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Technical Note

The role of rock strength criteria in wellbore stability and trajectory optimization

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1. Introduction

Studying behavior of rocks and soil was and also is the main subject for lots of studies. Many efforts have been done to characterize the behavior of rocks and until now numerous strength criteria have been proposed.

The role of the rock strength criterion in petroleum engineering is very important. It is used to calculate the minimum mud pressure required for ensuring wellbore stability,[1] and to determine the optimal well trajectory to minimize the risk of sand production.[2]

Some studies have been done to compare between some of those criteria and determine the best one or propose a new one to use in petroleum engineering. The results of those studies were based on a special case, however, it seems to be necessary to compare between those criteria in different inclinations and azimuths of well. Furthermore, in some studies, it has been stated that the strength criterion has not significant role in determining the optimal well trajectory.[3–8] Our study will criticize this statement and will show that is not completely true. Finally, comparing between some of famed criteria in minimum mud pressure prediction and well trajectory optimization, the paramount criterion will be recommended.

2. Rock strength criteria

The rock mechanics literature is rich with a number of shear strength criteria that have been developed. All strength criteria can be classified into two general categories based on the intermediate principal stress (σ_2): (1) σ_2-independent strength criteria such as Mohr–Coulomb or Hoek–Brown criteria and (2) σ_2-dependent strength criteria such as Drucker–Prager, Modified Lade and Mogi–Coulomb criteria. The strength criteria of the first category implicitly ignore the strengthening effect of the intermediate principal stress (σ_2). In contrast, the strength criteria of the second category incorporate the intermediate principal stress.

Some criteria of the second category, which sometimes frequently used in geomechanical analysis (Drucker–Prager criterion for instance), have been developed before the construction of the first apparatus that enabled polyaxial tests. Those criteria applied based on the assumption that a failure envelope, derived from triaxial test data ($\sigma_1 > \sigma_2 = \sigma_3$), represents the failure under polyaxial stress states ($\sigma_1 > \sigma_2 > \sigma_3$). However, this assumption sometimes leads to large errors in predicting the strength of rocks and also, in assessing the rock material properties.

The Mohr–Coulomb criterion has been reported to be very

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Table 1
Different shear failure criteria.

Mohr–Coulomb criterion	$\tau = C_O + \sigma_{m,2}\,.\ \tan\varphi$	$\tau = [(\sigma_1 - \sigma_3).\ \cos\varphi]/2$ $\sigma_{m,2} = (\sigma_1 + \sigma_3)/2 - [(\sigma_1 - \sigma_3).\ \sin\varphi]/2$
Dracker–Prager criterion	$\tau_{oct} = k + m\,\sigma_{oct}$	$\tau_{oct} = [\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2}]/3$ $\sigma_{oct} = (\sigma_1 + \sigma_2 + \sigma_3)/3$
Modified Lade criterion	$(I''_1)^3/(I''_3) = 27 + \eta$	$I''_1 = (\sigma_1 + S_I - P_0) + (\sigma_2 + S_I - P_0) + (\sigma_3 + S_I - P_0)$) $I''_3 = (\sigma_1 + S_I - P_0).\ (\sigma_2 + S_I - P_0).\ (\sigma_3 + S_I - P_0)$
Mogi-Coulomb criterion	$\tau_{oct} = a + b\,\sigma_{m,2}$	$\tau_{oct} = [\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2}]/3$ $\sigma_{m,2} = (\sigma_1 + \sigma_3)/2$

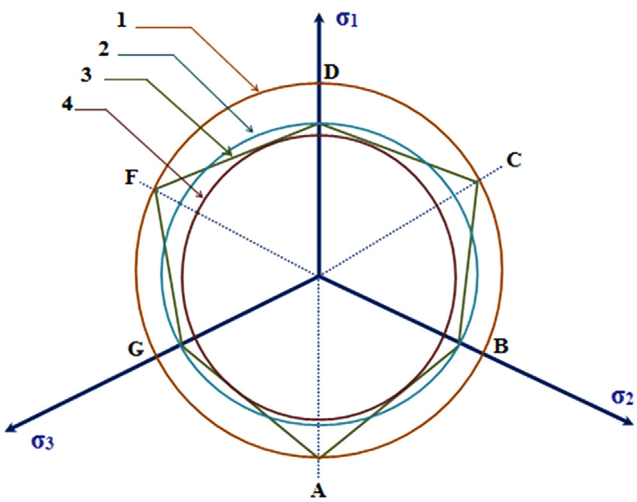

Fig. 1. Different linear forms of Drucker–Prager criterion in π-plane. [№1-Outer circle, №2-Middle circle, №4-Inner circle] and Mohr–Coulomb criterion [№3].

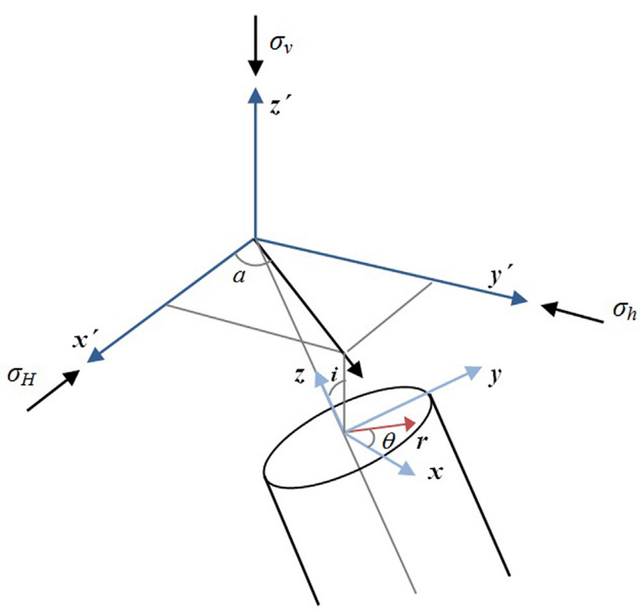

Fig. 2. Axes and inclination and direction angles of the inclined well.

conservative in predicting wellbore stability, whereas the Drucker–Prager criterion has been found to be overly optimistic about wellbore stability.[9–15] Regarding this fact, Ewy in 1999 proposed the Modified Lade criterion [10] and then, in 2005, Al-Ajmi and Zimmerman developed the Mogi–Coulomb rock failure law.[16] These criteria showed more acceptable results in the prediction of the minimum mud weight. These criteria with their parameters are shown in Table 1.

In the above table, the quantities σ_1, σ_2 and σ_3 are principal stresses and the parameters C_o and φ are cohesion strength and friction angle, respectively. The parameters k, m, S_I, η , a and b are also material constants and can be estimated based on the Mohr–Coulomb parameters, internal friction angle (φ) and rock cohesion strength (C_o).

There are different versions of the Drucker–Prager criterion which come from comparing this criterion with the Mohr–Coulomb criterion on π-plane. In Fig. 1 these three versions of this criterion are plotted in the π-plane. As can be seen in this figure, the criterion has a circular shape on the deviatoric plane. This feature gives the numerical stability to this criterion when conducting an elastic–plastic analysis [17] and precisely because of this feature, this criterion more widely used in geomechanics.

3. Geomechanical stress model

In the case of collapse problem analysis, analytical near wellbore stress model is a standard method. We use this method to quantify the effect of rock strength criteria in minimum mud pressure prediction and trajectory optimization.

To do an accurate analysis, it is necessary to choose an appropriate model of rock behavior. The elastic model in comparison with the elasto–plastic model is conservative [18] and the elasto-plastic model in stability analysis is more realistic than a simple elastic, since rocks rarely behave in a purely elastic manner up to ultimate failure. However, specifying the allowable extent of the plastic deformation before instability occurs is difficult and somewhat arbitrary. Furthermore, the poor definition of input parameters, in-situ stresses and material constants, only justifies a simple elastic model to be practically applicable.[19] So in engineering practice, a linear elastic model in combination with a rock strength criterion commonly used to determine the minimum mud pressure required for ensuring wellbore stability.[1]

By assuming an elastic medium with constant pore pressure, a Biot's coefficient of 1 and plane strain normal to the borehole axis and a well with impermeable wellbore wall, the effective stresses around the borehole (Fig. 2) could be calculated by modifying the equations which were published by Kirsch (1898). The stresses are given by: