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A strain-softening numerical model of core discing and damage

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Abstract

There has been a debate in the rock mechanics community regarding the mechanisms causing what is known as core discing. This phenomenon occurs when diamond drill cores are retrieved from rock masses in which high in situ stresses relative to rock strength are present. The interest in that phenomenon is to use it to estimate the in situ stresses from the shape and frequency of the failures along the core axis. In the present paper we argue that discing is only an indicator of high stresses, and that estimating in situ stresses from fracture observations is much too inaccurate.

As most of the literature found on the subject has tackled the problem using elastic numerical models, it is shown that the stress distribution in the core being formed obtained from such models does not exist once failure has been reached. Numerical analyses using Flac^{2D} with an elasto-plastic cohesion softening friction hardening model show that for a given stress state, discing or core damage may involve tensile failure, a combination of shear and tensile failure, or only shear failure, depending on the stress state and ratio of tensile to shear strength of the rock. The numerical model used is validated by replicating core discing observed under controlled laboratory conditions. Parametric analyses involving changes in mesh density, deformability parameters, dilatancy, drill bit pressure, drilling fluid pressure and applied stress states are also performed. Finally, it is shown that drilling-induced core discing or damage store important residual stresses in the core which may explain why recovered core samples tend to show a deterioration of their mechanical properties with time.

Keywords: Core discing; Core damage; Strain softening; Tensile failure; Shear failure; Numerical modeling; Residual stresses; Stress measurement

1. Introduction

Since the early sixties, core discing, defined as the breakeage of diamond drill cores in the form of discs under the influence of high in situ stresses, has been identified as a potential tool for estimating these stresses. Hast [1] was the first to link core discing to high in situ stresses. Jaeger and Cook [2] suggested that shear failure could occur in zones where the minor principal stress, σ_3, was in tension, since the major principal stress at failure was lower than the unconfined compressive strength. Jaeger and Cook also mentioned that the failure surfaces were always clean and unsheared suggesting a tensile failure, leaving the question open for further work. It should be noted that the experimental procedures used by Jaeger and Cook were varied and included biaxially pressurizing cores in a chamber shorter than the core length, which did not simulate the actual drilling operation. They also drilled in rock cylinders loaded radially with cylindrical bearing plates linked to a jack. This setup may have produced stress states that are very difficult to estimate. Later, Obert and Stephenson [3] set up a system which allowed drilling rock cylinders under triaxial stress conditions, the stresses being equal in the plane perpendicular to the core axis. They tested six different rock types, five of which lead to finding a linear relationship between the axial (S_a) and radial (S_r) applied stresses which would cause discing to occur. This relationship is

$$S_r = k_1 + k_2 S_a, \quad (1)$$

with k_1 being the radial stress initiating discing when the axial stress is null, and k_2 is a constant related to the type of rock tested which ranges between 0.59 and 0.89. Obert and Stephenson found that k_1 varied linearly with the cohesion of the rock which led them to assume that discing was

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initiated by or completely the result of shear stress. They also stated that the surfaces of the fractured discs are like those created by a tension failure or possibly a shear failure with virtually no normal compressive stress. Durelli et al. [4] performed 3D photoelastic analyses in order to study the stress patterns around the bottom of a forming core. The material they used had a Poisson's ratio of 0.5. This model lead them to assume that discing initiates at the bottom of the kerf (of semi-circular shape), where the maximum shear stress values are found. A linear relationship between the maximum shear stress value at this point and the applied stresses (S_a and S_r) was shown to require much higher applied stresses to induce discing than the values reported by Obert and Stephenson. Durelli et al. [4] suggested that non linear rock behavior, differences in Poisson's ratios, stress field changes caused by fracture initiation, drilling load, heterogeneity, anisotropy, kerf geometry and the influence of the intermediate principal stress could explain the observed differences between the photoelastic model and Obert and Stephenson's experimental results. Ishida and Saito [5] report the work of Sugawara et al. [6] who suggested a relationship between stress states and discing that implies it is controlled by tensile failure. Ishida and Saito compared measured in situ stress states with field observations of discing on a specific dam project site and concluded that the existing discing prediction models, whether in shear or tension did not work very well.

Various researchers [6–14] have studied the stress and strain distribution occurring while drilling cores using finite-element models. Matsuki et al. [14] have performed linear elastic finite element analyses and proposed a criterion for discing based on the assumption that tensile stresses control the fracture. This criterion links the mean in situ stress (σ_m), the stress component parallel to the hole axis (σ_z) and the minor in situ stress (σ_3) to the tensile strength of the rock (T_0) with the following relationship:

$$T_0 = 0.302\sigma_m - 0.340\sigma_z + 0.0910(\sigma_z - \sigma_3). \quad (2)$$

From their pseudo-3D analyses (axisymmetric geometry subject to nonaxisymmetric boundary conditions), Matsuki et al. [13,14] link the shape of the discs to the orientation the tensile stresses take in the central part of a zone located a certain distance under the top of the core. From field observations related to the geometry of the disks, they suggest possible means of determining both the orientation and magnitude of in situ stresses if certain conditions are fulfilled. What is common to these various researchers work is that their numerical models were all linear elastic. Consequently, the conclusions drawn from their analyses could be correct as long as the rock behaves as a linear elastic media, even after failure.

More recently, Kang et al. [15] have used a boundary-element model, also assuming the rock behaves as a linear elastic material, to study discing while performing in situ stress measurements using the conical-ended borehole overcoring technique. Other researchers have shown that although discing may not be present, modifications to the rock properties can result from drilling under certain in situ stress states [16]. As will be shown, mechanisms similar to the ones leading to discing are involved in core sample disturbance.

The objectives of the present paper are twofold: firstly, to identify the mechanisms leading to core discing or core damage while drilling under high in situ stresses relative to the rock strength. Secondly, to show that if failure is not considered in numerical analyses, discing clearly being a phenomenon where failure plays an important role, the stress fields under the borehole bottom or around the forming core are far from being correct, and attempts to use these analyses to infer in situ stresses from observed discing can be misleading.

2. Numerical model

Since failure is obviously present when discing occurs, elasto-plastic numerical analyses which simulate the coring operation in a rock were performed. As nonlinear stress–strain relationships are involved, the results are stress path dependent and the coring operation must be entirely modeled. It is for this reason that Flac version 5.0 [17] was used, since it has the ability to easily null elements in the path of the drill bit, and also has constitutive models, such as the plastic strain softening model, that allows the inclusion of the post-failure behavior of geomaterials, which, as will be seen, plays a very important role in the discing or damaging mechanisms. Moreover, when a sufficiently dense grid (mesh) is used, the failure localization phenomenon found in geomaterials can be simulated. In order to validate the numerical model, the well documented experimental results presented by Obert and Stephenson [3] were used. One advantage of their experimental work is that some of the rocks mechanical properties are available, amongst which are the tensile strength, unixial compressive strength and Mohr–Coulomb strength parameters. Moreover, a wide range of stress conditions producing discing or leaving the cores macroscopically intact is covered in their work, allowing to better adjust some of the rock parameters controlling discing.

2.1. Model geometry

For the analyses presented in this paper, a 2D axisymmetric model is used. This choice takes advantage of the axial symmetry found with the problem (and present in Obert and Stephensons's work) but limits the stress state normal to the borehole axis to an isotropic state (nonlinear stress–strain relationships preclude the use of the superposition principle to generate nonisotropic stress states normal to the core axis).

The model dimensions are shown in Fig. 1 and replicate the dimensions of the rock cylinders used by Obert and