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Analysis of borehole breakout development using continuum damage mechanics

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ABSTRACT

Damage distribution and evolution have a significant effect on borehole stress concentrations. To model the complex fracturing process and inelastic deformation in the development of the borehole breakout, we implement a continuum damage mechanics (CDM) concept that takes tensile and compressive failure mechanisms into account. The proposed approach explicitly models the dissipative behavior of the material due to cracking and its evolution, which leads to an inhomogeneous redistribution of material properties and stresses in the vicinity of the borehole wall. We apply a constitutive plastic model for Berea sandstone and compare our numerical results to laboratory experiments performed on Tablerock sandstone. We are able to reproduce several characteristics of the failure process during the breakout development as observed in experimental tests, e.g. localized crack distribution in the vicinity of the borehole wall, damage evolution, which exhibits a widening process in the beginning followed by subsequent growth in depth, and shear fracturing-dominated breakout growth in sandstone. A comparison of our results with laboratory experiments performed on a range of stress conditions shows a good agreement of the size of borehole breakouts. The importance of the constitutive damage law in defining the failure mechanisms of the damaging processes is discussed. We show that the depth and the width of breakouts are not independent of each other and no single linear relation can be found between the size of breakouts and the magnitude of the applied stress. Consequently, only one far field principal stress component can be estimated from breakout geometry, if the other two principal stresses are known and sufficient data on the plastic parameters are available.

1. Introduction

Continuum damage mechanics (CDM) was developed based on the work of Kachanov[1] and Rabotnov,[2] who considered the creep of metal. In this concept, the progressive material damage is used to explain distributed defects in the material and structure that lead to crack initiation and coalescence to fractures. The theoretical framework was not developed further until the work of Chaboche[3] who used the general framework of thermodynamics of irreversible processes. The CDM approach does not prescribe the microcracks that cause the damage, rather it uses a damage parameter to define the effect of damage on the free energy of the system.[4] CDM has been successfully applied to model the failure process in a wide range of materials, e.g. steel,[5] concrete,[6] ceramics[7] and others. One of the success factors of this approach stems from the use of a single constitutive model that governs the nonlinear behavior of the material including failure, both in tension and compression.[8]

Modeling the expected degree of damage of a rock mass around cavities is required in many subsurface geotechnical problems such as boreholes and tunnels. The importance of the material properties on the borehole breakout development have been highlighted in some studies, e.g. Zheng et al.,[9] Sahara et al.[10] among many others. Several modeling attempts, that take into account the changes of the material properties of the rock, have been conducted in order to model the damage propagation around boreholes. Cheatham[11] modeled the damage zone around the borehole as a soft inclusion and found that the residual stiffness in soft zones developing due to the damage is sufficient to alter the stress concentration. Nawrocki and Dusseault[12] modeled the damage zone by introducing a radius-dependent Young's modulus around the borehole wall, and calculated the corresponding stress distribution around the borehole. Detournay[13] further developed the concept for a plastic material. Gaede et al.[14] incorporated aniso-

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tropy in a non-linear plastic model. Schoenball et al.[15] analyzed time-dependent breakout formation with a simplified damage mechanics approach.

Previous laboratory experiments on borehole breakouts have shown that failure of the borehole wall is often governed by two different modes: tensile spalling and shear fracturing.[16,17] Laboratory experiments can be used to study the micromechanical failure of boreholes from the condition of breakouts at the end of an experiment. However, it is difficult to explain the failure processes that lead to the final breakout shape. CDM has led to considerable progress in understanding the onset, development and stabilization of failure. It typically requires extensive testing to determine the relevant constitutive damage laws as well as the strength and yielding criteria. Busetti et al.[18] developed a CDM model to describe the progressive damage accumulation that finally leads to brittle failure in Berea sandstone. Uniaxial and triaxial tests were performed to calibrate the model. It was found that the damage and fracturing patterns simulated by the CDM match the experimental features very well.

Herein, we intend to demonstrate that CDM is able to characterize key observations of the transient development of borehole breakouts in an elastoplastic material. Our investigation allows us to account for both tensile and compressive failure. We use the single constitutive law by Lee and Fenves[8] in our modeling scheme. The damage law obtained by Busetti et al.[18] is used as a basis for the non-linear deformation involved in the simulation. A sensitivity study is performed to analyze the significance of each parameter possibly affecting the dimensions of borehole breakouts. We compare our results to available experimental data from Ewy,[19] Haimson and Lee,[20] Haimson.[21] In general, a good match between modeling and laboratory experiment results is achieved.

2. Theoretical framework

2.1. Fracturing and damage

The failure of most rock materials is a process of crack initiation and propagation. A number of approaches to model those phenomena have been proposed in the past. Many of them were formulated for a linear elastic medium, e.g. fracture mechanics based on the Griffith theory.[22] Fracture mechanics assume that a fracture grows from a small initial crack that amplifies the local stresses at the crack tip and the fracture propagates when the local stresses exceed the strength of the material. Fracture mechanics assesses the strength of a stressed material through the relationship between the loading conditions, the geometry of the crack and the resistance to crack propagation in terms of strain energy release rate (G) or stress intensity factor (K). In this approach the propagation of the fracture is modeled either by cohesive crack tip[23] or a shielding zone.[24] This model is relevant for fracture propagation in rocks that exhibit macroscopic propagation via coalescence of microcracks within a damage front. However the rock stiffness degradation due to the increase of microcrack density[25,26] cannot be modeled with fracture mechanics. Furthermore, as experiments show, there exist inelastic deformations around the crack front which contradict the assumption of a linear elastic medium.[27] These inelastic deformations could be modeled by taking into account the plasticity in the modeling scheme, i.e. the strain hardening/softening phase due to the accumulation of microcracking .[28] Macroscopically, this degraded stiffness is linked to the evolution of stress-induced damage that leads to local fracturing and, eventually, to failure.[29]

A continuum damage mechanics concept is used in this study to handle the complex material failure process and the inelastic deformation that cannot be explained by the elastic approach. With this concept the deformation of the material is simulated, based on the damage evolution due to microcrack development, which might better represent the in-situ rock behavior. Unlike the insertion of cohesive or shielding zones, damage propagation is localized within weakening zones that are determined by the plastic deformation. Yielding is characterized by nonlinear inelasticity associated with stress-induced damage accumulation.[30] This approach has several advantages. First, field and experimental studies display inelastic deformation of complex networks of fractures that cannot be explained by elastic analysis. Second, damage mechanics does not require any special assumption, such as initial perturbations or non-realistic high stresses. Third, damage fracturing does not suffer from the present computational limitations of local element enrichment formulations (e.g., the extended finite element method (XFEM)).[31]

2.2. Continuum damage mechanics (CDM)

With this study we aim to model the typical failure mechanisms occurring around borehole walls shortly after drilling, as observed in laboratory experiments. It was observed that the mechanism of breakout development is governed by tensile spalling and shear fracturing.[16,17] An attempt was made to model those failure mechanisms by taking into account the different strength criteria for tension and compression in the modeling procedure. Because the responses of a quasi-brittle material to tensile and compressive failure are quite different, it is not sufficient to represent the failure processes by a single parameter. Hence, following,[8] the parameters of the plasticity used herein are decomposed into a tension and a compression part.

2.2.1. Framework of plastic-damage model

The theory of continuum damage models has been developed using a thermodynamical approach.[3] The constitutive equations for this plastic model and its thermodynamic interpretation can be found in Lemaitre.[32] In this model, the concepts of elastic modulus (E) and stiffness reduction with increasing microcrack density are applied by using a damage parameter D as a dimensionless approximation for stiffness degradation. In the initial stage, D=0 (no degradation) and, at failure, D=1, the material is completely damaged and the stress drops to zero.

$$\frac{E}{E_0} = (1 - D) \tag{1}$$

where E and E_0 are the current and initial elastic moduli of the material, respectively.

Decomposing strain into elastic (ε^e) and plastic strain (ε^p)and incorporating the damage parameters, the stress-strain relationship can be written as follows

$$\sigma_{eff} = (1 - D)(E_0)(\varepsilon - \varepsilon^p) \tag{2}$$

where σ_{eff} is the effective stress. The effective stress concept (here unrelated to the pore pressure) is used to degrade the elastic stiffness, which in turn controls the flow rule and the shape of the yield surface.

The plastic strain represents all irreversible deformations including those caused by microcracks. An internal variable of damage state $\boldsymbol{\kappa}$ is used to represent the impact of those deformations to the elastic properties of the material. The development of damage parameter D in Eqs. (1) and (2) is then determined as a function of the damage state, $D = f(\boldsymbol{\kappa})$.

Following Lubliner et al. [4] the damage variable, denoted by $0 \le \kappa_{\aleph} \le 1$, is defined by

$$\kappa_{\aleph} = \frac{1}{g_{\aleph}} \int_0^{\varepsilon^p} \sigma_{\aleph}(\varepsilon^p) d\varepsilon^p \tag{3}$$

$$g_{\aleph} = \int_0^{\infty} \sigma_{\aleph}(\varepsilon^p) d\varepsilon^p \tag{4}$$

To distinguish tensile and compressive damage, the variable $\aleph \in \{t, c\}$ is used. It is uniaxial tensile for $\aleph = t$ and uniaxial compressive for $\aleph = c$. The term $g_{\aleph}$ is the normalized energy during microcracking. For a continuum framework $g_{\aleph}$ is the energy released during