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A SENSITIVITY STUDY OF GEOMECHANICAL AND RESERVOIR PARAMETERS ON SAFE MUD WINDOW DURING DRILLING OPERATIONS

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Abstract

The integrity of the wellbore plays an important role in petroleum operations. Hole failure problems cost the petroleum industry several billions of dollars each year. Prevention of wellbore failure requires a strong understanding of the interaction between formation strength, in-situ stresses, and drilling practices.

This paper presents the sensitivity of the reservoir and geomechanical parameters on collapse and fracture pressures for oil and gas wells. This study is conducted based on the linear poroelastic model and Mogi-Coulomb failure criterion.

The results indicated that the collapse and fracture pressures increases with increasing the UCS of rock and Poisson's ratio. An increase in horizontal stress anisotropy ratio leads to decrease in the fracture pressure. Also, an increasing HSAR coefficient tends to increase collapse pressure.

Such predictions are necessary for providing technical support for well drilling decision-making and predicting the condition at which borehole instability occurs.

Keywords: Wellbore stability; Mud pressure; Mogi-Coulomb criterion; Analytical model; Constitutive model.

1. Introduction

During drilling, there are two types of mechanical borehole failure: compressive and tensile failures. Compressive failure occurs when the wellbore pressure is too low compared with the rock strength and the induced stresses. On the other hand, tensile failure occurs when the wellbore pressure is too high [1]. As in-situ stress and rock strength cannot be easily controlled, adjusting the drilling practices is the usual way to inhibit wellbore failure [2-3].

The main aspect of the wellbore stability analysis is to mitigate these drilling problems [4]. In order to avoid borehole failure, drilling engineers should adjust the stress concentration properly through altering the applied mud pressure and the orientation of the borehole with respect to the in-situ stresses. Since borehole allocation (in terms of orientation) is limited, pro-per adjusting of mud weight (borehole pressure) will play an essential role in prevention of drilling problems [5-6]. The true mud pressure in the borehole depends on the static weight of the mud column increased by the dynamic effect of the flow (known as ECD – Effective Circulating Density), together with occasional fluctuations as the drill string moves (pistoning or suction). In view of these fluctuations, the borehole stability conditions are often borderline [7].

In engineering practice, a linear poroelasticity stress model in combination with a rock strength criterion is commonly used to determine the minimum and maximum mud pressures required for ensuring wellbore stability. Therefore, a main aspect of wellbore stability analysis is the selection of an appropriate rock strength criterion. So far, the two most commonly used strength criteria in wellbore stability analysis are the Mohr–Coulomb criterion and the Drucker–Prager criterion [8]. Researchers have found that these two strength criteria can give very different minimum mud pressures. Mohr–Coulomb criterion suffers from two major limitations: (a) it ignores the non-linearity of strength behavior, and (b) the effect of intermediate principal stress is not considered in its conventional form. Thus, the criterion overestimates the minimum mud pressure due to neglecting the effect of the intermediate principal stress. In other hand, the Drucker–Prager criterion underestimates the minimum mud pressure because it exaggerates the intermediate principal stress effect [9].

Zhou [10] introduced a modified Wiebols and Cook [11] criterion and developed a computer program for the wellbore stability analysis. The results indicated the importance of the intermediate principal stress on the stability of wellbores. Ewy developed the Modified-Lade failure criterion and presented the advantages of this new criterion over Mohr-Coulomb and Drucker-Prager [12]. Colmenares and Zoback evaluated seven different rock failure criteria based on polyaxial test data, and they concluded that the Modified Lade and the Modified Wiebols and Cook fit best with polyaxial test data [13]. Al-Ajmi and Zimmerman [14] developed the Mogi–Coulomb failure criterion, according to polyaxial failure data of the variety of rocks. They concluded that Mohr–Coulomb failure criterion is conservative in estimating of collapse pressure during drilling and using Mogi–Coulomb failure criterion can minimize the conservative nature of the mud pressure predictions.

In this paper, the 3D Mogi-Coulomb strength criterion developed by is used to analyze wellbore stability. Furthermore, the analytical models are applied to field data in order to verify the applicability of the developed models. This paper presents the effects of the reservoir and geomechanical parameters on drilling mud safe window based on linear poroelastic model and Mogi-coulomb criterion

2. Calculation of rock mechanical properties

The mechanical properties of formations and dynamic elastic constants of subsurface rocks can derived from the measurement of elastic wave velocities and density of the rock. Sonic logging and waveform analysis provide the means for obtaining continuous measurements of compressional and shear velocities. These data, in conjunction with a bulk density measurement, permit the in-situ measurement and calculation of the mechanical properties of the rock. The elastic moduli relationships, in terms of elastic wave velocities (or transit times) and bulk density can be calculated from following equations [15].

$$\nu_d = \frac{\frac{1}{2}\left(\frac{\Delta t_s}{\Delta t_c}\right)^2 - 1}{\left(\frac{\Delta t_s}{\Delta t_c}\right)^2 - 1} \quad (1)$$

$$E_d = \frac{\rho_b\left[3 - 4\left(\frac{\Delta t_c}{\Delta t_s}\right)^2\right]}{\Delta t_s^2 - \Delta t_c^2} \quad (2)$$

$$\alpha_B = 1 - \frac{K_B}{K_R} \quad (3)$$

$$K_B = \rho_b\left(\frac{1}{\Delta t_c^2} - \frac{4}{3\Delta t_s^2}\right) b \quad (4)$$

$$K_R = \rho_{gr}\left(\frac{1}{\Delta t_c^2} - \frac{4}{3\Delta t_s^2}\right) b \quad (5)$$

where ν_d is the dynamic Poisson's ratio; E_d is the dynamic Young modulus (psi); α_B is Biot's coefficient; Δt_s is shear wave travel time (ft/s); Δt_c is compressional wave travel time (ft/s); k_B is dynamic bulk modulus (psi); K_R is the rock modulus (psi); ρ_b is the bulk density (gr/cm^3); ρ_{gr} is the grain density (gr/cm^3); and "b" is the constant coefficient which is equal to $1.34*10^{10}$.

For the Bangestan formation of mentioned oilfield, an equation developed for estimation of shear wave travel time by Nabaei *et al.* [16] was used:

$$\Delta t_s = 1.7891\Delta t_c + 7.622 \quad (6)$$

Dynamic data cannot directly be utilized to develop mechanical models. So, they should be first converted into static data through some calculation changes made and then used in geomechanical model [17]. Poisson's ratio and static Young's modulus are both calculated via the following relations in south west of Iran. The results show good conformity with laboratorial data [18].

$$\nu_s = \nu_d \quad (7)$$

$$E_s = 0.4145E_d - 1.0593 \quad (8)$$

where ν_s is the static Poisson's ratio and E_s is the static Young modulus (psi).

2.1. In-Situ stresses and pore pressure

In-situ stress magnitudes play a very important role in geomechanical analysis, and they are the most basic parameter inputs in analysis of hydraulic fracturing. Vertical stress is induced by the weight of the overlying formations. The vertical stress can be calculated by integration of rock densities from the surface to the depth of interest based on Eq. 9. In fact, density log can be used to calculate overburden stress [19].

$$\sigma_V = g\int_0^Z \rho(z)\ dh \approx \bar{\rho} g z \quad . \qquad (9)$$

where σ_V is vertical stress (psi); z is depth of interest (ft); ρ (z) is the density as a function of depth (gr/cm^3); g is gravitational acceleration (ft/s^2) and $\bar{\rho}$ is the mean overburden density of rocks (gr/cm^3).

Rocks of Bangestan formation have an average density of 2.6 gr/cm^3. By considering horizontal strain and deformation effect, Hooke's law can be applied to derive the horizontal stresses and strains relationships [19]. The following equations are obtained, and are used to calculate the minimum and maximum horizontal stresses with tectonic strain effects [20].

$$\sigma_h = \frac{\nu_s}{1-\nu_s}\left(\sigma_V - \alpha_B P_p\right) + \alpha_B P_p + \frac{\nu_s E_s}{1-\nu_s{}^2}\varepsilon_1 + \frac{E_s}{1-\nu_s{}^2}\varepsilon_2 \qquad (10)$$

$$\sigma_H = \frac{\nu_s}{1-\nu_s}\left(\sigma_V - \alpha_B P_p\right) + \alpha_B P_p + \frac{\nu_s E_s}{1-\nu_s{}^2}\varepsilon_2 + \frac{E_s}{1-\nu_s{}^2}\varepsilon_1 \qquad (11)$$

where σ_h is minimum horizontal stress; σ_H is maximum horizontal stress; P_p is pore pressure; ε_1 and ε_2 are strains due to tectonic forces in maximum and minimum directions and considered 1 and 1.5 , respectively. Based on drilling information pore pressure gradient in this formation is estimated 0.44 psi/ft.

3. Stress concentration around a wellbore at production condition

The stress concentration around a well drilled in an isotropic, elastic medium under anisotropic in-situ stress condition (Maximum and minimum horizontal stresses are different) was described by the Kirsch equations. The general expressions for the stresses at the wellbore wall for a deviated well in the production situation are [21]:

$$\begin{aligned}
&\sigma_r = P_{wf}\\
&\sigma_\theta = \sigma^\circ{}_x + \sigma^\circ{}_y - 2\left(\sigma^\circ{}_x - \sigma^\circ{}_y\right)\cos 2\theta - 4\tau^\circ{}_{xy}\sin 2\theta - P_{wf} + B(P_{wf} - P_p)\\
&\sigma_z = \sigma^\circ{}_z - \nu_s[2(\sigma^\circ{}_x - \sigma^\circ{}_y)\cos 2\theta + 4\tau^\circ{}_{xy}\sin 2\theta] + B(P_{wf} - P_p) \qquad (12)\\
&\tau_{\theta z} = 2(-\tau^\circ{}_{xz}\sin\theta + \tau^\circ{}_{yz}\cos\theta)\\
&\tau_{rz} = 0\\
&\tau_{r\theta} = 0
\end{aligned}$$

where σ_r is the radial stress; σ_θ is the tangential (hoop) stress; σ_z is the axial stress induced around a wellbore; P_{wf} is the bottomhole flowing pressure; θ is measured from the azimuth of maximum horizontal stress (Degree) and B is the poroelastic stress coefficient defined as

$$B = \frac{1-2\nu_s}{1-\nu_s}\alpha_B \qquad (13)$$

The shear stresses at the wellbore wall are denoted $\tau_{r\theta}$, $\tau_{\theta z}$ and $\tau_{\theta z}$, while the in-situ stresses in (x, y, z) coordinate system, denoted $\sigma^\circ{}_x$, $\sigma^\circ{}_z$, $\sigma^\circ{}_y$, $\tau^\circ{}_{xy}$, $\tau^\circ{}_{yz}$ and $\tau^\circ{}_{xz}$, and they are defined as [21]:

$$\begin{aligned}
&\sigma^\circ{}_x = (\sigma_H\cos^2\alpha + \sigma_h\sin^2\alpha)\cos^2 i + \sigma_V\sin^2 i\\
&\sigma^\circ{}_y = \sigma_H\sin^2\alpha + \sigma_h\cos^2\alpha\\
&\sigma^\circ{}_z = (\sigma_H\cos^2\alpha + \sigma_h\sin^2\alpha)\sin^2 i + \sigma_V\cos^2 I \qquad (14)\\
&\tau^\circ{}_{xy} = 0.5(\sigma_h - \sigma_H)\sin 2\alpha\ \cos i\\
&\tau^\circ{}_{yz} = 0.5(\sigma_h - \sigma_H)\sin 2\alpha\ \sin i\\
&\tau^\circ{}_{xz} = 0.5(\sigma_H\cos^2\alpha - \sigma_h\sin^2\alpha - \sigma_V)\sin 2i
\end{aligned}$$

where i is wellbore inclination and α is the azimuth angle due to the maximum horizontal stress (σ_H) direction (Degree).

Fig. 1 shows the stress transformation system in a deviated borehole where α is the rotation angle around the z′-axis (measured from the x′-axis) and i is the rotation angle around the y′-axis (measured from the z′-axis).

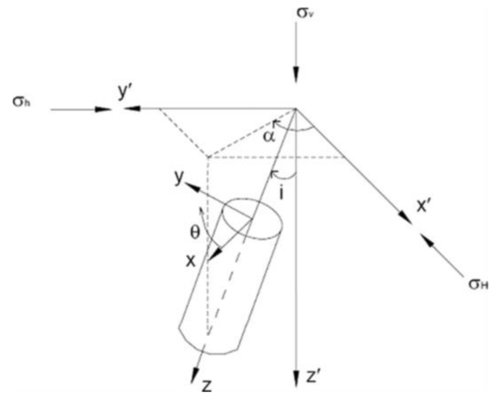

Fig. 1. Stress transformation geometry for a deviated borehole [21]

The tensile failure known as fracturing is expected to happen at the wellbore wall and at the point of minimum tangential stress (θ=0°) where the rock is under maximum tension [4]. For a vertical borehole, the inclination angle (i) is set to zero and the x-axis is oriented, so that it coincides with the major horizontal principal stress axis (i.e., α =0°). However, for a vertical well the minimum stress values will always be at θ=0° for any values of the in-situ stresses and Eqs. 12 become:

$$\sigma_r = P_{wf}$$
$$\sigma_\theta = 3\sigma'_h - \sigma'_H - P_{wf} + B(P_{wf} - P_p) \quad (15)$$
$$\sigma_z = \sigma_v - 2\nu(\sigma'_H - \sigma'_h) + B(P_{wf} - P_p)$$

The effect of reservoir pressure decline due to production can be accounted for in the above computation by updating the in-situ stresses. For a laterally large reservoir compared to its thickness, the change in vertical stress is considered negligible and therefore it is usually kept constant [22]. The maximum and minimum horizontal stresses are updated as follows, respectively:

$$\sigma'_H = \sigma_H - B\Delta P_r \quad (16)$$
$$\sigma'_h = \sigma_h - B\Delta P_r \quad (17)$$

where

$$\Delta P_r = P_{ri} - P_{rc} \quad (18)$$

and σ'_H and σ'_h are the maximum and minimum horizontal stresses at current production condition, respectively. P_{ri} and P_{rc} are the initial and current reservoir pressures, respectively

4. Mogi-Coulomb Failure Criterion

Al-Ajmi and Zimmerman [14] developed the three-dimensional Mogi–Coulomb failure criterion. This failure criterion has been justified by experimental evidence from triaxial tests as well as polyaxial tests. According to this criterion

$$\tau_{oct} = a + b\sigma'_{m,2} \quad (19)$$

Where $\sigma'_{m,2}$ and τ_{oct} are, respectively, the effective mean stress and the octahedral shear stress defined by:

$$\sigma'_{m,2} = \frac{\sigma'_1 + \sigma'_3}{2} \quad (20)$$
$$\tau_{oct} = \frac{1}{3}\sqrt{(\sigma'_1 - \sigma'_2)^2 + (\sigma'_2 - \sigma'_3)^2 + (\sigma'_3 - \sigma'_1)^2} \quad (21)$$

and a and b are material constants which are simply related to cohesive strength (S_o) and internal friction angle (ϕ_f) as follows:

$$a = \frac{2\sqrt{2}}{3} S_o cos\phi_f \quad (22)$$

$$b = \frac{2\sqrt{2}}{3} sin\phi_f \quad (23)$$

5. Field case study

The developed analytical models will be applied to a well (called well A) drilled in Ahwaz oilfield (One of southern Iranian field in the Middle East) for investigation of stability analysis during drilling. This oil field is one of the most important Iranian super giant oil fields, was discovered in 1956 and now has more than 450 producing wells. This oil field has an anticline structure 72 km long and 6 km wide with NW-SE trending symmetrical anticlinal, located in central part of north Dezful region. Its main reservoir is the Asmari formation and Bangestan Group with the production rate of 1000,000 barrels/day [23].

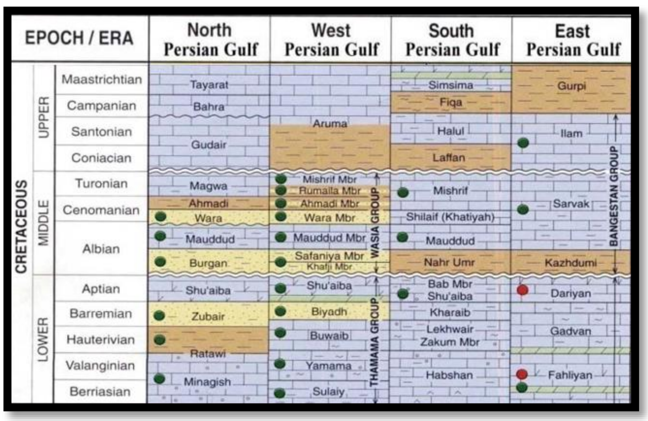

Fig. 1. Simplified Stratigraphy of Bangestan Group in Persian Basin [26]

The Bangestan reservoir is one of the carbonate reservoirs in southern of Iran, providing approximately 5% of the total production of the southern oil field region. Because of a sufficient amount of oil in place and the good quality of porosity with low permeability and flowing capacity in some of the production layers, it is a good candidate for a hydraulic fracturing operation [24]. This reservoir includes the thick Sarvak limestone (300m to 1000m thick) of Cenomanian-Turonian age and the thinner Illam formation (50m to 200m thick) of Santonian age (Fig. 1). These two reservoirs form a single reservoir in most of the Dezful Embayment and capped by the thick Gurpi/Pabdeh marls [25].

5.1. Effects of horizontal stress anisotropy ratio on collapse and fracture pressures

It is important to have a full knowledge of in-situ stresses before carrying out any rock stress analysis. The main reasons for the determination of horizontal in-situ stresses are: (1) To get a basic knowledge of formation structure and position of anomalies, groundwater flows (2) To find basic data on the formation stress state. (3) To get the orientation and magnitude of the major principal stresses. (4) To find the stress effects which may affect drilling and production processes [27].

Zoback [28] concluded that drilling-induced tensile fractures occur in vertical wells whenever there is a significant difference between the two horizontal stresses. So, it can easily be shown that the condition for tensile fracture formation in the wellbore wall in a vertical well leads to estimation of maximum horizontal stress. Brudy *et al.* [29] pointed out that the value of maximum horizontal stress required to induce drilling-induced tensile fractures (after correcting for excess mud weight and cooling) must be considered as a lower-bound estimate. This is because the drilling-induced tensile fractures might have occurred even if there had been no excess mud weight or cooling of the wellbore wall. This represents an upper bound value of maximum horizontal stress. Figure 2 shows the effects of horizontal stress anisotropy on collapse (Pwc) and fracture pressures (P_{wf}). The horizontal stress anisotropy ratio is defined as

$$HSAR = \frac{S_H}{S_h} \quad (24)$$

As Figure 2 depicts, an increase in HSAR leads to decrease in the fracture pressure. Also, it can be seen that increasing HSAR coefficient tends to increase collapse pressure.

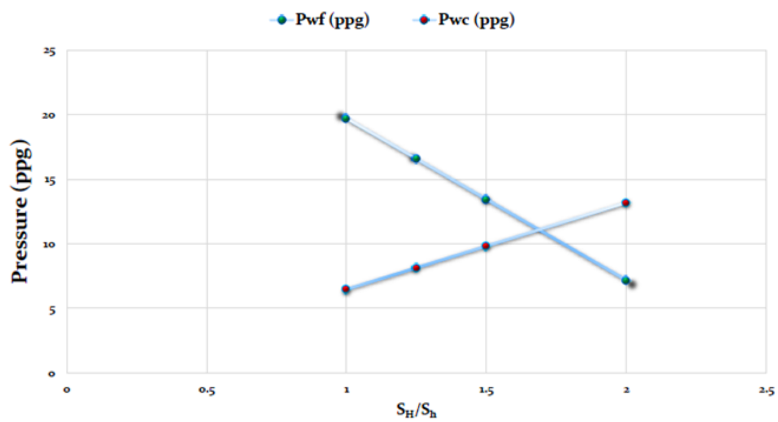

Fig. 2. Effect of HSAR on the collapse and fracture pressures

5.2. Effects of uniaxial compressive strength (UCS) on collapse and fracture pressures

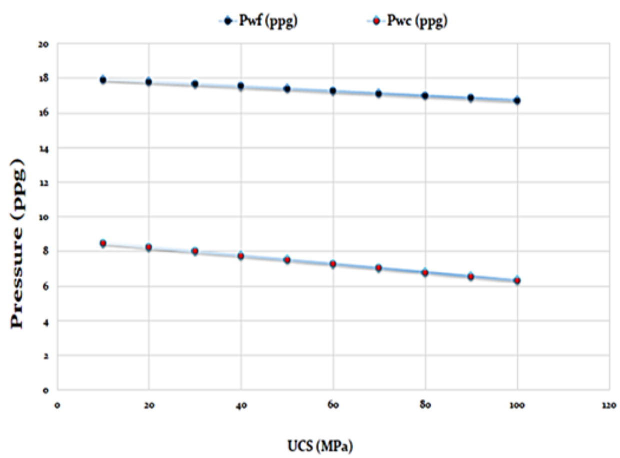

Fig. 3. Effect of UCS on the collapse and fracture pressures

Uniaxial compressive strength (UCS) of intact rocks is an important and pertinent property for characterizing rock mass. UCS is included as a main input parameter for rock mass characterization, rock classification and failure criteria [30-31]. This parameter is widely used in geological, geotechnical, geophysical and petroleum engineering projects [32].

Figure 3 shows the influences of the UCS on collapse and fracture pressures. It can be concluded that the collapse and fracture pressures increase by increasing the UCS. Furthermore, the sensitivity of UCS on the collapse and fracture pressures is very low.

5.3. Effects of Poisson's ratio on collapse and fracture pressures

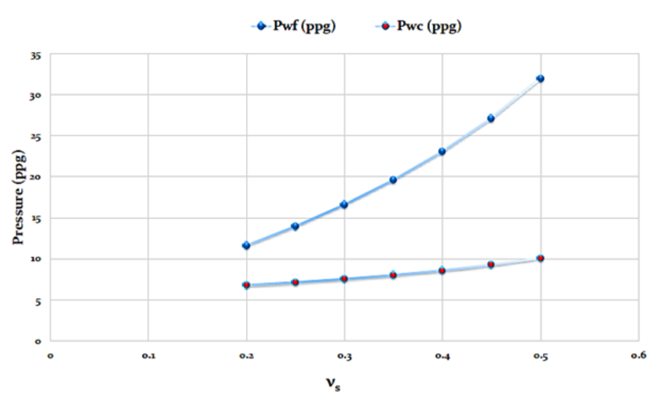

Fig. 4. Effect of Poisson's ratio on the collapse and fracture pressure

During fracturing, a change in stresses occurs at the borehole. The local stress field is affected in three dimensions, which implies a coupling between the stresses, taking account of the Poisson's ratio.

The starting assumption is that there exists a principal stress state in the rock before the hole is drilled. If the borehole pressure is equal to the in-situ stress state, the near wellbore stress state is still principal [33]. Lowering or increasing the mud weight from this stress level results in a Poisson's ratio effect on the stresses [27].

Figure 4 displays the effects of the Poisson's ratio on collapse and fracture pressures. It can be concluded that the collapse and fracture pressures increases by increasing the Poisson's ratio. Furthermore, the sensitivity of Poisson's ratio on the collapse pressure is very low.

4. Conclusions

This paper presents the effect of reservoir and geomechanical parameters on collapse and fracture pressures. The results indicated that the collapse and fracture pressures increases with increasing the UCS of rock and Poisson's ratio. An increase in HSAR leads to decrease in the fracture pressure. Also, an increasing HSAR coefficient tends to increase collapse pressure.

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