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Shear failure analysis of a shallow depth unsupported borehole drilled through poorly cemented granular rock

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ABSTRACT

Adopting an appropriate failure criterion plays a key role in the borehole stability analysis. In this paper the induced stresses on a vertical borehole wall were calculated based on the elastic theory. Then, to predict the stability of a borehole drilled through a poorly cemented sand formation, failure envelopes in different failure criterion domains were derived using the results from a series of precise laboratory tests conducted on solid and hollow cylinder specimens. The mixture used in specimen preparation was designed to simulate the properties of the samples collected from depths up to 200 m at a drilling site in South Australia. The hollow cylinder test apparatus was developed by modifying a Hoek triaxial cell. These modifications allowed observing the process of debonding of sand grains from the borehole wall during the test and consequently, acquiring a better understanding on the failure mechanisms of a borehole drilled through poorly cemented sand formations. Three well-known failure criterion domains; Coulomb, Drucker–Prager and Mogi, were considered versus the laboratory test data to investigate their capability to predict the shear failure of a borehole using the data from hollow cylinder tests. The obtained results showed the significance of selecting an appropriate failure domain for predicting the shear failure behavior of poorly cemented sands near the borehole wall. The results also showed that the Coulomb criterion is not well suited for predicting the borehole failure when there is no pressure acting inside the borehole. A failure envelope based on the Mogi domain was developed which can be used for the far-field stress states. The introduced failure envelope allows predicting the stability of a borehole drilled in poorly cemented sands.

1. Introduction

Exploration drilling is one of the most frequently used data collection methods in mining, petroleum and civil engineering. Drilling a borehole is an excellent method not only for monitoring and petrographic assessment of borehole walls but also for measuring spatial position of formations and for obtaining characteristics of faults and joints. Hence, borehole stability is one of the most important challenges to be addressed in geomechanics. A number of drilling companies in Australia have reported several borehole instability issues in poorly cemented formations in last few years. Thus, it is important to conduct a comprehensive research on borehole failure at shallow depths (up to 200 m) where unconsolidated/poorly cemented sand formations are present.

There are many closed form solutions (Fairhurst, 1968; Kemeny, 2003; Zoback, 2011) for analysing boreholes via thick-walled hollow cylinder samples. Most of the borehole stability analyses are based on the assumptions that the rock is isotropic and the directions of regional stresses are known. However, in many cases these assumptions may not be valid. Since the initial stress state at a point in a certain depth underground determines the stress concentration around an opening, it is desirable that this initial state to be known in advance, before the development of an underground structure (Fairhurst, 1968). When a borehole is drilled through a weak material, such as poorly cemented sand formation that is present in sedimentary geological formations, the release of the pre-existing in situ stresses underground may result in borehole instability. Tangential stress will be generated around the borehole wall and the radial stress on the borehole wall is zero in case of an unsupported borehole. If the strength of the borehole wall is not sufficient, the borehole may collapse. This happens due to re-establishment of the equilibrium to the ground after the borehole excavation of the borehole. To assess the stability of a borehole, the stresses redistributed at the borehole wall must be determined and compared to the critical stress condition using an appropriate failure criterion. If there is a need for a support system, it can be designed with respect to the limits of the failure criterion.

2. Underground in situ stress state

Prior to drilling a borehole, the underground formations are usually subjected to vertical compressive stress and horizontal stresses caused by the overlaying strata and lateral pressure respectively. The vertical

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Nomenclature

$TWHC$	thick-walled hollow cylinder
w_c	ratio of cement to sand grains weight
$\sigma_{\theta\theta}$	tangential stress (MPa)
σ_{rr}	radial stress (MPa)
σ_z	vertical stress (MPa)
τ	shear stress (MPa)
P_w	in-hole pressure (MPa)
UCS	uniaxial compressive strength (MPa)
ν	Poisson's ratio
k_o	σ_h/σ_v
D_i	internal diameter of a hollow cylinder (mm)
γ_d	dry density
D_{50}	mean grain diameter (mm)
C_u	coefficient of uniformity
σ_{conf}	confining stress (MPa)
ϕ	angle of internal friction (deg)
c	cohesion (MPa)
σ_n	normal stress (MPa)
$\sigma_{m,2}$	mean effective normal stress (MPa)
τ_{oct}	octahedral shear stress (MPa)
σ_{oct}	octahedral normal stress (MPa)
δ	ratio of fine to coarse sand weight
I_i	i^{th} normal stress invariant
w_{opt}	optimum water content

principal far-field stress can usually be estimated as the weight of the overburden (Fairhurst, 2003). The minimum horizontal stress can be measured by hydraulic fracturing and leak off test (Amadei and Stephansson, 1997). However, determining the in situ maximum horizontal stress is a matter of debate and it can be guessed only based on specific considerations (Zoback et al., 1985; Aadnoy et al., 2013; Della Vecchia et al., 2014). The in situ stress state can be defined in terms of the principal stresses, σ_v, σ_H, and σ_h. The ratio of minimum horizontal stress to the vertical stress ($k_o = \sigma_h/\sigma_v$) ranges from 0.3 to 1.5 and the ratio of maximum horizontal stress to minimum horizontal stress (σ_H/σ_h) varies from 1 to 2 in most of oil fields and exploration boreholes (Herget, 1988; Tan et al., 1993; Chen et al., 2002). Based on the tectonic and faulting condition, Anderson (1951) suggested three different stress regimes for the underground stress conditions. These three stress regimes are the permutation of σ_v, σ_H and σ_h in higher to smaller order as follows,

$$\begin{cases} \sigma_v \geq \sigma_H \geq \sigma_h \\ \sigma_H \geq \sigma_v \geq \sigma_h \\ \sigma_H \geq \sigma_h \geq \sigma_v \end{cases}. \tag{1}$$

Different faulting conditions that introduce in situ stress regimes are presented in Fig. 1. According to the placement of stresses in the above mentioned three inequalities (Eq. (1)), the maximum, intermediate and minimum stresses can be defined. The most likely conditions at drilling fields are given by the first and second inequalities in Eq. (1) (Al-Ajmi and Zimmerman, 2006).

This formation system is in a static equilibrium stress state assuming no movement exists due to any seismic activity nearby. Once a borehole is excavated, the balanced stress condition will be disturbed eventually causing instability in the adjacent rock formation. This causes an increase in the tangential stress and a decrease in the radial stress near the opening wall thus resulting in the elastic deformation of the formation near the opening at the very least (Ewy and Cook, 1990a,b). To re-establish the state of equilibrium the load, which was tolerated earlier by the removed material, must now be carried by the formation around the borehole. This new stress arrangement imposes a different set of stresses that can extend from the excavated area to a distance of up to few times the borehole diameter.

Depending on the conditions and purpose of drilling (e.g. air pressure or filled with a drilling mud) the walls of the excavated opening are usually supported by a corresponding supporting system exerting a pressure, P_w on the borehole wall. The borehole support system must be designed to prevent the onset of borehole shear collapse which is revealed by the failure of rock material at the borehole wall. On the other hand, the high in-hole pressure exerted by the support system can result in the tensile failure of the borehole, as is in the case of hydraulic fracturing due to high drilling mud pressure. Zoback et al. (2003) showed that the applied pressure cannot be exactly equal to the in situ stresses that have existed before drilling the borehole.

2.1. State of stress around a vertical borehole

The equations for calculating stress distribution around a circular hole in an infinite plate in linear elastic rock were initially introduced by Kirsch (1898). Kirsch equations can also be generalised to calculate stresses around vertical and deviated boreholes with anisotropic far-field stresses. After the completion of drilling operations in a formation

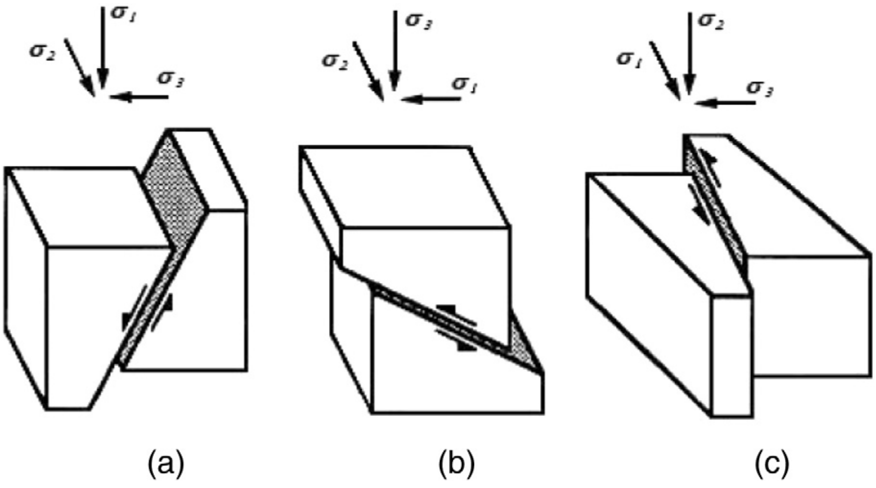

Fig. 1. Far field stress regimes: (a) Normal faulting (b) Reverse faulting (c) Strike-slip faulting (Al-Ajmi and Zimmerman, 2006).