha and Chatterjee, 2015). DTCOn is sonic compressional travel time, estimated from normal compaction trend (NCT) in low permeable zones. The well penetrated through the Raghavapuram Shale formation shows PP gradient varying from 10.11 – 10.52 MPa/km. The predicted PP is calibrated by the measured pore pressure from Repeat Formation Tester (RFT) data at the selected depths of this well.

Maximum horizontal stress in passive K-G basin had been computed by previous authors and related with vertical stress as (Singha and Chatterjee, 2015),

σH= 0.9σV --------------- (8)

Minimum horizontal stress considering poroelastic model anisotropic media (Equation 9) is given by (Gholami et al., 2015)

σh= EstatverticalEstathorizontalνstatverticalνstathorizontalσV-αPP+αPP+Estatvertical1-νstathorizontal2εh+Estatverticalνstathorizontal1-νstathorizontal2εH------- (9)

Where, α is Biot's co-efficient and is considered as 1 for K-G basin and subscript "stat" indicates the static property of E and ν in vertical and horizontal direction and εh and εH are tectonic strain parameters in minimum and maximum horizontal stress direction. Since K-G basin is considered as passive basin, the parameters εh and εH are considered as zero. Estimated σ_h is validated with measured minimum horizontal stress magnitudes from Leak-off Test (LOT) data at selected depths of the well.

The two rock failure criteria: Mohr-Coulomb andMogi-Coulomb are as follows.

Mohr-Coulomb (MC) Failure Criterion

The minimum mud pressure following the MC criterion is given by

$$P_{wMC} \leq \frac{3\sigma_H - \sigma_h - C_0 + P_0(q-1)}{1+q}$$ ----------- (10) (Song and Haimson, 1997)

Mogi-Coulomb (MG) Failure Criteria

The minimum mud pressure following the MG criteria is given by the following equation as:

$$P_{wMG} = \frac{A}{2} - \frac{1}{6}\sqrt{12[a' + b'(A - 2P_0)]^2 - 3(A - 2B)^2}$$ ----------- (11) (Zhou, 1994)

The minimum mud pressure under MG criteria will be computed using equation (11) for stability analysis of two wells.

Wellbore Stability Analysis

Drilling a vertical well redistributes the field stresses and produces local stress concentration that may lead to the formation of a zone of yielded rock or breakout. Rock failure at the borehole wall will initiate in the direction of greatest stress concentration. The tangential and axial stresses attain the largest magnitudes at θ = ±π/2. Therefore, shear failure will occur in the direction of σ_h, which leads to the breakout formation with the long axis parallel to σ_h. The tangential and radial stresses are functions of the mud pressure, *Pw*. Hence, any change in the mud pressure will affect these stresses.

If the well pressure or actual mud weight is below the predicted minimum MW, wellbore collapse or breakout will take place. If the mud weight is greater than the predicted, the mud will enter into the formation, causing tensile failure (fracture stress). On the other hand a lower mud weight can result in shear failure (collapse stress) of rock, which is known as borehole breakout. Actual MW for the well at specified depths is plotted in Figures 3. The predicted MW using MG criterion is better suitable for estimation of minimum allowable MW than the predicted MW using other two criteria. The bit size/caliper, GR logs are displayed for all wells.

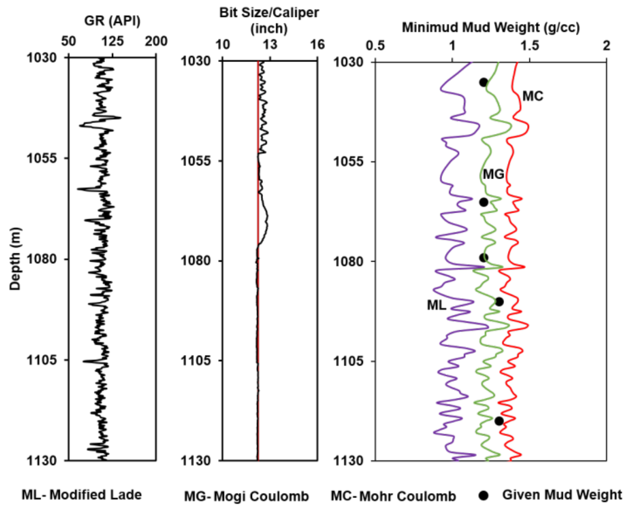
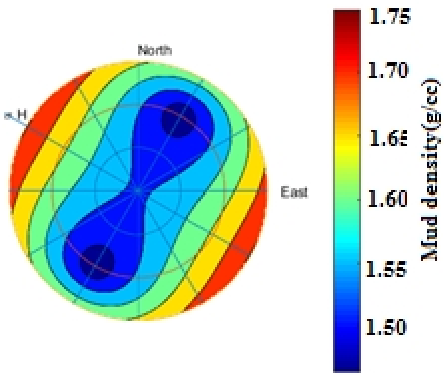


Figure 3: Shows the minimum MW for well W-1 using three different rock failure criteria:MC, MG and ML along with actual MW. GR, Gamma ray and Bit size/Caliper logs for W-1.

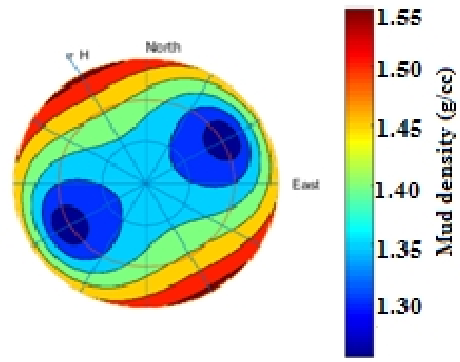
Wellbore Collapse Model

Matrix laboratory (MATLAB) program has also been developed to compute the critical collapse pressure (i.e. lower limit of mud weight) for the Mohr-Coulomb and the Mogi-Coulomb failure criteria. In order to determine if a wellbore is mechanically instable one must first model the stresses around it. When a wellbore is drilled the in-situ stresses will be modified and leads to a stress concentration around the wellbore. The largest stress concentration will occur at the wellbore wall for a linear elastic material. Therefore failure will initiate here. Using different rock failure criteria the wellbore instability will be analysed. The author has focused on providing an output of the mud weight density that is graphically easy to interpret with respect to the optimal deviation according to collapse pressure for the selected failure criterion. In order to present the required mud pressures for inclinations between 0˚ and 90˚ for all possible directions the procedure described above is performed in iterative loops for all values of θ, azimuth and inclination. The final output is plotted in a disc-plot. The minimum mud weight for MC and MG criteria for vertically oriented well is shown in Figure 4a and 4b through disc-plot respectively. This contour plot shows the equivalent circulating mud density (ECD) that is required to prevent extensive shear failure near the borehole wall with any given azimuth and deviation. A point at the center of the diagram corresponds to vertical well, while horizontal wells are located on the periphery of the diagram at the appropriate azimuth and radial distance. In the wellbore breakout model, the color shown represents the mud weight required to prevent wellbore breakout, with red color as the relatively unstable well orientations as higher mud weight is needed to prevent breakout and blue color signifies the stable zone indicating lower mud density. The results show that the vertical wells are the most likely to fail, while horizontal wells drilled parallel to the azimuth of maximum horizontal stress (SHmax) are the most stable.



(a)

Figure 4: Required mud weight to prevent wellbore breakout for well W-1 utilizing Mohr-Coulomb failure criterion, color bar indicates mud weight in density.



(b)

Required mud weight to prevent wellbore breakout for well W-1 utilizing Mogi-Coulomb failure criterion, color bar indicates mud weight in density.

Results and Discussions

We are concerned with shear failure or borehole collapse, the smaller root is the lower limit of the mud pressure related to the MG failure criterion. Considering the range of Poisson's ratio (0.22–0.44), and the facts that the ratio of the maximum horizontal stress to the minimum horizontal stress (σ_H / σ_h) ranges from 0.52 to 0.65 and the collapse pressure will not exceed the minimum horizontal stress. These borehole failure criteria, therefore, result in quite different minimum MW. This is mainly due to the existence of an intermediate principal stress that is not equal to the minimum principal stress at the wellbore wall. Therefore, for a weaker rock, a higher collapse pressure is required to maintain the stability of the wellbore. ML criterion has underestimated the collapse pressure, whereas the MC criterion has predicted a conservative collapse pressure. In contrast, rock failure criteria such as: ML and MG consider the effect of intermediate principal stress on rock failure. The field determination of the onset of shear failure has been inferred based on recorded caliper logs. Considering the level of failure, the result of MG could be a safe approach in drilling of the wellbore.Figure 4 shows that the Mogi-Coulomb failure criterion prefers the same deviation as the Mohr-Coulomb failure criterion. Lower mud density i.e. 1.50 and 1.30g/c is required to stable the vertical well W-1 at a depth of 1045m for MC and MG criteria respectively. The Mogi-Coulomb failure criterion predicts a slightly lower required mud weight to avoid collapse which coincides with the theoretical prediction.

Conclusions

In this paper, two rock failure criteria have been used to predict minimum MW and then evaluated based on the prediction of borehole shear failure for the well. MC failure criterion is not suggested because of overestimating borehole breakout and a conservative prediction of the minimum required MW. The results of MG criterion are always close to the field reported onset of failure. The actual and predicted MW is observed to be in close match using MG failure criterion. Additionally a MATLAB program has been developed to enhance the knowledge in mud weight prediction calculations and to compare the Mogi-Coulomb failure criterion with the Mohr-Coulomb failure criterion and it is a fast and convenient way to find the most beneficial deviation for a wellbore according to the chosen failure criterion. The Mogi-Coulomb and Mohr-Coulomb failure criteria predict the same optimal deviation concerning the collapse pressure.

Acknowledgement

Authors are very much thankful to GSPCL for providing the data.Authors acknowledge the financial support from the Ministry of Earth Science through the R&D project MoES /P.O./(Seismo)/1(138) 2011 dated 9.11.12.

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