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Impact of Failure Criterion Choice on Onset Sanding Prediction

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Abstract

Sand production is the migration of formation materials (sand grains) triggered by the flow of reservoir fluids. It is initiated when the failure of reservoir rock occurs around the perforation and/or cavity openings. Subsequently, fluid flow thrust the loose sand grains into the borehole causing problems ranging from reduced productivity to complete sanding up of the well. In this study, sanding potential of unconsolidated sandstone reservoirs was assessed using three sanding criteria developed by incorporating three well known failure criteria, i.e., Hoek-Brown, Murrell's Extension of Griffith and Mohr-Coulomb, into the general stability equation. Using these criteria, the condition for sanding was formulated to be a minimum well flowing pressure at which sanding is expected to occur. Therefore, sand production occurs if field well pressure is less than the predicted well pressure by these criteria. Results indicate that the three failure criteria give different estimates of sanding potential of the studied wells. Hoek-Brown failure criterion predicted the lowest well pressure for all the wells, while Mohr-Coulomb seems to be a bit conservative in terms of the estimated well pressures. Similar trend and close estimate were observed between Murrell's extension of Griffith and Hoek-Brown failure criterion.

***Keywords**:* Sand Production; Failure Criterion; Minimum well Pressure; Well-logs.

1. Introduction

Production of sand along with desired reservoir fluid is a common production challenge in weakly consolidated to unconsolidated sandstone reservoirs which play host to around 70 percent of global oil production [7]. Sand production is the migration of formation materials (sand grains) triggered by the flow of reservoir fluids. It is initiated when the failure of reservoir rock occurs around the perforation, and fluid flow thrust the loose sand grains into the borehole [3]. Depletion of reservoir pressures induces borehole stresses, when the maximum stress at the perforation or cavity opening exceeds the yield strength of the rock at the perforation or cavity opening, the formation rock fails in shear and sand production is initiated.

Associated problems with sand production include: plugging and eventual damage of production and completion equipment, plugging of sand control devices, pipe erosion, ground surface subsidence and environmental challenges of sand treatment and disposal [26]. Sanding is a two stage phenomenon: reservoir rock formation must first fail and followed by transport of formation materials by the flowing fluid.

The first stage is stress induced, and the flowing velocity caused the transportation of the detached sands [25]. Many techniques exist in the literature relating to sand production prediction, a number of which are effective and are still currently being used in the industry. They are based on parameters that indicate stress around an open cavity such as elastic and plastic models and also numerical models that are anchored on finite element methods. Of paramount importance is understanding and use of appropriate failure mechanism when developing a model for predicting sand production [15-16]. Numerous works has been done on sand production based on shear failure mechanism. Such works as Edwards, Sharma, and Charron [12];

Coates and Denoo [9]; Edwards, Joranson, and Spurlin [11] used elastic, brittle failure model to predict sand production, it is quite easy to implement, but does not offer a realistic description of the formation (friable and loose). Other researchers used an elastic plastic material model which gives a close description of the material behaviour. These models requires computational efforts [2,9,21-22].

In using a shear failure mechanism to model sand production, it is good to take note that the result of the model is largely dependent on the choice of failure criterion and yield envelope.

For instance, modeling could be based on Mohr-Coulomb [9,12,19] or Drucker-Prager yield envelope [4-6,11,19,21] and their failure criteria based on any of the following;

- Maximum plastic yield zone size
- Maximum plastic strain
- Maximum stress

Using any of these could lead to different results even though they are all based on the same triaxial test experimental data [20,24]. There exist other models based on tensile failure mechanism, these include; Bratli & Risne [8] and Risnes, Bratli & Horsrud [23], the authors used an assumed ideally plastic friction material to derive normalized pressure gradient. Javani, Aadnoy, Rastergarni, Nadimi, Aghighi & Maleki [17], evaluated the effect of failure criterion on solid production in an Iranian Carbonate reservoir rock by comparing estimated collapse pressure predicted using Mohr-Coulomb and Mogi-Coulomb failure criteria. The results show different estimations of the solid production potential of the studied reservoir. Therefore, it is imperative to assess sanding potential of unconsolidated reservoir rocks using different failure criteria when appropriate failure criterion cannot be assigned to a particular failure of reservoir rocks under study.

2. Sand prediction models

The onset of sand production is the failure of intact rock; thus, if this can be predicted and prevented, then sand production becomes no issue [13]. Therefore, the starting point for a most predictive tool for predicting sanding potentials in unconsolidated sandstones is identifying the stresses at the perforation cavity and failure prediction around the perforation cavity or open hole. The stepwise process in the model development is listed as follows:

1. Identifying the in-situ stress magnitude.
2. Assessing the stress state at the borehole wall or perforation tunnel, having in mind the orientation of the borehole.
3. Applying the appropriate failure criterion.

3. Failure Criteria

In this work, three well known failure criteria were used in estimating minimum well flowing pressure during production to evaluate the potential for sand production in a vertical wellbore drilled through a sandstone reservoir.

3.1. Hoek-Brown Failure Criterion

The Hoek-Brown failure criterion is an empirically derived failure criterion that describes the non-linear increase in peak strength of isotropic rock with increasing confining stress. The original non-linear Hoek Brown failure expression for intact was introduced in 1980 as;

$$\sigma_1 = \sigma_3 + \sqrt{mC_o\sigma_3 + SC_o{}^2} \tag{1}$$

where: *σ_1-major principal stress; σ_3-minor principal stress; C_o- uniaxial compressive strength of intact rock, m and S are dimensionless empirical constants.*

To account for reservoir rocks that are no longer intact, Hoek Brown criterion was updated in response to experience gained with its use and to address the practical limitation of friable rocks [14]. In achieving this, a generalized form of the criterion was reported in 1995 as follows;

$$\sigma_1{}' = \sigma_3{}' + C_o\left(M\frac{\sigma_3{}'}{C_o} + S\right)^{0.5} \qquad (2)$$

where: M – a term introduced to account for broken rock; a – empirical constant to account for system's bias towards hard rock.

3.2. Murrell's extension of Griffith failure criterion

The original Griffith criterion is applicable to plane stress and plain strain cases both in tension and shear. The criterion is given as;

$$(\sigma_1{}' - \sigma_3{}')^2 = -8T_o(\sigma_1{}' + \sigma_3{}') \qquad (3)$$

In 1963 Murrell extended the Griffith theory to a three-dimensional case and the result presented below:

$$(\sigma_1{}' - \sigma_3{}')^2 = C_o(2\sigma_1{}' + \sigma_3{}') \qquad (4)$$

3.3. Mohr-Coulomb

The Mohr-Coulomb failure criterion is a common failure criterion used in most rock mechanics and formation engineering applications. The criterion is expressed as:

$$\sigma_1{}' = 2\frac{S_o Cos\theta}{1 - sin\theta} + \sigma_3{}'\frac{(1 + sin\theta)}{(1 - sin\theta)} \qquad (5)$$

As earlier mentioned, sand production from shear dominated failure occurs when the maximum stress at the wellbore exceeds the yield strength of the formation. The two major stresses in the borehole environment as presented by [13] are the tangential stress and the radial stress given below;

$$\sigma_r{}' = (1 - \alpha)P_{wf} \qquad (6)$$

$$\sigma_\theta{}' = 2\sigma_h - \alpha\frac{1 - 2\nu}{1 - \nu}\bar{P} - \left(1 + \alpha\frac{\nu}{1 - \nu}\right)P_{wf} \qquad (7)$$

Considering a common case of borehole failure when $\sigma_\theta \geq \sigma_v \geq \sigma_r$, and taking tangential stress (Eq. 7) to be the maximum stress at the borehole wall, stability occur when the stress estimated by Eq. 7 is equal to the one estimated by each of the aforementioned failure criteria. i.e. Eq. 2, 4 & 5 written in cylindrical coordinates. That is;

For the Hoek-Brown failure criterion.

Substituting equation 6 for $\sigma_r{}'$ in each of equations (8a) and solving for well pressure, the minmum well flowing pressure at failure is given below;

$$2\sigma_{h\,(t)} - \alpha\frac{1 - 2\nu}{1 - \nu}\bar{P} - \left(1 + \alpha\frac{\nu}{1 - \nu}\right)P_{wf} = \sigma_r{}' + C_o\left[M\frac{\sigma_r{}'}{C_o} + S\right]^{0.5} \qquad (8a)$$

If $\frac{1-2\nu}{1-\nu} = n$

$$(2 - \propto n)^2 P_{wf}{}^2 - P_{wf}[MC_o(1 - \propto) - 2(2 - \propto n)(\propto n\bar{P} - 2\sigma_h)] + (\propto n\bar{P} - 2\sigma_h)^2 - SC_o{}^2 = 0$$

Using the general quadratic equation given as Eq. 9:

$$x = -\frac{b \pm \sqrt{b^2 - 4ac}}{2a} \qquad (9)$$

$a = (2 - \propto n)^2$

$b = [MC_o(1 - \propto) - 2(2 - \propto n)(\propto n\bar{P} - 2\sigma_h)]$

$c = (\propto n\bar{P} - 2\sigma_h)^2 - SC_o{}^2$

Let $(2 - \propto n) = R$ $\quad (\propto n\bar{P} - 2\sigma_h) = Y$ $\quad (1 - \propto) = U$

Then;

$a = R$ $\quad b = MC_oU - 2RY$ $\quad C = Y^2 - SC_o{}^2$

Therefore, P_{wf} is given as;

$$P_{wf} = \frac{-(MC_oU - 2RY) \pm \sqrt{MC_oU - 2RY^2 - 4R^2(Y^2 - SC_o{}^2)}}{2R^2} \qquad (10)$$

Hoek-Brown material constant M and S were reported according to Hoek *et al.* [14] as

$$M = m_i exp\left(\frac{GSI - 100}{24 - 14D}\right) \qquad (11)$$

$$S = exp\left(\frac{GSI-100}{9-3D}\right) \quad (12)$$

For Mohr-Coulomb failure criterion

$$2\sigma_h - \alpha\frac{1-2\nu}{1-\nu}\bar{P} - \left(1+\alpha\frac{\nu}{1-\nu}\right)P_{wf} = 2\frac{S_o Cos\theta}{1-sin\theta} + \sigma_r{}'\frac{(1+sin\theta)}{(1-sin\theta)} \quad (8b)$$

Substituting equation 6 for $\sigma_r{}'$ in each of equations (8b) and solving for well pressure, the minmum well flowing pressure at failure is given below;

$$\frac{2\sigma_h(1-\nu) - \alpha(1-2\nu)\bar{P} - C_o(1-\nu)}{1-\nu} = \left[\frac{2-2\nu+2\alpha\nu-\alpha(1+sin\theta)}{(1-\nu)(1-sin\theta)}\right]P_{wf} \quad (13)$$

$$P_{wf} = \frac{[2\sigma_h(1-\nu) - \alpha\bar{P}(1-2\nu) - C_o(1-\nu)][1-sin\theta]}{2[1-\nu+\alpha\nu]+\alpha(1+sin\theta)} \quad (14)$$

For Murrell's Extension of Griffith failure criterion

$$\left(2\sigma_h - \alpha\frac{1-2\nu}{1-\nu}\bar{P} - \left(1+\alpha\frac{\nu}{1-\nu}\right)P_{wf} - \sigma_r{}'\right)^2 = C_o\left[2\left(2\sigma_h - \alpha\frac{1-2\nu}{1-\nu}\bar{P} - \left(1+\alpha\frac{\nu}{1-\nu}\right)P_{wf}\right) + \sigma_r{}'\right] \quad (8c)$$

Substituting equation 6 for $\sigma_r{}'$ in each of equations (8c) and solving for well pressure, the minmum well flowing pressure at failure is given below;

$$\left[2 - \frac{2\propto}{1-\nu} + \propto^2 + 5\propto\nu(1-\nu) - \propto\omega - \frac{\alpha^2\nu\omega}{1-\nu}\right]P_{wf}{}^2 - [(2-\propto n)(4\sigma_h - 2\propto n\bar{P}) + C_o(1+\propto\beta)]P_{wf} + (\propto n\bar{P} + 2\sigma_h)^2 - 2C_o(2\sigma_h - \propto n\bar{P}) \quad (16)$$

Applying the general quadratic equation

$y = \frac{-b\pm\sqrt{b^2-4ac}}{2a}$ therefore, $P_{wf} = P_{wf} = \frac{-b\pm\sqrt{b^2-4ac}}{2a}$

where:

$$\boldsymbol{a} = \left[2 - \frac{2\propto}{1-\nu} + \propto^2 + 5\propto\nu(1-\nu) - \propto\omega - \frac{\alpha^2\nu\omega}{1-\nu}\right]$$

$$b = [(2-\propto n)(4\sigma_h - 2\propto n\bar{P}) + C_o(1+\propto\beta)]$$

$$c = (\propto n\bar{P} + 2\sigma_h)^2 - 2C_o(2\sigma_h - \propto n\bar{P})$$

4. Estimate of input parameters

To apply the developed models proposed in the methodology, estimates of in-situ stresses, minimum horizontal stress, average reservoir pressure, Poisson's ratio, poro elastic constant, uniaxial compressive strength together with the Hoek-Brown material constants are required. Generally, the parameters consist of elastic and strength characteristics of the rocks as well as the pore pressures. The details of the ideologies and correlations used in this work for estimates of the aforementioned parameters is presented in Khaksar, Taylor, Fang, Kayes, Salazar & Rahman [18] and the output results are corresponding to each wells were only presented.

4.1. Case study

Five hypothetical data from Almisned [1] was used to investigate the potential for solid production using different failure criteria. The data include different types of petrophysical logs such as density log and sonic compressive and shear travel time (Table 1). The initial reservoir pressure was given, and the field imposed well pressure was set at 2000 psi. From these logs, using correlations from Khaksar *et al.* [18], rock mechanical properties were estimated and presented in Figures 1 & 2, the results serve as input data for the developed sanding criteria models.

Table 1. Input data for the cases studied

Case A					Case B				
Depth (ft)	Initial Pressure (psia)	Log compressional time (mic.sec/ft)	Log shear time (mic.sec/ft)	Log bulk density (g/cm^3)	Depth (ft)	Initial Pressure (psia)	Log compressional time (mic.sec/ft)	Log shear time (mic.sec/ft)	Log bulk density (g/cm^3)
3000	2400	88	121	2.56	3000	2400	87	120	2.56
3250	2600	80	118	2.1	3250	2600	79	117	2.1
3500	2800	71	111	2	3500	2800	71	111	2
3750	3000	70	100	2.5	3750	3000	74	105	2.5
4000	3200	65	94	2.2	4000	3200	72	104	2.2

Case C					Case D				
Depth (ft)	Initial Pressure (psia)	Log compressional time (mic.sec/ft)	Log shear time (mic.sec/ft)	Log bulk density (g/cm^3)	Depth (ft)	Initial Pressure (psia)	Log compressional time (mic.sec/ft)	Log shear time (mic.sec/ft)	Log bulk density (g/cm^3)
3000	2400	85	121	2.56	3000	2400	85	125	2.56
3250	2600	84	111	2.1	3250	2600	92	128	2.1
3500	2800	75	110	2	3500	2800	85	130	2
3750	3000	78	107	2.5	3750	3000	90	124	2.5
4000	3200	72	100	2.2	4000	3200	80	115	2.2

Case C				
Depth (ft)	Initial Pressure (psia)	Log compressional time (mic.sec/ft)	Log shear time (mic.sec/ft)	Log bulk density (g/cm^3)
3000	2400	90	134	2.56
3250	2600	100	130	2.1
3500	2800	85	131	2
3750	3000	90	127	2.5
3000	2400	90	134	2.56

6. Results and discussion

In investigating the potential for sand production for the cases presented, predicted minimum well pressures from the three (3) failure criteria were compared to the field-imposed well pressure since we assume that shear failure corresponds to the initiation of sand production. Figures 1a & b shows the stress profiles for cases A to E, including the pore pressure trends and the rock mechanical properties estimated.

From Figures 2a and b for cases A to E respectively, it can be observed that minimum well pressure predicted by Mohr-Coulomb failure criterion is higher than the minimum well pressures predicted by Hoek-Brown and Griffith failure criteria. This is in agreement with the reported work of Javani *et al.* [17], in which he reported the result of comparing critical collapse pressure predicted from Mohr-Coulomb with Mogi-Coulomb predicted. Generally, from the current study, the predicted minimum well pressure from Hoek-Brown and Murrell's extension of Griffith failure criterion compared favorably, even with field imposed well-pressure. They both showed consistency and similar trends for all the cases analyzed, while minimum well pressure predicted using the Mohr-Coulomb failure criterion is somewhat conservative in terms of predictive accuracy.

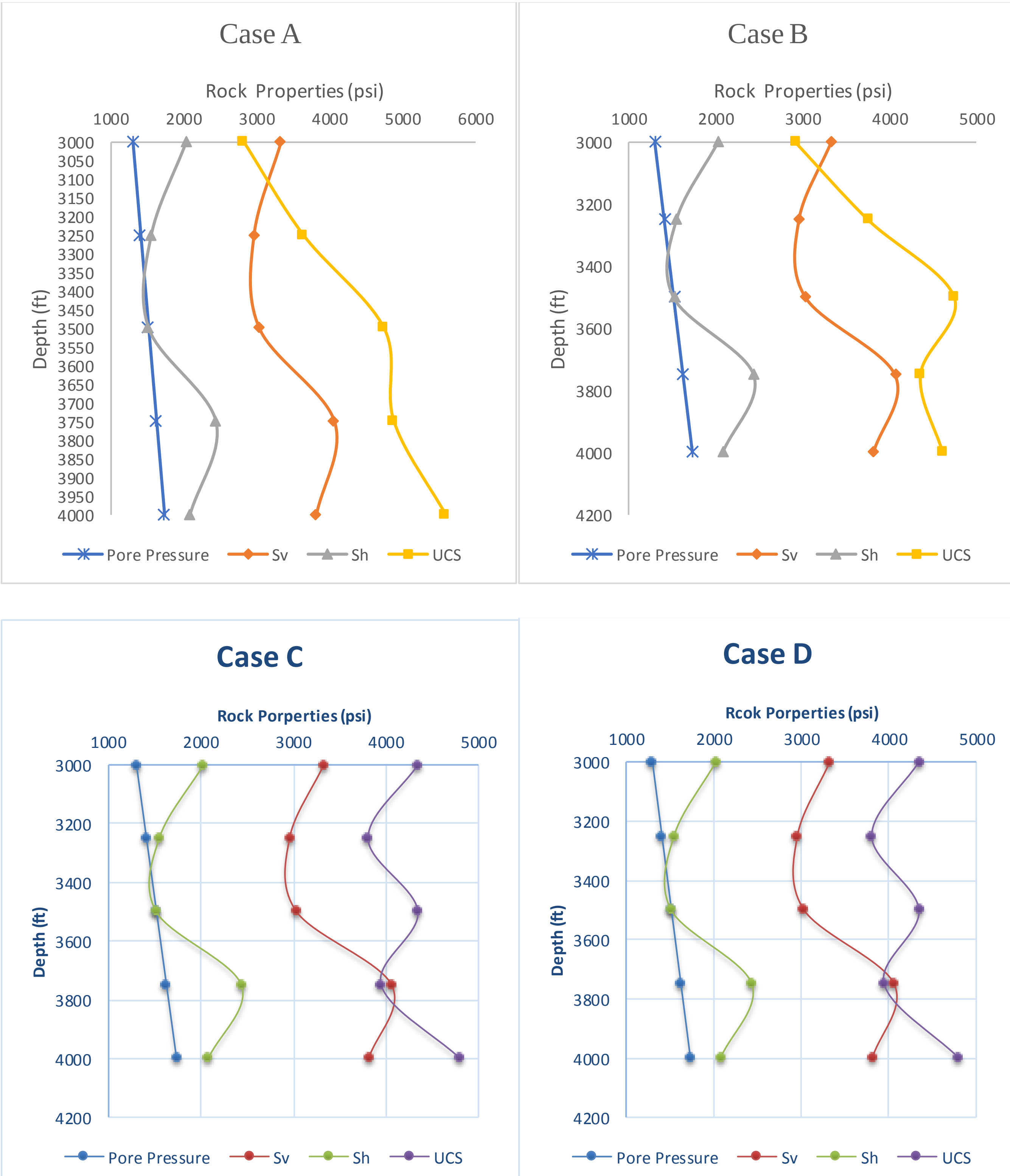

Figure 1a Estimated mechanical properties of the case studies, pore pressure and stress profile

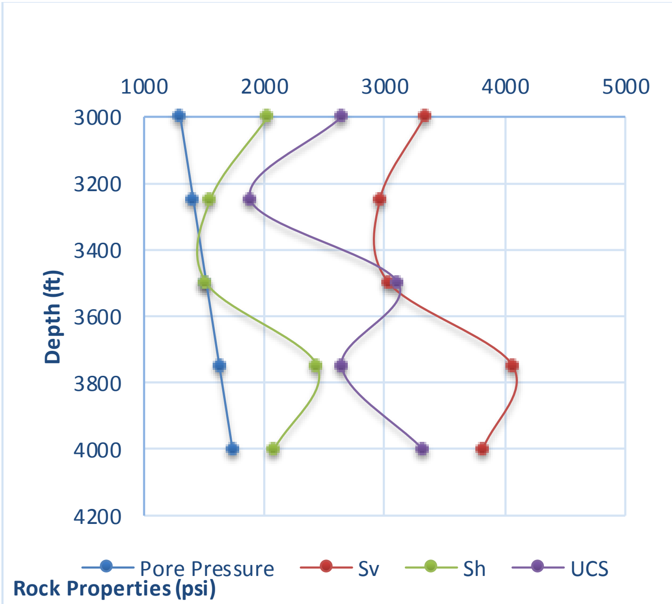

Figure 1b Estimated mechanical properties of the case E, pore pressure and stress profile

The choice of failure criterion depends on the ductility and brittleness of the reservoir rock under analysis. To understand a failure phenomenon, a specific and compatible criterion must be applied. While some rocks such as sandstone, fail in shear, others such as clay, fails as a result of plastic deformation. However, the understanding of the ductility and brittleness or the structural geology of such rock may not be available when determining the post drilling stability of reservoir rocks prior to completion.

Numerous empirical criteria have been established to predict reservoir rocks, and formation failure such are those employed in this study, but it is essential to understand the physical and practical interpretation of these criteria before they are been applied. Mohr-Coulomb failure criterion offers a more conservative, easy to use and less complex correlation with input parameters that can be easily estimated.

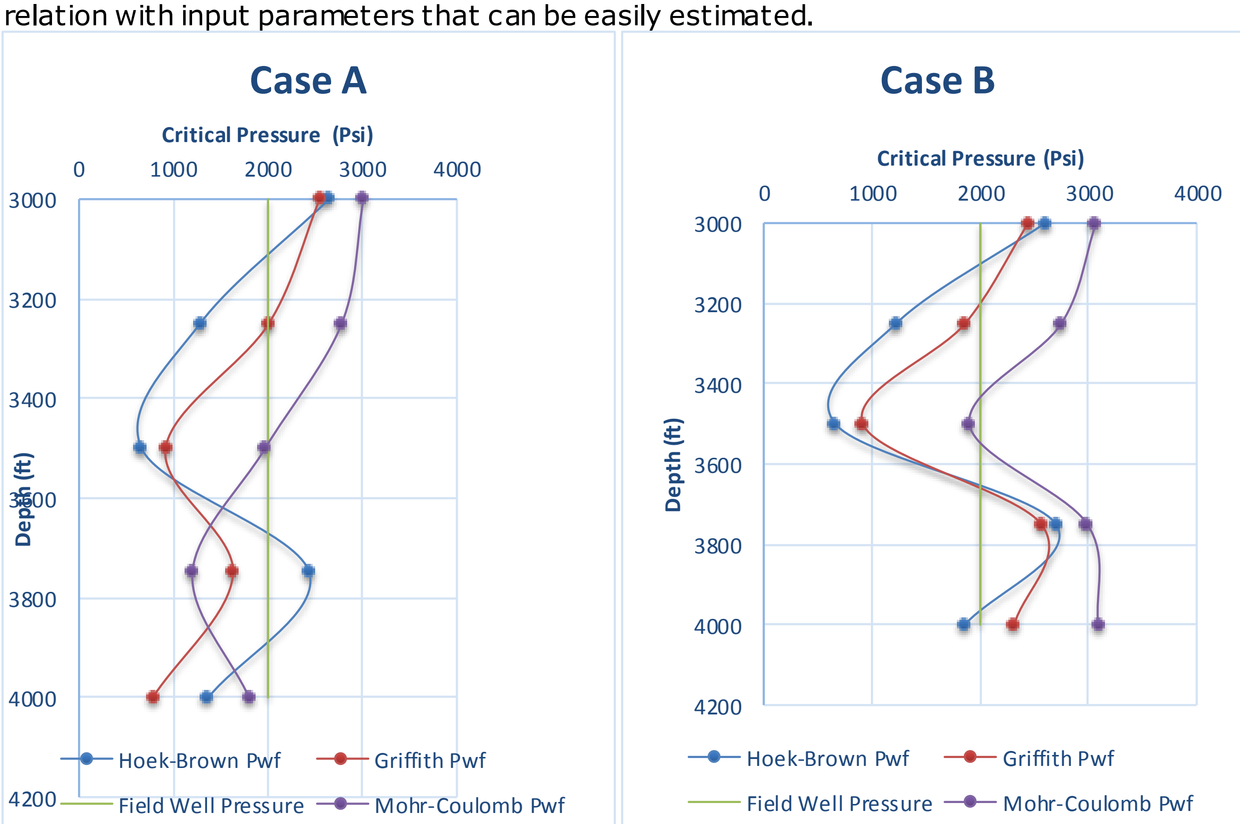

Figure 2a. Predicted minimum well pressure using different failure criteria for cases A and B

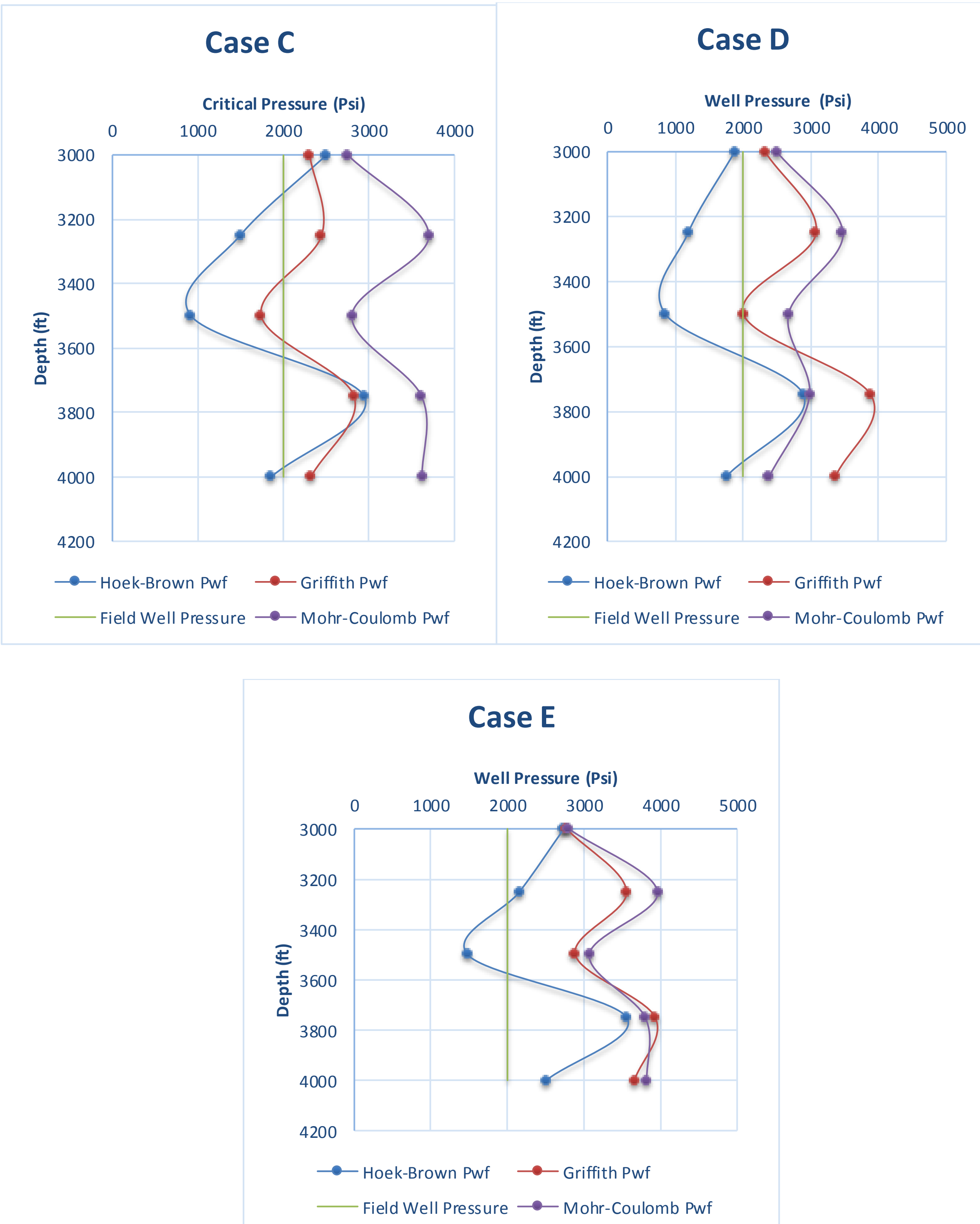

Figure 2b. Predicted minimum well pressure using different failure criteria for cases C, D and E

But can only be used to account for the failure of intact rocks, Hoek-Brown failure criterion can better describe the material quality of reservoir rocks at failure but with additional empirical constants that accurately estimating them may pose a serious question. Mogi-Coulomb introduced a third stress parameter in terms of the intermediate stress which was assumed to be negligible by the other two criteria but also introduced two new constants that make it application complex. In other words, since the results of sanding prediction with different failure criteria demonstrates different results, but generally show similar trends, it is proposed that when the brittleness and ductility cannot be ascertained, different sand onset prediction models should be used to predict sanding onset. This will allow the establishment of a stable margin of operation that will not induce sand failure.

7. Conclusions

In this study, sand production criteria assuming shear failure as the dominant failure mechanism was developed using three (3) well known failure criteria. These criteria were used to assess the potential for sand production in five hypothetical case studies. The condition for sand production was formulated to be minimum well pressure at/or below which sand is to be expected. From the results, minimum well pressures vary with the choice of failure criterion, Hoek-Brown and Murrell's extension of Griffith failure criteria showed consistency and similar trends while Mohr-Coulomb failure criterion predicted (conservative) higher minimum well pressure at failure than the two other criteria. For best practice, it is proposed that sanding onset predictive tools anchored on several failure criteria should be used to assess sand production potential when the ductility and brittleness of the reservoir rock under analysis is not known.

Nomenclature

$m\ =\ material\ constant\ in\ Hoek-Brown\ criterion, dimensionless$
$M\ =\ material\ constant\ in\ Hoek-Brown\ criterion, dimensionless$
$m\ =\ material\ constant\ in\ Hoek-Brown\ criterion, dimensionless$
$S =\ material\ constant\ in\ Hoek-Brown\ criterion, dimensionless$
$C_0 = \text{Rock Strength} = \text{Uniaxial compressive strength}, m/Lt^2, psi$
$T_0 = \text{Rock Strength}, m/Lt^2, psi$
$UCS = Uniaxial\ compressive\ strength\ m/Lt^2, psi$
$Pwf\ =\ bottom\ hole\ flowing\ pressure, m/Lt^2, psi$
$n\ =\ constant, dimensionless$
$P\ =\ average\ reservoir\ pressure, m/Lt^2, psi$
$r\ =\ radial\ coordinate, L, ft$
$x\ =\ coordinate, L, ft$
$y\ =\ coordinate, L, ft$
$z\ =\ coordinate, L, ft$
$\alpha\ =\ Biot's\ constant, dimensionless$
$\theta\ =\ angle, dimensionless, radian$
$v\ =\ Poisson's\ ratio, dimensionless, fraction$
$\rho f\ =\ density\ of\ gas, m/L^3, lbm/ft^3$
$\sigma\ =\ total\ normal\ stress, m/Lt^2, psi$
$\sigma'\ =\ effective\ stress, m/Lt^2, psi$
$\sigma 1\ =\ maximum\ principal\ stress, m/Lt^2, psi$
$\sigma 2\ =\ intermediate\ principal\ stress, m/Lt^2, psi$
$\sigma 3\ =\ minimum\ principal\ stress, m/Lt^2, psi$
$\sigma h\ =\ total\ minimum\ horizontal\ stress, m/Lt^2, psi$
$\sigma' h = Sh =\ effective\ minimum\ horizontal\ stress, m/Lt^2, psi$
$\sigma H\ =\ total\ maximum\ horizontal\ stress, m/Lt^2, psi$
$\sigma' H\ =\ effective\ maximum\ horizontal\ stress, m/Lt^2, psi$
$\sigma r\ =\ total\ radial\ stress, m/Lt^2, psi$
$\sigma' r\ =\ effective\ radial\ stress, m/Lt^2, psi$
$\sigma' v\ = Sv =\ effective\ vertical\ stress, m/Lt^2, psi$
$\sigma x\ =\ total\ normal\ stress\ in\ x\ direction, m/Lt^2, psi$
$\sigma' x\ =\ effective\ normal\ stress\ in\ x\ direction, m/Lt^2, psi$

$\sigma y\ =\ total\ normal\ stress\ in\ y\ direction, m/Lt^2, psi$
$\sigma z\ =\ total\ normal\ stress\ in\ z\ direction, m/Lt^2, psi$
$\sigma' z\ =\ effective\ normal\ stress\ in\ z\ direction, m/Lt^2, psi$
$\sigma' \theta\ =\ effective\ tangential\ stress, m/Lt^2, psi$
$a = empirical\ constant\ to\ account\ for\ system's\ bias\ towards\ hard\ rock$

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