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Wellbore stability analysis and prediction of minimum mud weight for few wells in Krishna-Godavari Basin, India

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ABSTRACT

Analysis of wellbore instability contains evaluation of rock mechanical properties and the state of in-situ stresses. In this analysis the only convenient factor is the mud weight i.e. the fluid density of the drilling fluid. If the mud weight is greater than the predicted, the mud will enter into the formation, causing tensile failure (fracture stress). Conversely a lower mud weight can result in shear failure (collapse stress) of rock, which is known as borehole breakout. Here we present three types of failure criteria - Mohr–Coulomb, Mogi–Coulomb and Modified Lade. Rock mechanical rocks such as: Poisson's ratio, Uniaxial Compressive Strength, Cohesion have been computed from compressional and shear wave velocities. Internal friction angle is obtained from gamma ray log. The failure criteria have been applied to two wells located at Krishna-Godavari (K-G) onshore and three wells at offshore to obtain minimum mud weight required to sustain its stability. The caliper log for above-mentioned wells have experienced complete to moderate failure, considered as a lower bound of onset of failure 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.

1. Introduction

Determination of minimum mud weight by rock failure analysis is a required step to control wellbore instability. 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. So, maintaining a stable wellbore is important job for oil and gas industry [1]. Generally wellbore instability is associated with drill pipe sticking, tight spots, caving production and unscheduled side-track. Study of wellbore stability helps in developing a reasonable plan before drilling require identification of challenging regions and improving of drilling operation. [2–5] The important part needed for wellbore stability is rock failure criteria [6] which are controlled by the in-situ stresses. 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. [7,8] There exists numbers of rock failure criteria for predicting minimum mud weight in wells under different stress regimes. e.g. [9–11]

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 ($\sigma_1 > \sigma_2 = \sigma_3$). [12,13] It is found that Mohr-Coulomb criterion overestimates the minimum mud pressure for wellbore analysis. [14] This criterion does not give reliable result [15] and very conservative [16] 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. [13,17–19] Previous authors [20,21] 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. The effect of intermediate principal stress has been considered for this criterion to avoid unrealistic solution.

This paper is focused on three common rock failure criteria namely; Mohr-Coulomb (MC), Mogi-Coulomb (MG) and Modified Lade (ML) for stability analysis of five vertical wells distributed in onshore and offshore part of Krishna-Godavari (K-G) basin, India.

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2. Study area

The onshore part of K-G basin is characterised by NE–SW trending en-echelon horst and graben formed during the Jurassic-Cretaceous breakup between India and Antarctica e.g. [22] The onshore basin is filled with 3–6 km thick volcanic lava flows comprising intertrappean clay, limestone and sand beds. [23–25] The offshore area is mainly comprised of claystone with sand and siltstone and the basement is overlain by the Early Cretaceous and Paleocene Shales with intertrappen Razole volcanic flows. [23–27] The Eocene Vadaparru shale, thin Oligocene Claystone, Miocene–Early Pliocene Ravva sandstone formations, and Godavari Clay of Pleistocene to Recent are the geological successions resting on the top of Paleocene. [24,28,29] The oil/gas fields located in the K-G offshore are producing since decades. Gas was discovered in the Lower Pliocene, the Upper Miocene and the Middle Miocene clastics of K-G offshore. [28,29]

The well data such as: gamma ray, density, compressional and shear sonic logs corresponding to five vertical wells are used to determine the minimum mud weight for wellbore stability studies. There are two onshore wells: W-13 and W-14 located at the East Godavari sub-basin and three offshore wells. The shallow offshore well W-1 is located at 30 m bathymetry whereas the bathymetry varies from 700 to 1500 m for wells W-9 and W-12 respectively. For the wellbore stability analysis selected depth intervals such as: 1030–1130 m, 2000–2150 m, 3465–3650 m, 2450–2900 m and 1100–1200 m are chosen from wells W-1, W-9, W-12, W-13 and W-14 respectively. Fig. 1(a to e) are displaying the log responses for these depth intervals for five wells. The lithology encountered in these depth intervals is mostly sand, shale, silty sand and alteration of sand and shale. The procedure of predicting minimum mud weight for these wells using three failure criteria such as: MC, MG and ML are described sequentially in following sections.

3. Estimation of rock properties

The rock properties has been modelled from rock features such as composition (shale content), density and acoustic velocities based on well logging tools – gamma Ray (GR), density (ρ_b) and sonic compressional transit time (DTCO) and sonic shear transit time (DTSM) logs. [30,31] The rock mechanical properties such as, Poisson's ratio (ν), internal friction angle (φ), cohesion (c) and uniaxial compressive strength (C_0) are computed from the empirical relationships as provided by several authors used for wellbore stability issues. [32,33]

Poisson's ratio is calculated using sonic DTCO and DTSM logs [33,34] using following equation for four wells excepting well W-14. DTSM log data is not available for well W-14.

$$\nu = \frac{0.5\left(\frac{DTSM}{DTCO}\right)^2-1}{\left(\frac{DTSM}{DTCO}\right)^2-1} \tag{1}$$

The empirical relations for computing internal friction angle (φ) [35] and uniaxial compressive strength (C_0) are given by [36,37],

$$\varphi = tan^{-1}\frac{(GR - GR_{sand})\mu_{shale} + (GR_{shale} - GR)\mu_{sand}}{GR_{shale} - GR_{sand}} \tag{2}$$

$$UCS = C_0 = 0.77V_p^{2.93} \tag{3}$$

Eqs. (2) and (3) are used for obtaining internal friction angle and UCS of rocks for five wells. The value for μ_{shale} and μ_{sand} has been assumed as 0.5 and 0.9 respectively. [35] The maximum value of GR for shale is 150, 137, 137, 177 and 175 API for W-1, W-9, W-12, W-13 and W-14 respectively. Similarly for sand, the GR value is 24, 64, 32, 18 and 22 API for W-1, W-9, W-12, W-13 and W-14 respectively.

There is an empirical relation between cohesion (c) and UCS (C_0) [5] as,

$$\text{Cohesion} = c = \frac{C_0}{2}\frac{cos\varphi}{1-sin\varphi} \tag{4}$$

Equation (4) is used to find cohesion of rocks for these wells. The rock properties such as Poisson's ratio, UCS, cohesion and internal friction angle for these wells are displayed in Fig. 2 (Fig. 2a to e). Poisson's ratio ranges from 0.30 to 0.36, 0.22–0.43, 0.33–0.44, and 0.27–0.28 for W-1, W-9, W-12, W-13 respectively. Shear sonic transit time for well W-14 is not available with us. We have assumed Poisson's ratio as 0.30 for the chosen depth interval at well W-14. UCS ranges from 12 to 17 MPa, 5.3–7.3 MPa, 6–15, 30–50 MPa and 8–20 MPa for W-1, W-9, W-12, W-13 and W-14 respectively. Cohesion ranges from 4 to 4.5 MPa, 1–1.8 MPa, 2–2.7 MPa, 9–12 MPa and 2.7–3.3 MPa for W-1, W-9, W-12, W-13 and W-14 respectively. Friction angle ranges from 30° to 32°, 33–40°, 30° to 35°, 36–37° and 30–40° for W-1, W-9, W-12, W-13 and W-14 respectively (Fig. 2a to e).

4. Estimation of in-situ stress and pore pressure

Commonly the in-situ stresses are the vertical principal stress (σ_V) and two unequal horizontal stress: minimum horizontal stress (σ_h) and maximum horizontal stress (σ_H). Three faulted stress regimes exist based on the order of the magnitude of vertical and horizontal stresses. [38] For extensional or normal fault regime stress order will be $\sigma_V \geq \sigma_H \geq \sigma_h$, for reverse or thrust faulting, it will be $\sigma_H \geq \sigma_h \geq \sigma_V$ and for strike-slip faulting the stress magnitudes will be $\sigma_H \geq \sigma_V \geq \sigma_h$.

Overburden or vertical stress (σ_V) is assumed to be equivalent to the weight of the overburden rock. The required equation for the calculation of the overburden stress is expressed as [39]:

$$\sigma_V = \int_0^z \rho(z)gdz \tag{5}$$

Where, z, ρ(z) and g are the depth, bulk density of rock at the point of measurement and acceleration due to gravity respectively. In general, vertical stress gradient in K-G basin ranges from 19 to 23 MPa/km. [31] Vertical stress is calculated using equation (5) for selected depth intervals of five wells.

Maximum horizontal stress from two wells in K-G basin had been computed by previous authors. [30,34] It is related with vertical stress as,

$$\sigma_H = 0.9\sigma_V \tag{6}$$

Maximum horizontal stress magnitudes for five wells have been computed using equation (6). Minimum horizontal stress for five wells is calculated using the following equation [40,41]

$$\sigma_h = PP + \frac{\nu\ (\sigma_V - PP)}{1-\nu}, \tag{7}$$

where, PP is the pore pressure and ν is the Poisson's ratio of the rock. Estimated σ_h is validated with measured minimum horizontal stress magnitudes from Leak-off Test (LOT) data at selected depths of five wells. [30,34]

The pore pressure gradient (PP_g) has been calculated using Eaton's sonic equation [42] as

$$PP_g = VSG - (VSG - P_{hg})\frac{DTCOn^3}{DTCO} \tag{8}$$

where, VSG is the vertical stress gradient, P_{hg} is the hydrostatic pressure gradient, assumed as 10 MPa/km for all wells in K-G basin. [43–45] $DTCOn$ is sonic compressional travel time, estimated from normal compaction trend (NCT) in low permeable zones. NCT for all five wells have been obtained by fitting a linear curve to compressional wave log data. [30,34] For normally pressured formation, pore pressure gradient varies from 10.11 to 10.52 MPa/km. [30,33] PP is computed using equation (8) for five wells. The predicted PP is calibrated by the measured pore pressure from Repeat Formation Tester (RFT) data at the selected depths of five wells.

Fracture pressure (FP) has been calculated by Matthews–Kelly's equation [46],