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Determination of breakout failure zone around the borehole using the Mohr-Coulomb and Hoek-Brown failure criteria

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ABSTRACT: By drilling borehole in the ground, the distribution of stress around it changes, and stress concentration is created. If the shear stress induced by in- situ stresses is more than rock strength, it causes a kind of failure around the borehole, which is called breakout. It has been observed that breakout failure zones are initiated and propagated in the direction of the minimum in- situ stress. In this paper, by the assumption of elastic behavior of rock mass, the analytical 2D analysis of breakout failure using the Mohr-Coulomb and Hoek-Brown failure criteria is addressed and the failure zone is obtained by using these two criteria. According to the results of the mathematical model, the effective parameters in the depth and width of the breakout occurring around the borehole are depended on the mechanical properties of the materials in the medium as well as the amount and ratio of in- situ stresses. If the ratio of stresses is one, breakout failure will not occur. Also, with increasing the rock quality, the breakout depth decreases, and with decreasing rock strength and increasing the amount and ratio of stresses, the breakout area becomes larger.

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1. INTRODUCTION

Deep rocky environments are always under the influence of a lot of stresses caused by their weight. When drilling in these environments, the in-situ stresses around the drilling zone vary several times the largest drilling size. When this stress redistribution occurs, the effect of inhomogeneity or cavity as stresses in the drilling boundary is shown as a concentration of stress. If the stresses created at these points are more than the failure resistance of the rock, then tensile or shear failure occurs [1]. One of these types of failure is the breakout phenomenon. This failure is some points around the borehole; the concentration of stress increases the resistance of the rock to minimum horizontal stress [2]. Structurally, the breakout is a failure phenomenon that has been seen in most rocks. The researchers found that the shape of the breakout in the vertical wells depends on the maximum and minimum horizontal stresses so that the geometry can estimate the direction and magnitude of the stresses [3]. In 1964, Leeman considered the spalling of the well as a result of high stresses and stated that the size of the failure in the borehole wall could provide quantitative information on the variation of rock stress along the borehole length [4]. Bell and Gough in 1979 justified the increase in well radius through shear fractures [5]. In 1982 Gough and Bell used Mohr-Coulomb's criterion to determine the state of stress in the borehole wall [6]. Zoback et al. (1985), based on the model provided by Gough and Bell in 1982, obtained a method for linking the in-situ stress and breakout [2]. In 1984, Mastin contracted a type of rock under uniaxial loading and observed the most important mechanism for the development of the borehole breakout (spalling) [7]. In 2017, Zhang et al. concluded that reverse analysis based on finite element modeling of the borehole breakout and artificial neural network could be effective in determining the stresses [8].

The purpose of this paper is to obtain the breakout zone using the Hoek-Brown criterion. Zoback et al has already done theoretical analysis based on the Mohr-Coulomb criterion., and the analysis of relationships is provided only using the Hoek-Brown criterion. Based on the analysis, the relationship between the in-situ stress and failure zone is presented by the diagram and the shape of the arc on the borehole. Eventually, the breakout of both criteria is compared with the breakout of a real borehole.

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2. THEORY MODEL, ASSUMPTIONS AND ANALYSIS PROCESS BASED ON HOEK-BROWN CRITERIA

Consider a vertical hole in homogenous, isotropic and linear elastic rock mass subjected to effective stresses σ_h and σ_H acting at infinity ("Figure 1"). At each point around the borehole, the three radial σ_r, tangential σ_θ, and shear stresses $\tau_{r\theta}$ are calculated in accordance with the Kirsch's solution, where *r* is the distance from the center of the cavity and θ the angle to the minimum horizontal stress [9].

The breakout zone includes points where the shear stresses in those points are bigger or equal to the shear strength of

Table 1. Comparison of observed and theoretical breakout maximum depth in Auburn, New York (M-C and H-B criterion)

	Observed		Theoretical	
			M-C	H-B
Depth (m)	$\theta_b(^\circ)$	r_b (mm)	r_b (mm)	r_b (mm)
1471.9	19	115.0	114.1	114.1
1473.1	20	119.1	114.5	114.4
1474.6	22	120.0	115.0	114.9
1476.3	15	115.0	113.3	113.3
1476.3	22	117.0	115.0	114.9

the rock in accordance with the criterion of failure, so that by combining the Kirsch's relations with the chosen criterion of failure, points can be obtained on the boundary or the arc of the failure, arc The points on it and inside it represent the extent of the failure. For each state of stress and mechanical properties of materials, a pair of symmetric lateral failures is obtained in the direction of minimum principal stress. Based on "Figure 1", each failure arc has two characteristic points; the A point $(r_b, 0^\circ)$ with the polar coordinates represents the depth of the breakout along the minimum stress and the B point (a, θ_b) with the polar coordinates representing the point on the arc that has the highest width.

The non-linear Hoek-Brown criterion is an experimental criterion introduced in 1980. This criterion for intact rock is as follows [10]:

$$\sigma_1 = \sigma_3 + (m\,\sigma_c\,\sigma_3 + \sigma_c^2)^{0.5} \tag{1}$$

Where σ_1 and σ_3 are the major and minor effective principal stresses at failure σ_c is the uniaxial compressive strength (UCS) of the intact rock material and m is material constant.

Given that the Hoek-Brown criterion is based on the principal stresses, first, the Kirsch's relations are obtained from the principal stresses and placed in the Hoek-Brown relationship; thus the main relationship is obtained as follows.

$$\left[(\sigma_\theta - \sigma_r)^2 + 4\tau_{r\theta}^2\right] - \sigma_c^2 = 0.5\, m\sigma_c\left[(\sigma_\theta + \sigma_r) - \left((\sigma_\theta - \sigma_r)^2 + 4\tau_{r\theta}^2\right)^{1/2}\right] \tag{2}$$

Now, by inserting the properties of B point, the following relations are obtained:

$$\beta = \sigma_H + \sigma_h \times \alpha \tag{3}$$

Where

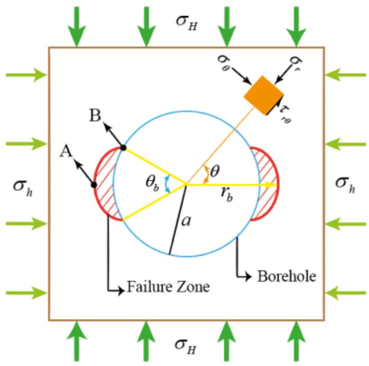

Fig. 1. Schematic figure of the breakout zone and its depth and width

$$\alpha = (1 - 2\cos\theta_b)/(1 + 2\cos\theta_b) \tag{4}$$

$$\beta = \sigma_c/(1 + 2\cos\theta_b) \tag{5}$$

Now, by inserting the properties of the A point, the following relations are obtained:

$$a_1^2 \times \sigma_H^2 + b_1^2 \times \sigma_h^2 + 2a_1 b_1 \sigma_H \sigma_h = m\,\sigma_c\,c_1\sigma_H + m\,\sigma_c\,d_1\sigma_h + \sigma_c^2 \tag{6}$$

Where

$$a_1 = 1 - \rho^2 + 3\rho^4 \tag{7}$$

$$b_1 = -1 + 3\rho^2 - 3\rho^4 \tag{8}$$

$$c_1 = 0.5 \times (3\rho^2 - 3\rho^4) \tag{9}$$

$$d_1 = 0.5 \times (2 - 5\rho^2 + 3\rho^4) \tag{10}$$

By combining Equation 3 with relation 6 and placement σ_h in σ_H terms of the number of two unknown variables is reduced and the following equation is obtained in terms of the variable σ_h:

$$\sigma_h^2\, e_1 + \sigma_h\, f_1 + g_1 = 0 \tag{11}$$

Where

$$e_1 = a_1^2\alpha^2 + b_1^2 - 2a_1 b_1\alpha \tag{12}$$

$$f_1 = -2a_1^2\alpha\beta + 2a_1 b_1\beta + m\sigma_c c_1\alpha - m\sigma_c d_1 \tag{13}$$

$$g_1 = a_1^2\beta^2 - \sigma_c^2 - m\sigma_c c_1\beta \tag{14}$$

3. RESULTS AND DISCUSSION

"Figure 2" shows the relations 3 and 11 for the rock with the m parameter of the variable (5, 10 and 15), this diagram shows changes in the ratio of the depth of the breakout to the borehole radius relative to the in-situ horizontal stress ratio at the fixed depth of the breakout (50°, 80° and 110°). In this

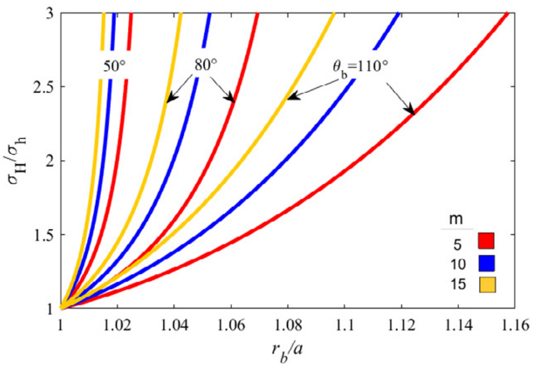

Fig. 2. The variation of the in-situ stresses ratio with the failure depth ratio for three different width and friction angles (based on the Hoek-Brown failure criterion)

figure, it is observed that in the case of hydrostatic stresses, the breakout zone is approximately zero, and with increasing the ratio of stresses, the failure zone becomes deeper and wider. This set of graphs is due to the use of the in-situ stresses ratio, independent of the UCS of the rock.

"Figure 3" shows the variation of the failure curve based on the Hoek-Brown criterion for the rock with the *m* parameter of the variable (5, 15 and 25) and the UCS of 90 MPa under the minimum in-situ stress of 35 MPa in the ratio of different stresses (1.5, 2, 2.5 and 3). According to the results had shown with the increasing in the ratio of in-situ stresses, the breakout failure zone increases. It is noteworthy in" Figure 3" that the width of the breakout is constant, since according to Equation 3, this width is not dependent on the *m* parameter, and that the *m* parameter is in each of the curves of these shapes (If the desired variable is the UCS or minimum horizontal stress, the widths are unequal).

In "Table 1", the depth of the breakout of obtained from two analytical methods was compared with the depth of the breakout of data obtained from the five-section data from the New York Auburn well. The average mechanical properties at this depth (1471-1477 m) are as follows: internal friction angle 31°, cohesion 10 MPa, *m* parameter 4.5 and UCS 36 MPa. The ratio of stresses obtained by the hydraulic fracturing method (at a depth of 1480 m) is 2.24 [3]. As can be seen in Table 1, there is a good match between the observations made using the televiewer data and both theoretical methods.

4. CONCLUSION

A failure of caverns, especially high oil boreholes, is a breakout. This failure occurs along the minimum horizontal stresses and occurs due to shear stress caused by the surrounding pressure of the borehole .In this paper, according to the two criteria of known failure in the rock, the Mohr-Coulomb and Hook-Brown criteria were applied to the mathematical analysis of this phenomenon and the extent of the failure along the borehole was obtained following these two criteria. Both the magnitude and the ratio of the stresses are two factors affecting the formation and development of the breakout areas around the borehole. If the stress ratio is one, there will be no shear failure area around the borehole, and increasing the stress ratio will increase the depth and width of the failure. In addition to these two factors, the mechanical characteristics of the rock, in accordance with the criteria for the failure, are another important factor in the depth and width of the breakout. With the mechanical characteristics of the rock weakened, the breakout area becomes larger.

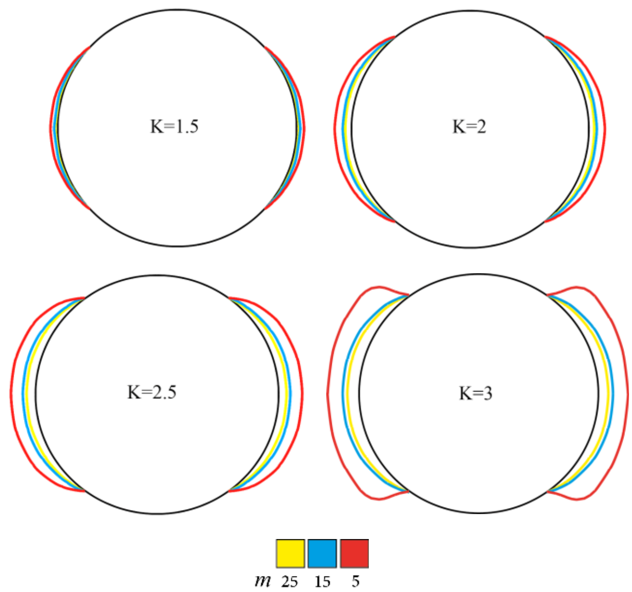

Fig. 3. The breakout zone for the different values of the ratio of in-situ stresses and the *m* parameter (UCS and minimum stress are equal to 90MPa and 35MPa)

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