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Time-Dependent Model for estimating Wellbore-Formation Failure: Analytical Approach

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Abstract
The long-term strength of the rock is controlled by the time-dependent weakening of the undamaged rock. Under long term constant stress loading most rocks experience a reduction in strength. The influence of time on long term performance at the site scale has been recognized in literature, but most failure prediction models are yet to consider the failure time effect. This study proposed a model consisting of linear poroelastic constitutive model and rock failure criterion with the consideration of failure time in predicting rock strength failure. The time-dependent failure of the rock strength is in the time-dependent weakening of intact rock. The results showed that the internal wellbore pressure has a direct and linear relationship with formation strength failure time. Also, the formation strength failure time is dependent on the instantaneous rock strength. It was observed that at low borehole pressures, the tangential stress becomes high, which ultimately leads to failure. Rock fragments fall from the borehole walls and often form an elliptic borehole.

Keywords: *Time-dependent failure, Formation failure, Rock strength, Numerical approach*

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1. Introduction

Well stability control is the prevention of unwanted destruction or deformation of the rock surrounding the well due to mechanical stress or chemical imbalances. Before drilling, the stresses in the formation are less than the strength of the rock (Okoro et al., 2019). Rock is also in a state of chemical equilibrium or changes slowly at a rate over geological time, and rocks at or near this equilibrium are stable (Aslannezhad et al., 2020). Various geological processes (such as compaction, and sedimentation), mechanical strength of rocks, and petrophysical properties control the pore pressure distribution and in turn affect the stability of the wellbore walls. Sufficient mud balance (hydrostatic pressure) in the safe drilling window is the minimum requirement to ensure a safe and stable drill hole down to the target depth (Ganguli and Sen, 2020). By detecting overpressure and shear fracture pressure distribution, geophysicists and drilling engineers can better plan well design and apply the most appropriate completion strategy. Therefore, analysis of pore pressure and wellbore stability has become a necessary part of pre- and post-drilling studies for research, development, and lifecycle abandonment applications (Baouche et al., 2020).

In-situ stress can affect and limit subsurface activities, such as oil exploration and production. However, these subsurface activities, in turn, will alter the distribution of stresses in the subsurface formation (Figure 1) and result in geological activity (Yaghoubi and Zeinali, 2009). Accurate prediction of in-situ stresses, including maximum horizontal stresses, vertical stresses and minimum horizontal stresses, can help the oil and gas industry avoid hazards or reduce damage during exploration and production operations (Figure 2). There are many methods for estimating in-situ stresses, and oil production has made it easier to determine stresses at depth. It is now possible to determine the stress of a deep formation using core testing, fracture testing, and logging (Tang et al., 2012). Hydraulic failure or leak-off test can be used to determine the minimum principal stress, which is not a viable method of determining the maximum horizontal stress at depth. When drilling a well, the formation around the borehole must withstand the in-situ stress previously supported by the removed formation cuttings, resulting in a concentration of stress around the well. If the stress concentration in the wellbore exceeds the resistance rock strength of the borehole wall, the formation collapses under compression and causes the wellbore to fail (Peska and Zoback, 1995).

Several strength criteria have been proposed in literature to describe the state of stress in rocks at the time of failure Yu (2015). Obviously, the ideal strength criterion must exactly match the test data with acceptable precision relative to the stress condition expected in practice. Therefore, the rock strength predicted by the strength criterion is generally used to evaluate the criterion. The rock strength predicted by the Coulomb and Griffiths criteria is much higher than the values measured for some rocks, although these two criteria have a clear physical basis (Jaeger et al., 2007). The inclusion of failure time would be an extremely critical tool for petroleum engineers to be able to accurately predict the effect of failure time on different parameters that have direct effect on rock strength. This study proposed a model consisting of linear poroelastic constitutive model and rock failure criterion with the consideration of failure time in predicting rock strength failure, because the strength of intact rock is time-dependent. Lajtai (1990) highlighted that time is one of the most important parameters in formation stability. Therefore, in order to propagate a model that can successfully forecast and replicate what happens in the subsurface formation with time, a linear poroelastic model and a failure time which is incorporated in the failure criterion is needed (Mufundirwa and Kodama, 2010).

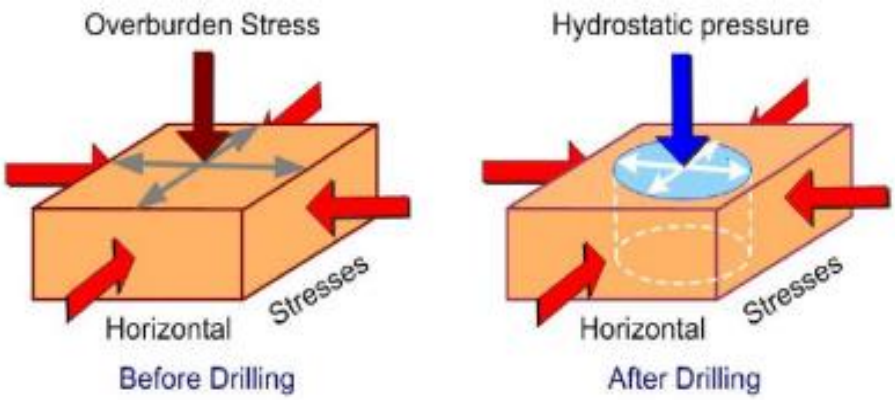

Fig. 1: Near Borehole Stress-State Before and After Drilling Operation (Peska and Zoback, 1995).

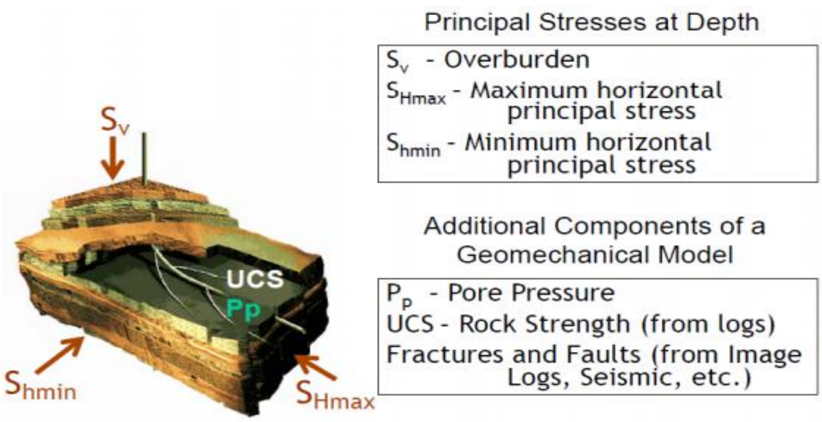

Fig. 2: Subsurface In-Situ Stress (Peska and Zoback, 1995).

2. Brief background

The problem of wellbore instability is one of the main challenges in the field of drilling, especially in shale formation with bedding planes and natural fractures. The failure of shale formation can be divided into two parts: failure by shear in the intact rock matrix and slip failure in shale formation bedding, which results to serious instability during drilling (Fan et al., 2020). The initial study on wellbore instability was carried out by Bradley (1979) under the assumption of linear elasticity, that is, an isotropic rock. This traditional model does not take into account the effect of strength anisotropy on borehole stability (Jaeger et al., 2007). Most borehole stability model cannot predict the fault zone around the well. To solve the problem, Lee et al. (2012) proposed a well stability model for anisotropic strength formations and predicted the position of the collapse in different drilling directions. Zhang et al. (2017) investigated the impact of the deposit on fracture zones around a well in a shale formation. Failure areas, which take into account both slip failure and shear, are very different from those in undamaged rock. When weak plane slip failure and rock shear failure coexist and overlap, the area will have the largest failure zone, adversely affecting wellbore stability (Bautmans et al., 2018).

Accurate information on the magnitude and orientation of in-situ stress at depth allows reasonable calculations of mud density and well trajectory to avoid well collapse and the complexity involved. The technique of estimating the magnitude of the maximum horizontal stress using borehole breakouts observed from well logs has been widely accepted, but the influence of thermo-poroelastic cohesion of formation rocks has been widely neglected. Tang et al. (2021) analyzed borehole breakout and stress distribution using thermo-poroelasticity model and proposed that the borehole breakouts during drilling and maximum horizontal stress in depth can be simulated accurately using the Mogi-Coulomb criterion and thermo-poroelastic rock mechanics theory. The results from the study showed that the borehole is more prone to shear failure due to the thermo-poroelastic effect of the formation. Aslannezhad et al. (2020) highlighted in their study the importance of choosing an optimum rock failure criterion for predicting safe drilling window based on all mechanical, physical and chemical effects. Ghasemi et al. (2018) estimated the tensile failure and dynamic shear condition in the near borehole zone. Their study further considered stress dependency of the rock formation properties, and the results showed the direct and indirect relationship of rock properties on estimated tensile strength.

The effect of time on failure models has not been extensively studied in literature; thus, this study proposed a model consisting of linear poroelastic constitutive model and rock failure criterion with the consideration of failure time in predicting rock strength failure.

3. Materials and methods

3.1 Theory of the model

The linear elastic model is popularly used because: (1) most of the rocks exhibit a linear plastic behavior before the onset of any damage, and (2) this model requires fewer parameters compared to more complex models. However, because the rocks are composite and non-homogenous materials, a Linear Poroelastic constitutive model is adopted, and it accounts for the dependence on pore pressure and is used to determine the Critical pressure for failure. In addition, the elastic constitutive model requires fewer input parameters compared to other more intricate models. A linear poroelastic constitutive model is used in this study to determine stress at the borehole. In addition to the constitutive law, which is used to obtain a stress state around the well, a rock failure criterion is required (Al-Shaaibi et al., 2013; Zhu et al., 2020).

3.2 Model development

The time-dependent model was developed with the following assumptions:

1. The Mohr-Coulomb criteria $\sigma_\theta \geq \sigma_z \geq \sigma_r$ is applicable to a vertical borehole with isotropic horizontal stresses.
2. Maximum stress is equal to the horizontal stress. i.e. $\sigma = \sigma_H$.
3. The rock is homogeneous.
4. The rock is isotropic
5. Brittle shear failure would induce sand production.
6. The well is vertical.

To derive this model, the following stress equations were used for the vertical well:

$$\sigma_r = P_w \tag{1}$$

$$\sigma_\theta = 3\,\sigma_H - \sigma_h - P_w + 2\,\eta\big(P_f - P_{fo}\big) \tag{2}$$

$$\sigma_z = \sigma_v + 2\,v\,(\sigma_H - \sigma_h) + 2\,\eta\big(P_f - P_{fo}\big) \tag{3}$$

$$\tau_{t\theta} = \tau_{r\theta} = \tau_{rz} = 0 \tag{4}$$

Considering Mohr-Coulomb's failure criterion,

$$\sigma_\theta - P_f = C_o + q\,(\sigma_r - P_f) \tag{5}$$

Substituting equations (1) to (3) into (4),

$$3\sigma_H - \sigma_h - P_w + 2\eta P_f - P_w = C_o + q\big(P_w - P_f\big) \tag{6}$$

When $P_w = P_f z$,

$$3\sigma_H - \sigma_h - P_w + 2\eta\big(P_f - P_{f0}\big) = C_o + q(P_w - P_w) \tag{7}$$

$$3\sigma_H - \sigma_h - P_w + 2\eta P_f - 2\eta P_{f0} = C_o + q(P_w - P_w) \tag{8}$$

$$3\sigma_H - \sigma_h - P_w + 2\eta P_w - 2\eta P_{f0} = C_o + qP_w - qP_w \tag{9}$$

$$3\sigma_H - \sigma_h + 2\eta P_w - P_w - 2\eta P_{fo} = C_o \tag{10}$$

$$3\sigma_H - \sigma_h + P_w(2 - 2\eta) - 2\eta P_{fo} = C_o \tag{11}$$

$$3\sigma_H - \sigma_h - 2\eta P_{fo} - C_o = P_w(2 - 2\eta) \tag{12}$$

$$P_w(2 - 2\eta) = 3\sigma_H - \sigma_h - C_o - 2\eta P_{fo} \tag{13}$$

$$P_w = \frac{3\,\sigma_H - \sigma_h - C_o - 2\eta P_{fo}}{2 - 2\,\eta} \tag{14}$$

where σ_H is the maximum horizontal stress. According to Das and Scholz (1981) and Wiederhorn and Bolz (1970), an exponential relationship exists between the average time and the applied stress which is given as equation (15):

$$t_f = t_o \exp\left(-b\frac{\sigma}{\sigma_0}\right) \quad (15)$$

where t_f = failure time; σ = major stress; σ_0 = instantaneous strength.

Also, a failure time has been developed based on the power law as follows (Charles, 1958):

$$t_f = t'_o\left(\frac{\sigma}{\sigma_0}\right)^{-b} \quad (16)$$

The equations (15) and (16) shows that the failure time relies on both properties of the rock and the ambient conditions.

$$\ln\left(\frac{t_f}{t_0}\right) = -b\frac{\sigma}{\sigma_0} \quad (17)$$

where σ is the major stress and equation (17) can be rewritten as:

$$\sigma = \left(-\frac{\sigma_0}{b}\right)\ln\left(\frac{t_f}{t_o}\right) \quad (18)$$

Now applying the Mohr-Coulomb criterion for vertical bore-hole with isotropic horizontal stresses for the case when $\sigma_\theta \geq \sigma_z \geq \sigma_r$ and $\sigma = \sigma_H$. Making σ_H the subject of formula,

$$\sigma_H = \frac{2\eta P_w - 2P_w}{\sigma_h + C_o + 2\eta P_{fo}} \quad (19)$$

Thus,

$$\left(-\frac{\sigma_0}{b}\right)\ln\left(\frac{t_f}{t_o}\right) = \frac{2\eta P_w - 2P_w}{\sigma_h + C_o + 2\eta P_{fo}} \quad (20)$$

Multiply both sides of equation (20) with $\left(-\frac{b}{\sigma_0}\right)$

$$\frac{2P_w + 2\eta P_w}{\sigma_h + C_o + 2\eta P_{fo}}\left(-\frac{b}{\sigma_0}\right) = \ln\left(\frac{t_f}{t_o}\right) \quad (21)$$

$$\frac{t_f}{t_o} = \exp\frac{2P_w + 2\eta P_w}{\sigma_h + C_o + 2\eta P_{fo}}\left(-\frac{b}{\sigma_0}\right) \quad (22)$$

$$t_f = t_o \exp\frac{2P_w + 2\eta P_w}{\sigma_h + C_o + 2\eta P_{fo}}\left(-\frac{b}{\sigma_0}\right) \quad (23)$$

where P_w is the internal wellbore pressure, P_{fo} is the far field pore pressure, P_f is the pore pressure at the wall of the well, σ_θ, σ_z and σ_r are the tangential stress, the axial stress and the radial stress, respectively, in a cylindrical coordinate, t_O is the characteristic time, σ_O is the instantaneous strength, σ_h is the minimum stress, and η is the poroelastic stress coefficient.

4. Results and discussion

In this section, the proposed model is applied to simulate the time-dependent rock strength failure using data from literature (Al-Ajmi, 2006). Also, model parameters that have direct or indirect relationship with the rock formation time-dependent failure were identified. Figure 3 shows that the internal wellbore pressure has a direct and linear relationship with formation strength failure time. Rock strength failure will occur when the internal wellbore pressure is less than or equal to the lower limit of the drilling fluid pressure. Borehole collapse in this case is a shear influenced borehole failure that occurs at low wellbore pressures. At low borehole pressures, the tangential stress becomes high, which ultimately leads to failure. Rock fragments fall from the borehole walls and often form an elliptic borehole (Aadnoy and Looyeh, 2019).

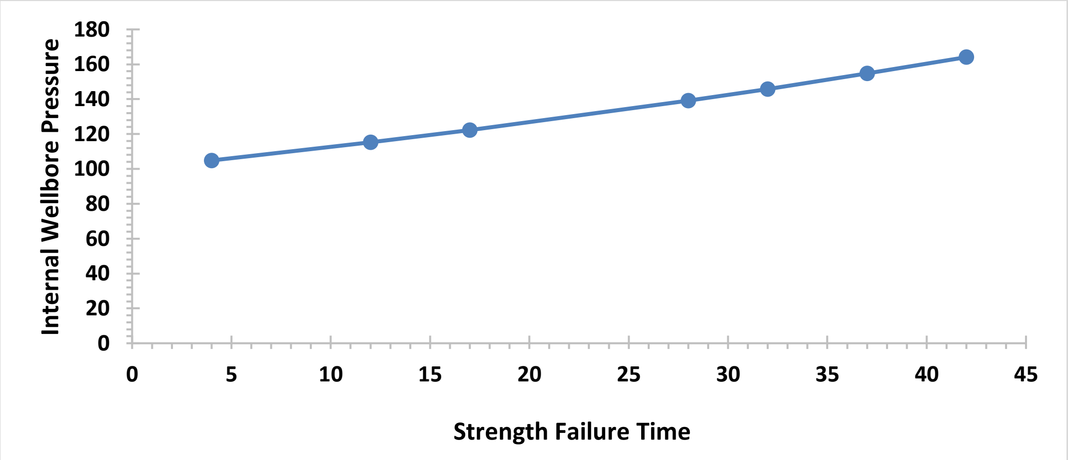

Fig. 3: Effect of internal wellbore pressure on rock strength failure time

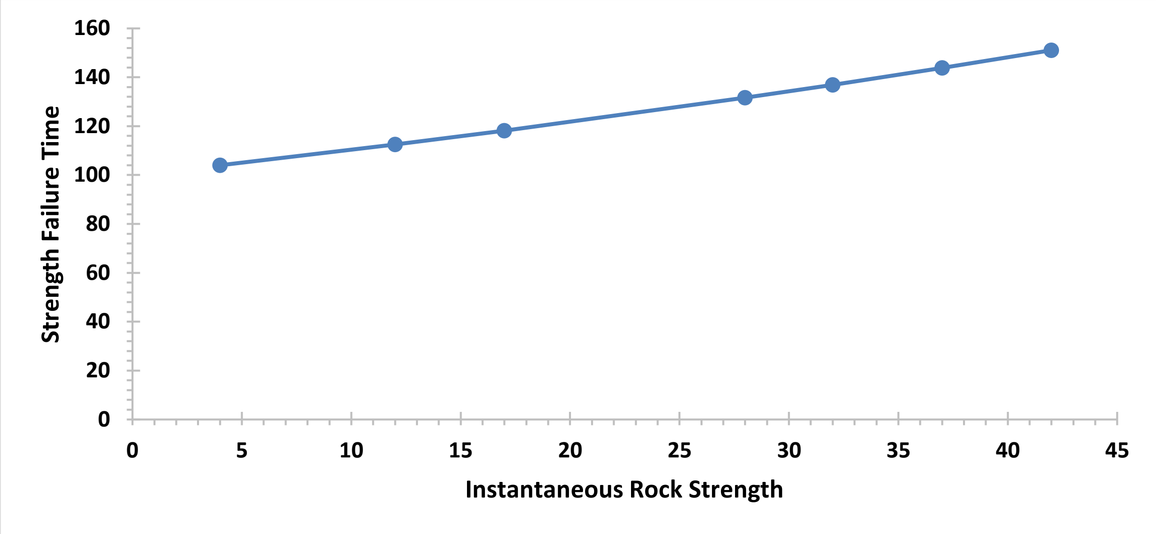

Fig. 4: Relationship between instantaneous rock strength and predicted strength failure time

The constitutive model describes the reaction of a material as a whole without considering time. Figure 4 shows that the formation strength failure time is dependent on the instantaneous rock strength. This result indicates that the instantaneous rock strength has significant impact in wellbore stability, and this parameter is not precisely estimated in many cases. Liu et al. (2020) also considered the instantaneous rock strength in their numerical investigation of time-dependent failure.

It is key to understand the deformation and failure of a rock formation (Gray, 2017) because the rock formation may consist of a continuous fracture, a combination of intact rock and fractures, or solely intact rock. The extent of failure is sensitive to a number of mechanical parameters of which the residual strength of the rock is most critical (Hawkes and McLellan, 1999). The strength of exposed rock formations in the wellbore is likely to decrease over time.

5. Conclusion

Most drilling problems are related to borehole stability problems that introduces lost time in exploration operation and cost millions of dollars. Unforeseen instability events increase risk, reduce safety, cause downtime and can also affect crew. This is due to the failure of the rock around the wellbore that occurs when the effective stresses in the borehole wall exceed the resistance of the rock. In order to overcome wellbore collapse problems, many theoretical and experimental studies have been conducted to investigate various factors such as force anisotropy, fracture mechanisms, and physicochemical interactions between drilling fluids and formations. This study proposed a model for predicting and replicating the subsurface formation failure with time. A linear poroelastic model and a failure time criterion were used in the model development.

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