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Wellbore Stability Analysis and the Safe Mud Weight Window Determination for a Well in One of the Southwest Iranian Oil Field

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Introduction

Wellbore stability is the prevention of brittle failure or plastic deformation of the rock surrounding the wellbore due to mechanical stress or chemical imbalance [1]. Numerous parameters effect on wellbore stability, including mud weight, drilling fluid type and chemistry, well azimuth and inclination, in-situ stresses, rock strength, rock mechanical properties, etc. Between these parameters, determination of the mud weight window using rock failure criteria is the most popular approach [2]. The most common failures and wellbore instabilities are shear failure (breakout) and tensile failure. The predicted safe mud weight window using rock failure criteria includes two limit bounds which are the minimum required mud weight (MRMW) to prevent breakout (the lower bound), and the maximum allowable mud weight to prevent breakdown or tensile failure (the upper bound) [3]. Many researches have been conducted to investigate wellbore stability problems. For instant, wellbore stability for two wells in the south of Iran under underbalance drilling conditions using numerical methods (finite difference and finite element methods) was performed by Salehi et al [4]. Mansourizadeh et al utilized three Mogi-Coulomb, Mohr-Coulomb and Hoek-Brown criteria for wellbore stability analysis in the southwest of Iran to determine optimum mud weight and the effect of inclination and azimuth [5]. Das and Chatterjee performed wellbore stability analysis to predict the safe mud weight window for five wells in Krisha in India by three rock failure criteria [6].

This paper is focused on two rock failure criteria, namely Mohr-Coulomb (MC) and Mogi-Coulomb (MG) to predict the safe mud weight window for a well. Furthermore, the best failure criterion is specified that has the most precise results with respect to the real observations from caliper logs.

Case Study

The interest field is one of the most important oil fields in Iran which is located in the southwest of Iran. The current well was drilled in the four separate holes, that the last hole is investigated in this study. This hole has been drilled from 3537 m to 4120 m with bit size, 6.125-inch.

Methodology

In this study, the wellbore stability analysis has been implemented to predict MRMW or breakout pressure and Breakdown Pressure (a safe mud weight window) for 6.125-inch hole of the current well, which discussed as follow:

Petrophysical Logs Gathering

The petrophysical logs including compression and shear sonic slowness (DTC and DTS respectively) (μs/ft), neutron porosity (NPHI, V/V), bulk density (ρb, kg/m^3), and gamma-ray (API) for the current well have been illustrated in Figure 1.

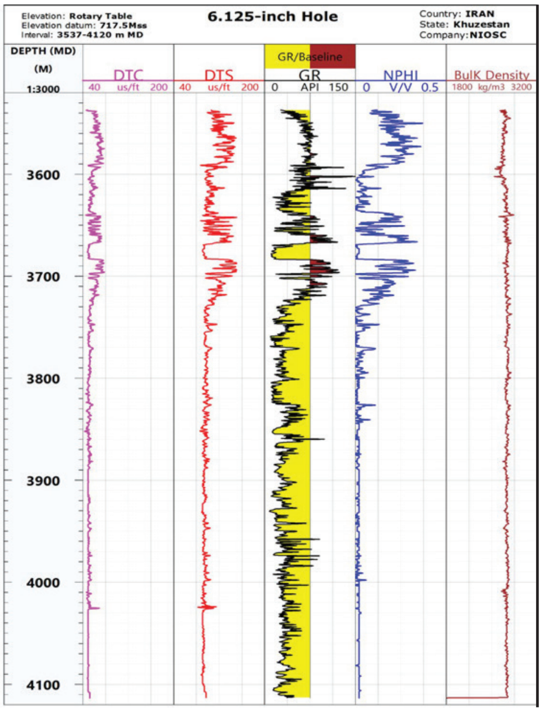

Fig. 1 Petrophysical logs data for 6.125-inch hole of the Current well.

Rock Mechanical Properties

Rock mechanical properties and rock strength are some of the main steps to investigate wellbore stability. Rock mechanical properties (static and dynamic Young's modulus (E_d) and (E_{static}), Poisson's ratio (ϑ), uniaxial compressive strength (UCS), internal friction angle (φ), and cohesion (C) have been calculated by various equations as expressed in below (Equations 1 to 6) [7,8].

$$E_d = 1.82 \times 10^5 \rho_b \times \frac{\frac{1}{(DTS)^2} \times (3(DTS)^2 - 4(DTC)^2)}{(DTS)^2 - (DTC)^2} \quad (1)$$

$$E_{Static} = 0.7 \times E_d \quad (2)$$

$$\vartheta = \frac{\frac{1}{2} \times (DTS/DTC)^2 - 1}{(DTS/DTC)^2 - 1} \quad (3)$$

$$\varphi = 26.5 - 37.4(1 - NPHI - V_{shale}) + 62.1(1 - NPHI - V_{shale})^2 \quad (4)$$

$$UCS = 2.27 \times E_{Static} + 4.7 \quad (5)$$

$$C = UCS \times (1 - \sin\varphi / 2\cos\varphi) \quad (6)$$

Also, the UCS and Estatic correlations have been suggested by NISOC, after performing several experimental tests on various specimens of the current field.

The computed rock properties have been shown in Figure 2.

In-situ Stresses and Pore Pressure Estimation

In situ stresses are commonly vertical stress, maximum horizontal stress, and minimum horizontal stress. The vertical stress (S_v) was computed by integral equation, and also the horizontal stresses (S_{Hmax} and S_{hmin}) have been calculated via poroelastic horizontal strain model (Equation 7,9, and 10) [7]. The pore pressure (Pp) has been computed from Eaton's equation (Equation 8) for the nonproductive formations [9]. However, for the reservoir formation water-oil contact (WOB), gas-oil contact (GOC), datum depth, the pore pressure of oil, gas and water in datum depth and pressure gradient for oil, gas and water data were provided by NISOC from the offset wells. Hence, the pore pressure has been calculated through the mentioned data in all depths of the reservoir formation.

$$S_v(z) = \int_0^z \rho_b .g.dz \quad (7)$$

$$P_p = S_v - (S_v - P_{pn}) \times (\frac{DTC_n}{DTC})^3 \quad (8)$$

$$S_{h\min} = S_v\left(\frac{\vartheta}{1-\vartheta}\right) + \left(\frac{1-2\vartheta}{1-\vartheta}\right)\alpha P_p + \left(\frac{E_{Static}}{1-\vartheta}\right)\varepsilon_x + \left(\frac{E_{Static}}{1-\vartheta}\right)\varepsilon_y \quad (9)$$

$$S_{H\max} = S_v\left(\frac{\vartheta}{1-\vartheta}\right) + \left(\frac{1-2\vartheta}{1-\vartheta}\right)\alpha P_p + \left(\frac{E_{Static}}{1-\vartheta}\right)\varepsilon_y + \left(\frac{E_{Static}}{1-\vartheta}\right)\varepsilon_x \quad (10)$$

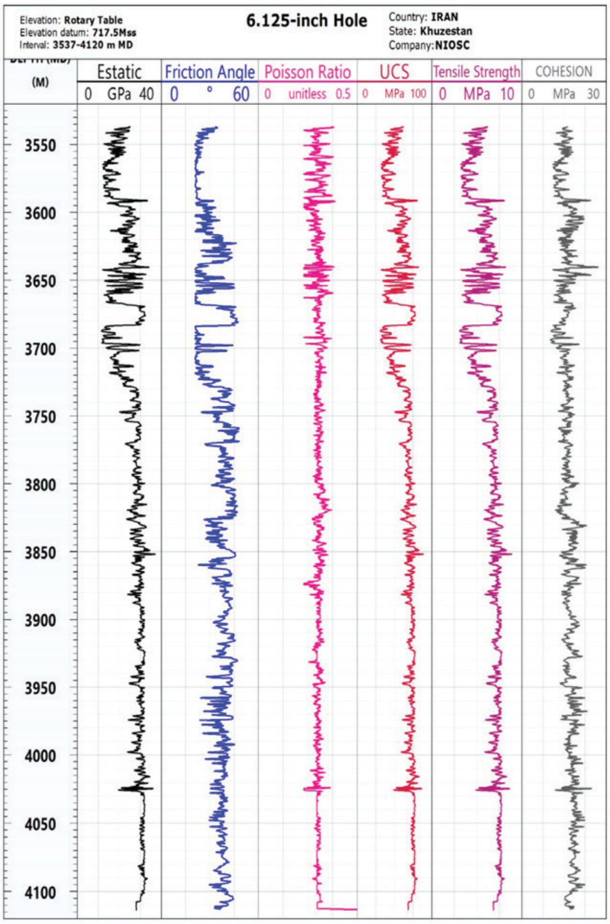

Fig. 2 Estimated rock mechanical properties for 6.125-inch hole of the Current well.

The estimated values of in-situ stresses and pore pressure have been demonstrated in Figure 3. Moreover, the estimated minimum horizontal stress (S_{hmin}) is validated via the direct measurement of Leak-off test (LOT) data (a black triangular dot). According to Figure 3, the estimated values of the minimum horizontal stress and LOT result have a reliable agreement.

Rock failure criteria for determination of the safe mud weight window and wellbore stability

The induced stresses after drilling are not equal to in-situ stresses and they are applied around the wellbore. These stresses are divided into three kinds, containing tangential stress (σ_θ), axial stress (σ_z) and radial stress (σ_r). The radial stress is assumed to be equal mud pressure in the wellbore (P_w). The magnitudes of the induced stresses in the wellbore wall can be computed through Kirsch's equations [10]. The worse condition for breakout or shear failure condition is when the tangential stress is maximum, and the stress regime of $\sigma_\theta > \sigma_z > \sigma_r$ is considered to be in the wellbore wall. In addition, the worst condition for breakdown condition is when the tangential stress is minimum, and the most prevalent stress regime is $\sigma_r > \sigma_z > \sigma\theta$ [11]. Therefore, they can be formulated as:

$$\sigma_\theta^{max} = A - P_w \tag{11}$$

$$A = 3S_{H\,max} - S_{h\,min} \tag{12}$$

$$\sigma_z = B \tag{13}$$

$$B = \sigma_v + 2\vartheta(S_{H\,max} - S_{h\,min}) \tag{14}$$

$$\sigma_\theta^{min} = D - P_w \tag{15}$$

$$D = 3S_{h\,min} - S_{H\,max} \tag{16}$$

$$\sigma_z = E \tag{17}$$

$$\sigma_z = E \tag{18}$$

$$E = \sigma_v - 2\vartheta(S_{H\,max} - S_{h\,min}) \tag{19}$$

In this paper, two rock failure criteria MC and MG have been employed to obtain the safe mud weight window, including the breakout pressure ($P_{w(BO)}$) (as a lower bound of mud window or MRMW) and breakdown pressure ($P_{w(Break)}$) (as an upper bound of mud window). As explained before, based on two failure criteria and regarding breakout, the maximum principal stress is equal to the tangential stress ($\sigma_\theta = \sigma_1$), and the minimum principal stress is radial stress ($\sigma_3 = P_w$). Additionally, the maximum principal stress is mud pressure ($\sigma_1 = P_w$), and the minimum principal stress is the tangential stress ($\sigma_\theta = \sigma_3$) for breakdown.

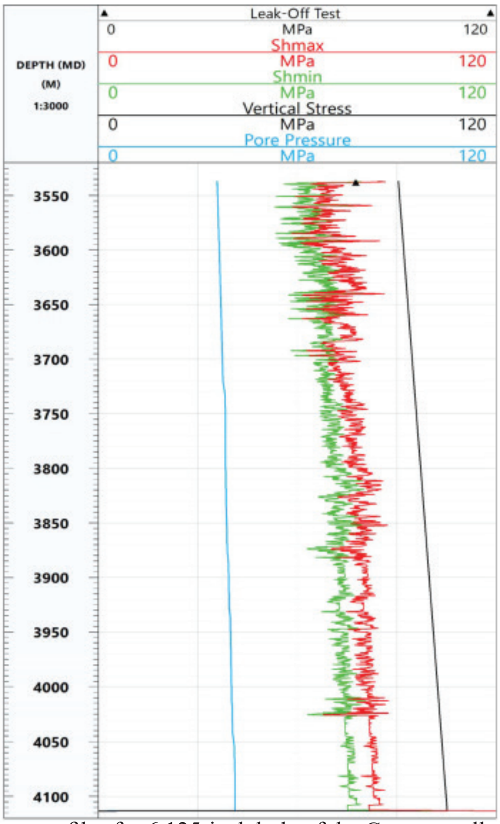

Fig. 3 Pore Pressure and In-situ Stresses profiles for 6.125-inch hole of the Current well with LOT result.

Finally, the equations used for calculating the safe mud weight window are written as:

Mohr-Coulomb:

$$P_{w(BO)} = \frac{\left[A - UCS - P_p(q-1)\right]}{1+q} \quad (20)$$

$$P_{w(Break)} = \frac{\left[UCS + P_p(q-1) + qD\right]}{1+q} \quad (21)$$

Mogi-Coulomb:

$$P_{w(BO)} = \frac{A}{2} - \frac{1}{6}\sqrt{12[a' + b'(A - 2P_p)]^2 - 3(A - 2B)^2} \quad (22)$$

$$P_{w(Break)} = \frac{A}{2} + \frac{1}{6}\sqrt{12[a' + b'(D - 2P_p)]^2 - 3(D - 2E)^2} \quad (23)$$

Moreover, the caliper and bit size logs are utilized to verify the wellbore stability results.

Results and Discussion

The safe mud window predicted using MG and MC failure criteria have been represented in Figure 4 with caliper log and bit size. According to this Figure and tracks 2 and 3, the grey line or area shows the pore pressure or kick pressure. The orange (yellow area) and dark blue profiles indicate the predicted minimum required mud weight (breakout pressure) and the predicted maximum allowable mud weight (breakdown pressure) respectively. The green profile or area displays mud loss pressure which is equal to the minimum horizontal stress value. The actual mud weight utilized for drilling this hole has been presented in the black line. All variables in Figure 4 are in ppg or Lbm/Gal. Finally, the last track demonstrates the caliper logs data based on inch(in), and the serious breakouts are observed in the intervals of 3540-3600 m, 3640-3665 m and 3685-3730 m from this log. Based on Figure 4, the MC overestimates the breakout pressure and shows a conservative approach which can be due to ignoring the intermediate principal stress effect. Contrarily, the predicted breakout pressure via MG criterion is more realistic, and thus the MG criterion appears to give a better match with the real observed breakouts from the caliper log. Since this failure criterion takes into account the effect of the intermediate principal stress. As a result, it could be concluded that the Mogi-Coulomb failure criterion and its results are the most reliable approach for drilling of the hole with 6.125- inch size in the current well or a similar well.

Conclusions

In this study, two rock failure criteria have been used to predict the safe mud weight window for 6.125-inch hole of a well in the southwest of Iran. First, rock mechanical properties, in-situ stresses and pore pressure were obtained and then were calibrated through LOT data. Afterwards, the safe mud weight windows were determined using two Mohr-Coulomb and Mogi-Coulomb failure criteria. Based on real observed breakouts from caliper log, the MC criterion is not suggested due to overestimating of the MRMW.

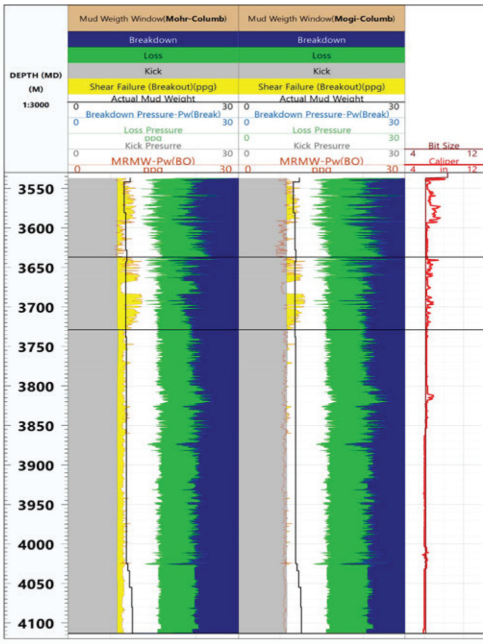

Fig. 4 Mud weight windows predicted for 6.125-inch hole of the current well using MC and MG criteria with bit Size/caliper Logs and actual mud weight.

Furthermore, the MG criterion provides a more realistic prediction in comparison with the MC criterion and has a good agreement with the real observations. Eventually, the MG criterion was chosen as a most appropriate failure criterion and consequently, it is recommended in designing the mud weight for 6.125-inch hole of the current well, and also for drilling a similar well in this oil field.

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