International Journal of Rock Mechanics & Mining Sciences 91 (2017) 112–118

Contents lists available at ScienceDirect

International Journal of Rock Mechanics & Mining Sciences

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

A new method of diametrical core deformation analysis for in-situ stress measurements

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ARTICLE INFO

Keywords:
Stress relief
Core sample
Elastic deformation
In-situ differential stress

ABSTRACT

A new method of diametrical core deformation analysis (DCDA) is proposed for evaluating the in-situ stress of rocks from an elliptical deformation of boring cores following stress relief. When a piece of rock at depth is cut out to be a core sample by drilling, it becomes free from the in-situ stresses resulting in the expansion of its diameter. Even if the rock is homogeneous and isotropic, the core sample should expand in an asymmetric manner with the relief of anisotropic in-situ stresses. A newly developed apparatus allows us to measure the asymmetric variation of the core diameter. The difference between the maximum and minimum stress components and the stress orientations in a plane perpendicular to the drilled hole can then be estimated from the circumferential variation of the measured core diameters based upon a theoretical relationship between the in-situ stresses and the core diameters, assuming elastic deformation. We carried out laboratory experiments in which core samples were cut out from cubic specimens under uniaxial compression, and we confirmed that the stress magnitude and orientation estimated from the measured core diameters by the proposed DCDA method agreed well with those of the actually applied stress.

1. Introduction

Measurement methods for in-situ rock stress can be classified into two types: (i) methods based upon in-situ tests such as over-coring and hydraulic fracturing (HF), and (ii) core-based methods such as ASR (Anelastic Strain Recovery), DSCA (Differential Strain Curve Analysis), DRA (Deformation Rate Analysis) and AE (Acoustic Emission). The former in-situ methods are understood to be reliable but require a moderate cost to carrying them out at depth in boreholes, and the cost and difficulty of the tests increase drastically with depth. In contrast, the latter core-based methods allow us to estimate the in-situ stress state from laboratory tests using a cylindrical piece of rock, i.e., a core sample which is cut out from a rock mass at depth by core drilling. Such methods are usually rather inexpensive in comparison to the former ones; however, they are generally considered to be less reliable because the basic link between the observed data and the stress state remains vague.[1]

Taking into account the problems and limitations for conventional core-based methods, we have developed a new method referred to as Diametrical Core Deformation Analysis (DCDA). When a piece of rock at depth is cut out to be a core sample by drilling, it becomes free from in-situ stresses, resulting in an expansion of its diameter. We investigate the possibility of using this core expansion to determine in-situ stress. To accomplish this, we develop a theoretical model to estimate the core expansion caused by the stress relief brought about by drilling. This model indicates that a core sample cut out under anisotropic in-situ stress field should expand into a slightly elliptical shape in transverse cross section. Then, the difference between the maximum and minimum stress components in a plane perpendicular to the drilled hole, and also the stress orientations, can be estimated from the difference between the maximum and minimum core diameters and the diameter orientations. This method is verified through laboratory experiments in which core samples are cut out from cubic specimens under uniaxial compression.

2. Concept and theory of DCDA

Consider a rock mass compressed by maximum and minimum stresses, S_{max} and S_{min} ($S_{max} > S_{min}$). Then virtually draw a dashed circle with a diameter d_0 on the rock surface, as illustrated in Fig. 1a. Subsequently, if the rock is relieved of S_{max} and S_{min}, it should expand as illustrated in Fig. 1b. The rock expansion should be larger in the direction of S_{max} than S_{min}, and simultaneously the originally circular region bounded by the dashed line should expand to be elliptical, where

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http://dx.doi.org/10.1016/j.ijrmms.2016.11.002
Received 25 December 2015; Received in revised form 3 May 2016; Accepted 2 November 2016
Available online 25 November 2016

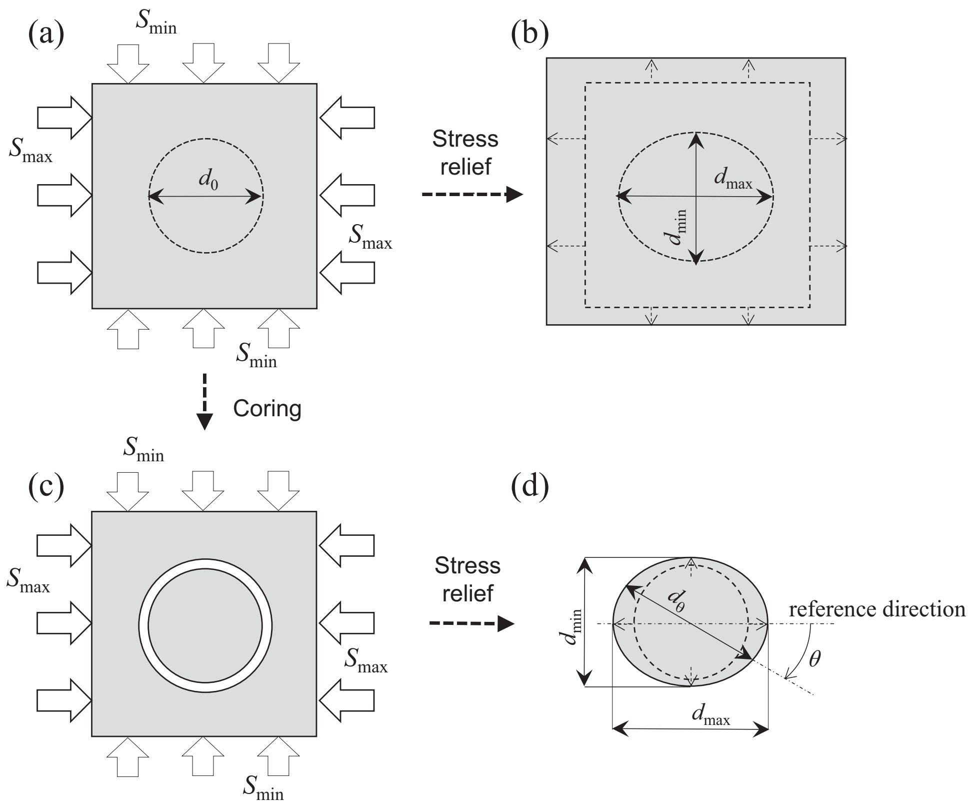

Fig. 1. Schematic diagram showing how core expansion is caused by stress relief with drilling.

the maximum and minimum diameters of the region are denoted here by d_{max} and d_{min}, respectively.

In a similar fashion, during core drilling, a core bit cuts into the exposed surface of rock at the bottom of a borehole with a rotating motion, and as a result, a column of rock is cut out to be a core sample. In Fig. 1c, the cross section of the column at the cutting edge is illustrated, which should be perfectly circular, since the column is cut out by a rotating bit. The column at the cutting edge is adjacent to the surrounding rock mass, which should therefore restrict the deformation of the column. However, the same cross section of the column being away from the cutting edge is able to expand freely from the surrounding rock mass in response to the relief of the in-situ stresses S_{max} and S_{min}. Such deformation of the column occurs continuously with drilling. As a result, the core sample should be uniform in cross sectional shape with d_{max} and d_{min} as illustrated in Fig. 1d.

The relationship between in-situ stresses, S_{max} and S_{min}, and diameters of the core sample, d_{max} and d_{min}, can be derived theoretically assuming that the strain condition of Fig. 1c is the same as that of Fig. 1a. When the strains in the rock of Fig. 1a are assumed to be zero, the stress relief leads to tensile strains being induced in the rock (Fig. 1b). This also should be the case in the core sample of Fig. 1d. Assuming a homogeneous, isotropic rock and small deformations in accordance with the linear elastic theory, the tensile strains ε_{max} and ε_{min}, in the directions of S_{max} and S_{min}, respectively, are given by

$$\varepsilon_{max} = \frac{1}{E}\{S_{max} - \nu(S_{min} + S_z)\} \tag{1}$$

$$\varepsilon_{min} = \frac{1}{E}\{S_{min} - \nu(S_{max} + S_z)\}, \tag{2}$$

where S_z is the in-situ stress parallel to the borehole axis, and E and ν are the Young's modulus and the Poisson's ratio of the rock, respectively. The strains ε_{max} and ε_{min} are calculated from d_{max} and d_{min} as follows:

$$\varepsilon_{max} = \frac{d_{max} - d_0}{d_0}, \quad \varepsilon_{min} = \frac{d_{min} - d_0}{d_0}. \tag{3}$$

By using ε_{max} and ε_{min} and the diameter d_θ of the core sample at a circumferential angle θ from a reference position, the strain ε_θ at θ is given by

$$\varepsilon_\theta = \frac{d_\theta - d_0}{d_0} = \varepsilon_{max}\cos^2(\theta - \alpha) + \varepsilon_{min}\sin^2(\theta - \alpha), \tag{4}$$

where α is the value of θ at the position of d_{max}. Using Eq. (3), an expression for d_θ is derived from Eq. (4) as follows,

$$d_\theta = \frac{d_{max} + d_{min}}{2} + \frac{d_{max} - d_{min}}{2}\cdot\cos 2(\theta - \alpha). \tag{5}$$

Thus, d_θ should change with θ in a sinusoidal manner with a period of π.

In contrast, by subtracting Eq. (2) from Eq. (1), in which ε_{max} and ε_{min} are substituted with the expressions of Eq. (3), the relationship between in-situ stresses and core diameters is given as follows,

$$S_{max} - S_{min} = \frac{E}{1+\nu}\frac{d_{max} - d_{min}}{d_0} \approx \frac{E}{1+\nu}\frac{d_{max} - d_{min}}{d_{min}}, \tag{6}$$

where the denominator of d_0 in the expression is replaced with d_{min}, assuming that the deformation caused by the stress relief is small. Eq. (6) indicates that the differential stress (S_{max}–S_{min}) can be determined from the measured values of d_{max} and d_{min}. If the core sample is oriented, the directions of S_{max} and S_{min}can be determined to be those of d_{max} and d_{min}, respectively.

This is the basic idea of Diametrical Core Deformation Analysis (DCDA) proposed in this paper. If a hydraulic fracturing (HF) test is carried out nearby the depth of the core sample, the magnitude of S_{max} can be determined as the sum of the differential stress (S_{max} – S_{min}) from DCDA and the S_{min} determined from the shut-in pressure measured by the HF test. The idea of combining HF test and DCDA offers an additional advantage in that the S_{max} direction can be