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Three-dimensional numerical simulation of drilling-induced core damage using bonded block model

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1 INTRODUCTION

Rock mechanics parameters such as the Unconfined Compressive Strength (UCS) and the Young's modulus (E) are required at different design stages of any deep underground project. This is the case for projects involving excavations in deep mines and nuclear waste repositories, and those requiring fluid flow at depth for the energy sector (e.g., oil & gas extraction, deep geothermal, CO_2 sequestration). The standard procedure to determine these parameters is to perform laboratory tests on cored samples. The process of core drilling may induce damage in the form of micro-cracks to the cored samples particularly in deep operations, where the cores experience large stress relief during drilling. This raises a question of whether the mechanical properties of samples determined in the laboratory are representative of those in situ. The work presented here aims at introducing a numerical modeling approach that can capture core damage processes in order to quantify their impact on mechanical properties of rocks obtained from laboratory tests.

The drilling-induced core damage has been studied by several researchers using continuum (Li & Schmitt 1997, Corthésy & Leite 2008, Valley et al. 2010a) and discontinuum (Bahrani et al. 2015, Wu et al. 2018) numerical methods. However, only few have explicitly simulated this phenomenon using full three-dimensional (3D) discontinuum models (e.g., Wu et al. 2018). There are two important factors that need to be considered when using numerical models to realistically simulate core damage initiation and accumulation processes: 1) grain-scale heterogeneities due to grain shapes and geometrical arrangements (Bewick et al. 2012) as well as the stiffness contrast between mineral grains (Valley et al. 2010b); 2) complex 3D coring stress path (Bahrani et al. 2015). The former results in the generation of local tensile stresses and associated cracks at an overall stress that is much lower than the material peak strength, and the latter results in progressive initiation and accumulation of cracks inside the core at different orientations relative to the core axis.

This paper presents the results of a preliminary study using the numerical program *3DEC* and its bonded block modelling methodology (Garza-Cruz et al. 2014) to simulate drilling-induced core damage. The laboratory test data from the well documented case of AECL's Underground Research Laboratory (URL) was used for model calibration. A two-step simulation procedure was used: 1) a laboratory-scale rock specimen was first simulated in *3DEC* (Itasca 2016) and calibrated to the properties of undamaged Lac du Bonnet (LdB) granite; 2) a larger *3DEC* model was constructed to simulate the process of core drilling and associated core damage observed at the URL. The outcome of this research is a step towards a more realistic simulation of core damage, potentially offering a tool to help derive relevant rock mechanics parameters for the design of deep underground projects.

2 BONDED BLOCK MODEL OF LAC DU BONNET GRANITE

A laboratory-scale rock specimen was simulated in *3DEC* by dividing the model into several tetrahedral blocks bonded together at their triangular faces (contacts). This model is referred to as the Bonded Block

Model (BBM). The BBM has been used to simulate the failure processes of brittle rocks in *UDEC* (Gao & Stead 2014) and *3DEC* (Ghazvinian et al. 2014). In the BBMs of laboratory-scale rock specimens, the blocks and the contacts serve as grains and grain boundaries, respectively. First, a 5 cm × 10 cm cylindrical specimen was generated in *3DEC* and then converted to a BBM consisting of 9895 blocks (Fig. 1a). The UCS test was simulated by applying a constant vertical velocity to the top boundary of the specimen while the bottom boundary was fixed in the vertical direction. The simulation of direct tensile test was carried out by applying a constant vertical velocity to the top and bottom model boundaries in opposite directions. The axial stress was calculated by averaging the axial stress in the zones of blocks whose centroids fell within a 1 cm × 1 cm × 1 cm cube in the center of the specimen. The axial strain was calculated from the displacement of a grid point in the center of the top boundary of the specimen.

The BBM calibration was conducted with respect to the average UCS, direct tensile strength and elastic modulus of undamaged LdB granite. To reduce the computation time, several assumptions had to be made. For example, the grains were simulated as elastic blocks, forcing the failure to occur only at the grain boundaries. Furthermore, one mineral grain type was used in the BBM, and all the grain boundaries were assigned the same properties. The BBM calibration was initiated by adjusting the grain boundary peak tensile strength to match the direct tensile strength of undamaged LdB granite. The BBM was then calibrated to the UCS of undamaged LdB granite by adjusting the grain boundary peak cohesion, and to its Young's modulus by adjusting the grain elastic modulus and grain boundary stiffness properties. Figure 1b and c show the stress-strain curves of the calibrated BBM in the unconfined compression and direct tensile tests, respectively.

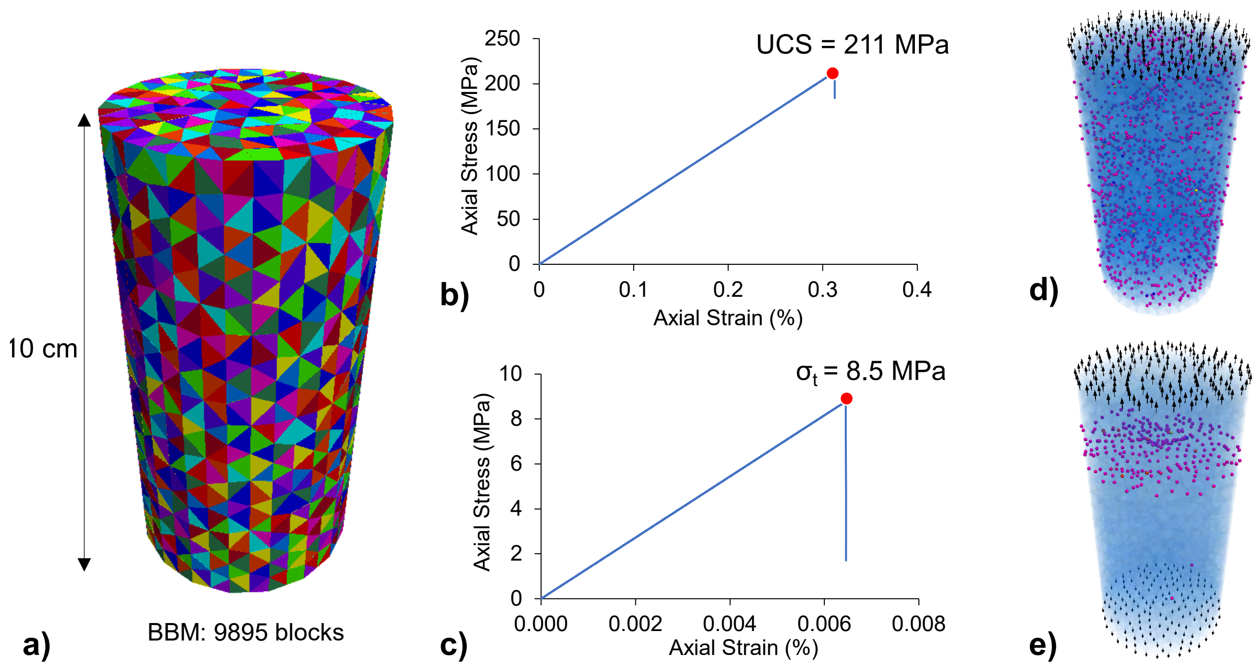

Figure 1. a) Generated BBM in *3DEC*; b and c) stress-strain curves of BBM in unconfined compression and direct tensile tests; d and e) failure modes (contact failure) of BBM in unconfined compression and direct tensile tests.

Table 1 summarizes the micro-properties obtained from the calibration process. The simulation results presented in Table 2 indicate an agreement between laboratory properties of undamaged LdB granite and macro-properties of the calibrated BBM.

The failure modes of the BBM were found to be consistent with those observed in the laboratory. In the UCS test, cracking in the BBM initiated at an axial stress of 70 MPa, which is about 30% of the peak strength. The number of cracks increased with increasing the axial stress. At the peak stress, the cracks were uniformly distributed inside the specimen (Fig. 1d). In the direct tensile test, cracking initiated at about

95% of the peak stress, and then propagated just past the peak stress to generate a single fracture perpendicular to the specimen axis (Fig. 1e). In the next section, the calibrated BBM is used as part of a larger *3DEC* model to explicitly simulate drilling-induced core damage.

Table 1. Micro-properties of calibrated BBM.

Block (grain) properties	Young's modulus (GPa)	75 GPa
	Poisson's ratio	0.22
Contact (grain boundary) properties	Normal stiffness (GPa/m)	50,000
	Shear stiffness (GPa/m)	20,000
	Peak tensile strength (MPa)	13
	Residual tensile strength (MPa)	0
	Peak cohesion (MPa)	140
	Residual cohesion (MPa)	0
	Peak friction angle (°)	0
	Residual friction angle (°)	30

Table 2. Comparison between laboratory and simulation test results for undamaged LdB granite.

Parameters	Laboratory test results	BBM macro-properties
UCS (MPa)	213 ± 20	211
σ_t (MPa)	7 ± 1	8.5
E (GPa)	65 ± 5	68

3 SIMULATION OF CORE DRILLING AND ASSOCIATED CORE DAMAGE

Several laboratory studies have been performed on samples of LdB granite at various locations from surface quarries to a depth of 420 m at the URL. Martin and Stimpson (1994) reported on changes in UCS, Young's modulus and acoustic velocity for LdB granite with increasing depth due to drilling-induced core damage. The extent of core damage is related to the drilling depth and associated in situ stress magnitudes. They identified three distinctive stress domains at the URL; no sample disturbance was encountered in domain 1 extending from surface to a depth of 200 m, however, samples retrieved from domain 2 at 240 level and domain 3 at 420m were partially to severely damaged, respectively.

3DEC was used as a coupled continuum-discontinuum model to simulate the core damage observed at three stress domains at the URL. In this approach, the discontinuum domain is used to explicitly capture the brittle damage, and the continuum domain allows for elastic stresses to redistribute far from the excavations, where brittle damage or failure is not expected (Bahrani & Hadjigeorgiou 2018). In this study, the discontinuum domain is a BBM representing a section of the core where damage is explicitly simulated. The BBM, with calibrated micro-properties summarized in Table 1, is embedded in a 60 cm × 60 cm × 60 cm continuum model with elastic properties of undamaged LdB granite. Figure 2a presents the geometry of the *3DEC* model showing the core in the continuum and discontinuum domains. The total length of the core is 55 cm. Several excavation stages were used to capture the progressive drilling process. The simulation of core drilling starts from one side of the *3DEC* model. The first 30 cm of the core is inside the elastic continuum domain. The core length in the discontinuum domain (BBM) is 10 cm. The drilling in this domain is simulated in 10 excavation stages with 1 cm drilling advance per stage. After the BBM is cored, the drilling simulation continues in the continuum domain with a length of 15 cm. Figure 2b shows the core in the discontinuum domain before and after drilling.

Core drilling simulations were carried out for three stress domains at the URL (Fig. 2c). The boreholes were assumed to be vertical, therefore aligned with the vertical stress component (Sv). Figure 2d shows the simulated core damage (failed contacts in BBM) in three stress domains. The simulation results indicate that the amount of core damage increases from domain 1 to 3. In domain 1, no damage is observed inside the core, while sporadic failed contacts appear at the outer surface of the core. In domain 2, more systematic damage can be seen at the core boundary. The core in domain 3 is heavily damaged. It is therefore concluded that the proposed coupled continuum-discontinuum numerical modeling approach can capture the drilling-induced core damage observed at different stress domains at the URL (compare Fig. 2c and Fig. 2d).

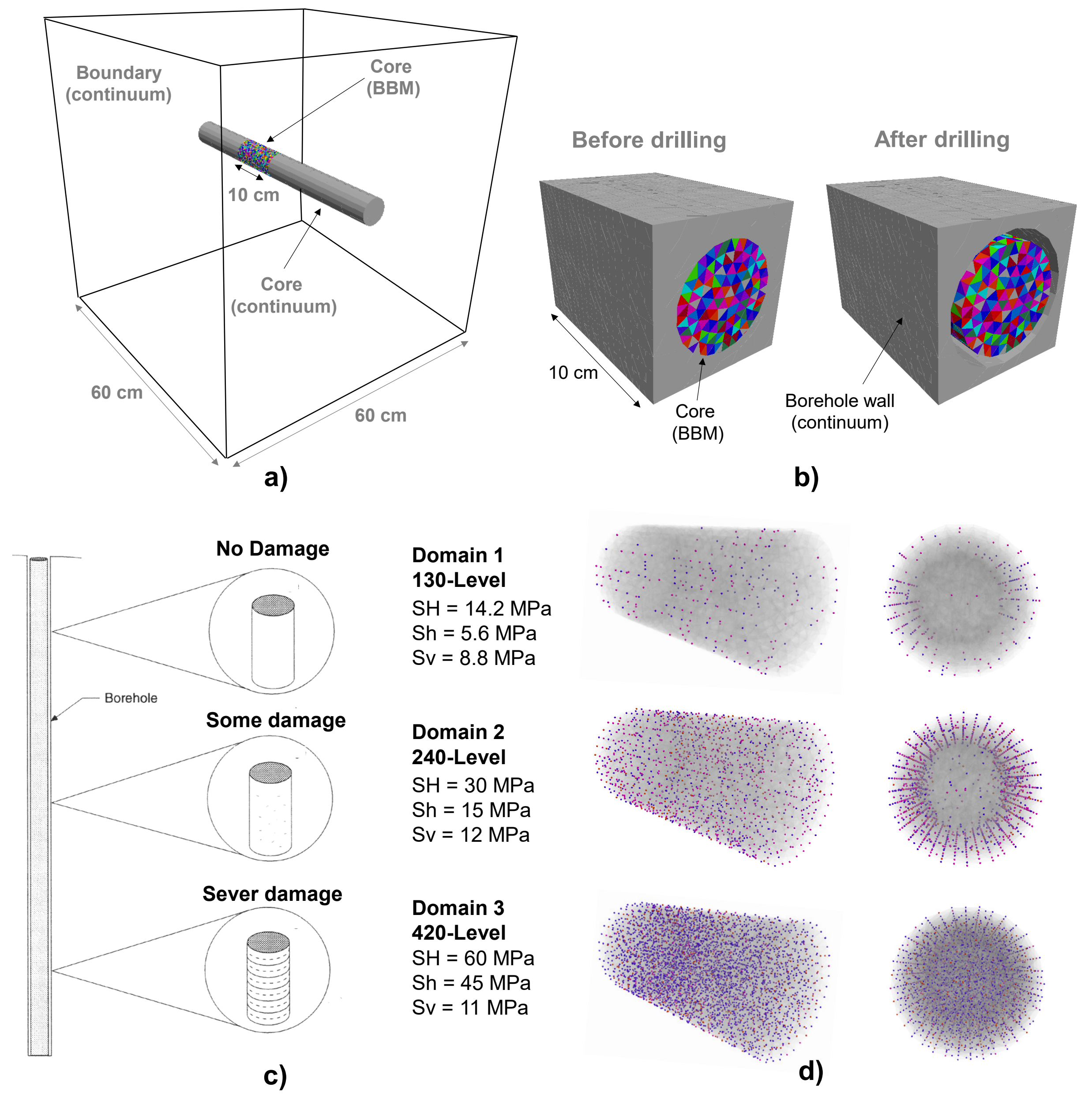

Figure 2. a) *3DEC* model showing the core in the continuum and discontinuum domains; b) BBM before and after drilling; c) observed core damage at three stress domains at URL (after Martin and Stimpson, 1994); and d) simulated core damage (contact failure) using BBM at three stress domains.

4 CONCLUSIONS

The results of preliminary numerical simulations presented in this paper demonstrated the capability of the proposed continuum-discontinuum modeling approach for realistically simulating drilling-induced core damage. It was found that the calibrated BBM can capture different levels of core damage observed at three stress domains at the URL. Several improvements to the proposed modeling approach are foreseen for future studies, e.g., the use of more realistic grain geometries and the consideration of grain property heterogeneities. Following recent findings of Bahrani et al. (2019), the proposed modeling approach will be used to further investigate the influence of core damage on the results of core-based stress measurement techniques such as the Kaiser effect and overcoring methods.

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