Geomechanics for Energy and the Environment 2 (2015) 15–21

Contents lists available at ScienceDirect

Geomechanics for Energy and the Environment

journal homepage: www.elsevier.com/locate/gete

Using different rock failure criteria in wellbore stability analysis

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HIGHLIGHTS

- The minimum allowable mud pressure of Mogi–Coulomb is much less than the other two criteria.
- The minimum and maximum allowable mud pressure resulted from Mohr–Coulomb and Hoek–Brown criteria are not significantly different.
- The Hoek–Brown criterion is more conservative than the other two criteria.
- The mud window resulted from Mogi–Coulomb is the broadest and Hoek–Brown is the most limited.

ARTICLE INFO

Article history:
Received 4 November 2014
Received in revised form 6 April 2015
Accepted 10 April 2015
Available online 23 April 2015

Keywords:
Allowable drilling mud pressure
Mohr–Coulomb
Mogi–Coulomb
Hoek–Brown
Wellbore stability

ABSTRACT

The minimum and the maximum allowable drilling mud pressures for two wellbores are calculated analytically by Mohr–Coulomb, Hoek–Brown and Mogi–Coulomb failure criteria and numerically using a Fish program which is implemented in FLAC. The allowable drilling mud pressures that resulted from these methods are compared with each other and then with the field data: two wellbores in two Iranian oilfields are investigated as case studies to assess the results. Finally the criterion that matches closely field data is identified. It is shown that the minimum allowable drilling mud pressure obtained from the Mogi–Coulomb criterion is close to actual data collected during drilling operation. Hence, this criterion is considered more appropriate for wellbore stability analysis than the other two criteria.

1. Introduction

Underground formations are subjected to a vertical compressive stress caused by the weight of the overlying strata, and horizontal stresses due to the confining lateral restraints. Under the action of these in situ stresses, prior to drilling a borehole, the rock mass is in a state of equilibrium that will be destroyed by the excavation. When a borehole is drilled, the load carried by the removed rock is taken over by the adjacent rock to re-establish equilibrium. As a result, a stress concentration is produced around the well, and the in situ stresses are modified. If there is no support pressure introduced into the borehole, failure in the formation may take place. Therefore, maintaining equilibrium in the field to prevent rock failure requires the use of a support pressure which during drilling is provided by a pressurized fluid called "drilling mud" or by maintaining pressure properly during production.

Wellbore instability during drilling is one of the most important issues for engineers in oil industry. These instability issues involve stuck pipe or tight hole, drilling mud loss or lost circulation, wellbore breakout or collapse and wall tensile fracture. Exact determination of the allowable drilling mud pressure needs application of a suitable rock failure criterion which considers the wellbore condition and the rock properties.

The most common failure criterion that is used is Mohr–Coulomb. It was used by Fjaer et al.[1] to determine the drilling mud pressure window; i.e. the minimum well pressure permitted to prevent hole collapse (or fluid

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http://dx.doi.org/10.1016/j.gete.2015.04.001
2352-3808/

influx) and the maximum well pressure permitted to prevent loss of fluid to the formation by flow into existing or induced fractures. When these limits are known, the well may be designed. Wiprut and Zoback,[2] Zoback et al.[3] employed Mohr–Coulomb failure criterion to determine the principal stresses around a well and analyze its stability. Vernik and Zoback[4] found that using the Mohr–Coulomb criterion to relate the wellbore breakout to the in situ stresses in crystalline rocks does not provide realistic results. They recommended the use of a failure criterion which considers the influence of intermediate principal stress (σ_2) on the rock strength. Song and Haimson[5] conducted laboratory tests to investigate the wellbore breakouts in Westerly granite and Berea sandstone, and compared the observations with different failure criteria approximations. Al-Ajmi and Zimmerman[6,7] developed Mogi–Coulomb failure criterion based on true-triaxial test results, in which the effect of σ_2 on the stability of wellbores is considered.

Ewy[8] used modified Lade criterion for analyzing the wellbore stability. Wiebols and Cook[9] proposed criterion based on the shear strain energy which consists of octahedral and normal shear stresses. In rock mechanics, there are some empirical failure criteria; among them Hoek–Brown failure criterion is the most popular. Pan and Hudson[10] have reviewed several criteria which include the influence of the intermediate principal stress and have proposed a three dimensional variation of the Hoek–Brown criterion. Kim and Lade[11] used the first and the third stress invariants and proposed a 3D criterion.

In this paper, maximum and minimum allowable drilling mud pressures are determined analytically using three rock failure criteria, namely Mohr–Coulomb, Mogi–Coulomb and Hoek–Brown. The analytical results are compared to computation performed with the Finite Difference Method and the FLAC[12] software employing a Fish program and actual field data. Moreover, implemented models are validated by comparing its result against analytical results. These three failure criteria are applied to obtain the allowable drilling mud pressure window related to two vertical wells from two Iranian oilfields. Finally, the results of this analysis are compared with the field data (actual drilling mud pressure).

2. Stresses at wellbore wall

The stress distribution at the borehole wall in an infinite plate in one-dimensional tension was first published by Kirsch.[15] The Kirsch formulas generalize easily to a vertical well with unequal far field stresses. As the well is drilled, the wellbore wall must bear stresses previously carried by the removed rock. This causes the stresses to concentrate about the wellbore. These stress concentrations depend on the wellbore orientation and the far field in situ stresses.[13,14] Assuming that the vertical stress is a principal stress, the three principal stresses acting at the vertical wellbore wall are:

1. The effective radial stress (σ_{rr}) which acts normal to the wellbore.
2. The effective axial stress (σ_{zz}) which acts parallel to the wellbore axis and;

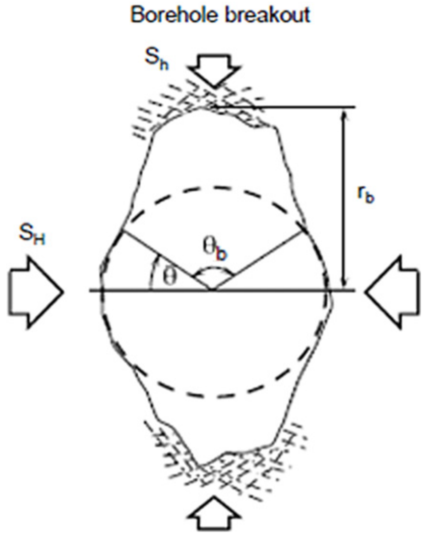

Fig. 1. Schematic view of wellbore breakout.[17]

3. The effective circumferential stress ($\sigma_{\theta\theta}$), which acts orthogonal to σ_{rr} and σ_{zz}.

According to the Kirsch solution, the three effective stresses at wellbore wall are given by[15]

$$\begin{aligned}\sigma_{rr} &= P_w - P_0,\\ \sigma_{\theta\theta} &= \sigma_H + \sigma_h - 2(\sigma_H - \sigma_h)\cos 2\theta - P_w - P_0,\\ \sigma_{zz} &= \sigma_v - 2\nu(\sigma_H - \sigma_h)\cos 2\theta - P_0,\end{aligned} \tag{1}$$

where σ_H is the maximum horizontal stress, σ_h is the minimum horizontal stress, P_w is the drilling mud pressure acting on the wellbore wall, P_0 is the pore pressure inside the formation, ν is Poisson's ratio of the rock and θ is measured from azimuth of maximum horizontal stress.

Since oil wells are typically drilled overbalanced and drilling mud cake is formed at the wellbore wall, the assumption of impermeability is also generally considered valid for wellbore walls.[16]

During drilling operations two instability issues, wellbore collapse and Drilling Induced Tensile Fracture, are possible. From hydraulic fracturing test, it is known that the direction of the fracture is perpendicular to the minimum horizontal principal stress and parallel to the maximum horizontal principal stress (Figs. 1 and 2).

By employing the laboratory test results, Hubbert and Willis[18] confirmed that the work required to open a fracture by a particular length is proportional to the stress value acting perpendicular to the fracture plane. Since there are three principal stresses, six permutations are possible. According to Eq. (1) σ_{rr} and $\sigma_{\theta\theta}$ are the functions of drilling mud pressure, P_w.

When P_w increases, σ_{r_r} also increases and $\sigma_{\theta\theta}$ decreases toward the tensile strength. Therefore, the upper limit of the drilling mud pressure is associated with fracturing which is happening when $\sigma_{\theta\theta}$ is lower than σ_{r_r} and is equal to tensile strength of the rock. On the other hand, when P_w decreases, $\sigma_{\theta\theta}$ increases toward the compressive strength. Thus, the lower limit of the drilling mud pressure is associated with wellbore collapse, in which $\sigma_{\theta\theta}$ is greater than σ_{r_r}.