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International Journal of Rock Mechanics & Mining Sciences 44 (2007) 157–173

International Journal of
Rock Mechanics
and Mining Sciences

www.elsevier.com/locate/ijrmms

Micromechanisms of borehole instability leading to breakouts in rocks

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Accepted 1 June 2006
Available online 31 July 2006

Abstract

This paper reviews the different borehole breakout failure micromechanisms observed during a multiyear laboratory research effort at the University of Wisconsin. Vertical borehole drilling experiments were conducted in a variety of granites, limestones, and sandstones under a wide range of pre-existing stress fields. Test samples that developed breakouts during drilling were analyzed under optical and scanning electron microscopes to establish the micromechanics of failure. All rocks tested, except for the quartz-rich sandstones, develop dog-eared breakouts along the minimum horizontal far-field stress springline, even though the grain-scale mechanisms leading to the final appearance may differ considerably. The common denominator is the incipient failure in the form of dilatant microcracking in the zones of the highest compressive stress concentration around the borehole. Dependent on rock type, these microcracks could be tensile or shear openings, extending inter- or intra-granularly. A type of failure not hitherto recognized was discovered in quartz-rich sandstones, which develop tabular slot-shaped breakouts that maintain a constant very narrow width over an extensive length, resulting in a fracture-like appearance. Such breakouts are the result of a largely non-dilatant micromechanism consisting of localized grain debonding and repacking leading to the formation of an apparent reduced-porosity compaction band along the minimum horizontal far-field stress springline. Breakouts are produced by the removal, with the help of the circulating drilling fluid, of loose grains and grain fragments that were debonded in the process of compaction band forming.
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Keywords: Borehole breakouts; Borehole instability; Failure micromechanism; Compaction bands; Micromechanics

1. Introduction

In this paper the term 'borehole breakout' is limited to vertical-borehole cross-section elongation along a preferred direction resulting from stress-induced rock failure. Early reports of stress-induced breakouts came from Leeman [1], who observed sidewall spalling in South African gold mine openings. Carr [2] reported on preferential borehole-enlargement orientation in six holes in Yucca Flat, Nevada that was consistent with the direction of the in situ minimum horizontal principal stress, σ_h, as inferred by other methods. While Carr's assertion received only little consideration at the time, Bell and Gough's [3,4] hypothesis of a remarkably uniform state of stress over a substantial part of the North American plate, as exemplified by the consistent orientation of breakouts in numerous oil wells in Alberta, Canada, drew the attention of interested scientists with follow-up research projects aimed at verifying, and complementing Bell and Gough's findings [5–8]. Laboratory experiments by Mastin [5] and Haimson and Herrick [7,8] supported the Bell and Gough hypothesis that stress-induced borehole breakouts are aligned with the direction of σ_h. Numerous boreholes all over the world have since been logged and consistent orientations found, which were used to estimate regional principal in situ stress directions. Today, a World Stress Map is available [9], based primarily on fault plane solutions and borehole breakout orientations, showing the principal crustal stress directions in many regions of the globe.

Extensive research has been conducted in an effort to also determine whether breakouts can be used to gain information on in situ stress magnitudes. Haimson and Herrick [7,8] found definite correlations between far-field principal stress magnitudes and borehole breakout dimensions in laboratory carbonate rock samples. Zoback et al.

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1365-1609/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijrmms.2006.06.002

[6] proposed a model based on the theory of elasticity and a rock failure criterion to relate breakout dimensions to in situ stress magnitudes. Zheng et al. [10] carried out a numerical simulation of borehole wall condition under critical far-field stresses and obtained predicted borehole breakout span and length dimensions for different stress regimes. Vernik and Zoback [11], Haimson and Song [12], Brudy et al. [13], and Haimson and Chang [14] further developed the original Zoback et al. [6] model to include the concept that the criterion of failure at the borehole wall should involve the effect of the intermediate principal stress, which Mohr-based criteria fail to consider. This approach was successfully applied, for example, to estimate the maximum horizontal in situ stress, σ_H, in the deep scientific holes of Cajun Pass, California and KTB, Germany.

Numerous attempts have been made to explain the mechanism that brings about the phenomenon of borehole breakouts, notably using pressure-dependent elasticity [15,16], microstatistics [17], elasto-plasticity [18], bifurcation theory [19], and fracture mechanics [20–22]. A comprehensive review of the many theoretical, numerical, and experimental approaches to explaining the sources of borehole instability leading to breakouts in rocks is provided by Germanovich and Dyskin [22]. The present paper concentrates on observations of grain-scale mechanisms that bring about borehole breakouts, based solely on microscopic studies of specimens tested in the laboratory during a multi-year research program at the University of Wisconsin. Drilling experiments in several categories of rocks revealed some similar breakout characteristics, and some strikingly different micromechanisms. Details are presented in the following sections.

2. Apparatus and experimental procedure

Drilling experiments were conducted on rectangular prismatic rock samples varying in size between $127 \times 127 \times 178\,\text{mm}^3$ and $153 \times 153 \times 229\,\text{mm}^3$, subjected to pre-existing far-field stress conditions. The dimensions used were dependent on the availability of sufficiently large blocks from which specimens were prepared, and on the level of far-field stresses required to induce breakouts in a particular rock type. The three major components of the testing equipment were the drill rig, the loading frame and actuator, and the biaxial pressure cell.

The electric drill rig was affixed to the top of the loading frame crosshead (Fig. 1). The typical drilling bit used was a diamond-impregnated coring bit that creates a 22 mm (in diameter) central vertical hole along the largest sample dimension, although tests have also been conducted using bi-cone bits and other borehole diameters (ranging from 16 to 38 mm). A pneumatic cylinder applied downward drilling pressure, and a potentiometer depth-gage reading of the bit penetration was recorded both digitally and on an analog chart plotter.

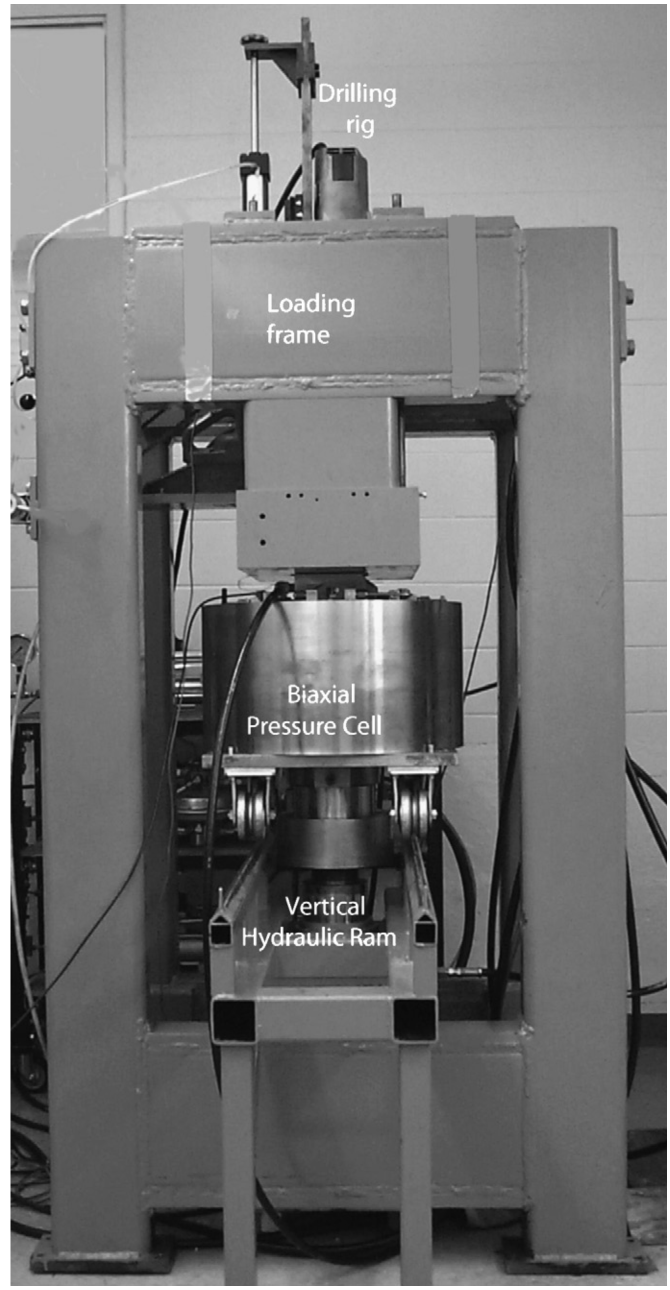

Fig. 1. The University of Wisconsin compressive loading frame, which facilitates the application of three independent mutually perpendicular servo-controlled loads to a rectangular prismatic rock specimen, followed by drilling a central vertical hole of various diameters into a pre-stressed sample.

The loading frame, which was designed and fabricated in-house, is unique in that it accommodates the drilling rig and enables vertical drilling into a rectangular prismatic specimen that is subjected simultaneously to three unequal mutually perpendicular loads (Fig. 1). The hydraulic actuator attached to the lower reaction beam of the frame produces a vertically acting force of up to 1.35 MN, and was used to apply the vertical load to the specimen. The two horizontal loads were applied to the specimen through a high-capacity biaxial pressure apparatus, which was also

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