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Comparison of rock failure criteria in predicting borehole shear failure

Reza Rahimi *, Runar Nygaard

Department of Geosciences and Geological and Petroleum Engineering, Missouri University of Science and Technology, 129 McNutt, 1400 N. Bishops Ave., Rolla, MO 65409, United States

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ABSTRACT

Selection of the appropriate rock failure criteria is one of the key steps in determining minimum required mud weight in wellbore stability analysis. Numerous failure criteria have been used for rock failure analysis, but there is no common agreement of which failure criterion to select. In this paper, thirteen failure criteria used in predicting borehole shear failure were evaluated for four field cases. In a comparison of the results with actual field failure cases, Tresca, Von Mises, and Inscribed Drucker–Prager overestimated the rock breakout and predicted the highest required minimum required mud weight for all cases. Also the results of these criteria are significantly higher than the actual borehole shear failure. Circumscribed Drucker–Prager underestimated the rock breakout and predicted the lowest bound of the minimum required mud weight in most cases which is mainly less than actual onset of borehole breakout. The minimum required mud weights determined by Modified Lade, Modified Wiebols–Cook and Mogi–Coulomb is above, but close to, the onset of breakout based on the field reported failure cases. This means that using of any of these three criteria in wellbore stability analysis could be a safe approach. Furthermore, Modified Lade, Modified Wiebols–Cook and Mogi–Coulomb provided similar results for all studied cases, so these failure criteria may be used interchangeably.

1. Introduction

Determining the appropriate minimum required mud weight by rock failure analysis is an essential step to control wellbore instability. To determine wellbore failure stresses, rock strength must be known, an appropriate constitutive model should be selected, and an accurate rock failure criterion must be chosen. There are numerous rock failure criteria that have been used in wellbore stability analysis to determine the minimum required mud weight, as outlined below, but there is no agreement on which failure criterion should be used in practical wellbore stability analysis.

The previous studies on evaluation of rock failure criteria can be divided in two groups. First the group addressed how well the failure criteria can be fitted to triaxial test data. Seven different rock failure criteria were evaluated by Colmenares and Zoback[1] based on fitting polyaxial test data, and they concluded that the Modified Lade and the Modified Wiebols–Cook fit best with polyaxial tests. Quantitative comparison of the six rock failure criteria was done by Benz and Schwab[2] to determine which criterion gives the best fit with polyaxial test data. The second group of previous studies focused on minimum mud weight prediction for different failure criteria. Mclean and Addis[3] compared Mohr–Coulomb and different forms of Drucker–Prager to predict the minimum required mud weight. Results showed that a criterion can predict a realistic result in one situation but give unrealistic results for other conditions. The Mohr–Coulomb failure criterion was recommended for wellbore stability analysis because of the more realistic results compared with the different forms of Drucker–Prager.[3] The Modified-Lade failure criterion was developed by Ewy[4] and the advantages of this new criterion over Mohr–Coulomb and Drucker–Prager was presented. The borehole breakout pressure was predicted by Nawrocki[5] based on evaluation of four rock failure criteria and the Modified Lade criterion was recommended. Some of the previous studies evaluated failure criteria both in fitting polyaxial test data and estimation of the minimum required mud weight. Al Ajmi and Zimmerman[6,7] developed the linear form of Mogi–Coulomb and compared that with the Mohr–Coulomb failure criterion. They proposed the use of Mogi–Coulomb over Mohr–Coulomb with regard to fitting polyaxial test data as well as prediction of the borehole breakout pressure. Three rock failure criteria were compared by Yi et al.[8] based on minimum mud weight estimation, and it was concluded that the failure criterion which best fits the polyaxial test data can better describe rock failure, and therefore provide more reliable results for the minimum required mud weight. Based on their results, no specific failure criterion can consistently estimate higher or lower minimum mud weight compared with the other failure criteria.[8] Corresponding parameters of five failure criteria

* Corresponding author.
E-mail address: rr3q8@mst.edu (R. Rahimi).

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were determined by Zhang et al.[9] using triaxial test data, where Mogi–Coulomb and Hoek–Brown criteria were recommended for wellbore stability analysis.

The review reveals that a few failure criteria, including Stassi d'Alia, have not been considered.[1–9] Some of the previous studies were only focused on quantitative comparison or determination of the best fitting parameters for the different rock failure criteria based on triaxial test results data.[1,2] Also, in some previous studies, hypothetical data sets were used for the stress data, rock mechanical properties, and well depth which caused results to be unrealistic in some cases.[5,8,9] For example, true vertical well depths of 12,000 m or 28,000 m, were chosen for analysis and therefore, the results were not directly applicable to the stability of wells for petroleum exploitation.[9] Furthermore, quantitative comparisons have been previously studied on selected failure criteria, but few evaluations of the failure criteria were based on typical petroleum related situations. Finally, estimated shear failure by different rock criteria were not compared with the actual field case shear failure. Rahimi and Nygaard[10] addressed the first three challenges by statistical comparison of the result of different rock failure criteria for different lithology using the field data set from Rulison field in western Colorado.[11] They investigated similarities and differences of rock failure criteria for prediction of the minimum required mud weight under different rock lithology and stress data.

The present paper is focused on the last shortcoming of previous studies, which is the lack of comparison between the estimated borehole shear failure under compressive stresses by different criteria and actual field reported shear failure. Thirteen of the most common rock failure criteria were evaluated based on prediction of borehole failure using the data set from four field cases. The results of failure criteria were compared with actual field case shear failure in order to investigate using which of these failure criteria could be a safe approach in wellbore stability analysis. There are many different factors which affect stability of borehole including anisotropic rock properties, weakness planes, chemically induced plasticity, time dependent behavior, but the purpose of this study was to evaluate the rock failure criteria based on the classical shear failure in a linear poro-elastic material using the Kirsch's equations which gives the maximum differential stress concentration on the borehole wall.

2. Rock failure criteria

A shear rock failure criterion specifies the stress conditions at failure. Common rock failure criteria can be classified based on two main characteristics-linearity (or nonlinearity) of the governing equation, and consideration (or neglect) of the effect of intermediate principal stress. One group of the rock failure criteria have a linear form, such as Tresca, while other failure criteria have a nonlinear form, such as Drucker–Pager. The second characteristic involves considering the effect of intermediate principal stress on rock strength. Mohr–Coulomb and Hoek–Brown are examples of

Table 1
Rock failure criteria.

Failure criteria	Governing equation	Linearity	The effect of intermediate principal stress (σ_2)
Mohr–Coulomb (MC)	$\sigma_1 = q\sigma_3 + C_0$ $q = \frac{1+\sin\phi}{1-\sin\phi},\ C_0 = \frac{2c\cos\phi}{1-\sin\phi}$	Linear	No
Mogi–Coulomb (MG)	$\tau_{oct} = a + b\sigma_{m,2}$ $a = \frac{2\sqrt{2}}{3}\frac{C_0}{q+1},\ b = \frac{2\sqrt{2}}{3}\frac{q-1}{q+1}$	Linear	Yes
Tresca (TR)	$\frac{(\sigma_1-\sigma_3)}{2} = c = \tau_{max},\ \frac{C_0}{2} = c$	Linear	No
Von Mises (VM)	$\sqrt{J_2} = \sqrt{\frac{(\sigma_1-\sigma_3)^2+(\sigma_2-\sigma_3)^2+(\sigma_1-\sigma_3)}{6}} = \frac{C_0}{3}$	Non linear	Yes
Ins. Drucker–prager (IDP)	$\sqrt{J_2} = k + \alpha J_1$ $\alpha = \frac{3\sin\phi}{\sqrt{9+3\sin\phi^2}},\ k = \frac{3C_0\cos\phi}{2\sqrt{q}\sqrt{9+3\sin\phi^2}}$	Non linear	Yes
Cir. Drucker–prager (CDP)	$\sqrt{J_2} = k + \alpha J_1$ $\alpha = \frac{\sqrt{3}(q-1)}{(2+q)},\ k = \frac{\sqrt{3}C_0}{2+q}$	Non linear	Yes
Hoek–Brown (HB)	$\sigma_1 = \sigma_3 + \sqrt{mC_0\sigma_3 + sC_0^2}$	Non linear	No
Modified Lade (ML)	$\frac{I_1^3}{I_3} = \eta_1 + 27$ $S = \frac{c}{\tan\phi},\ \eta = \frac{4\tan^2\phi(9-7\sin\phi)}{(1-\sin\phi)}$	Non linear	Yes
Modified Wiebols–Cook (MWC)	$\sqrt{J_2} = A + BJ_1 + CJ_1^2$ $C = \frac{\sqrt{27}}{2C_1+(q-1)\sigma_3-C_0}\left(\frac{C_1+(q-1)\sigma_3-C_0}{2C_1+(2q-1)\sigma_3-C_0} - \frac{q-1}{q+2}\right)$ $C_1 = (1+0.6\mu)C_0$ $B = \frac{\sqrt{3}(q-1)}{q+2} - \frac{C}{3}[2C_0 + (q+2)\sigma_3]$ $A = \frac{C_0}{\sqrt{3}} - \frac{C_0}{3}B - \frac{C_0^2}{9}C$	Non linear	Yes
Griffith (GR)	$(\sigma_1-\sigma_3)^2 = 8T_0(\sigma_1+\sigma_3)$ $\sigma_3 = -T_0\ if\ \sigma_1+3\sigma_3<0,\ T_0 = \frac{C_0}{8}$	Non linear	No
Modified Griffith (MGR)	$\sigma_1[\sqrt{\mu^2+1} - \mu] - \sigma_3[\sqrt{\mu^2+1} + \mu] = 4T_0$ $\frac{C_0}{T_0} = \frac{4}{\sqrt{\mu^2+1} - \mu}$	Non linear	No
Murrell (MR)	$(\sigma_1-\sigma_3)^2 + (\sigma_1-\sigma_2)^2 + (\sigma_2-\sigma_3)^2 = 24T_0(\sigma_1+\sigma_2+\sigma_3)T_0 = \frac{C_0}{12}$	Non linear	Yes
Stassi D'alia (SD)		Non linear	Yes