Novel numerical approach to modeling excavation in hard rocks

Erick Rógenes
University of Brasília / DF+ Engenharia, Belo Horizonte, Brazil

Leandro Rasmussen
University of Brasília, Brasília, Brazil

Márcio de Farias
University of Brasília, Brasília, Brazil

Alessandra Gomes
DF+ Engenharia, Belo Horizonte, Brazil

ABSTRACT: In this work, a new numerical approach based on the Finite Element Method and an implicit continuum formulation, called Continuum Voronoi Block Model-CVBM, is proposed to represent the fracturing process in hard rocks and also the rupture of underground works with high field stresses. In this model, developed with the RS2 program, the rock mass was simulated by a set of blocks, formed by a Voronoi mosaic, joined at their interfaces by joint elements. Different case studies were represented on a laboratory and field scale. The model proved to be robust on the laboratory scale and described the rock's relevant macro-properties in conventional tests: crack initiation stress, crack damage stress, and peak strength. On a field scale, the model represented the mass deterioration process explicitly, captured the rupture geometry, and the excavations' displacements. Such results show the CVBM's potential for modelling the behavior of underground works with high field stress.

Keywords: Brittle Failure, FEM Model, Voronoi Tessellation, Hard Rocks.

1 INTRODUTION

Underground works may involve excavation in hard rock with high field stresses. These works commonly have a brittle failure process during the excavation steps, known as spalling. The deteriorated rock mass tends to increase in volume due to fracture opening, shear between planes, and geometric incompatibility between blocks. This volume in-crease promotes excessive convergence displacements known as bulking (Diederichs 2007, Kaiser 2016).

Researchers have developed constitutive models to represent this type of failure, based on the concept of initial cohesive strength demobilization followed by subsequent mobilization of frictional strength (Diederichs 2007). These models have been applied to predict the depth of failure in underground excavations caused by spalling. However, the physical processes related to the damage and loss of integrity are not explicitly represented, and bulking is not captured either.

From these limitations, a new numerical approach for rock mass simulation was developed in this work, which is called the Continuum Voronoi Block Model-CVBM. The CVBM is a pseudo-discontinuum modeling technique based on the Finite Element Meth-od-FEM, implemented using the RS2 software. (Rocscience 2019). This model uses Voronoi cells interconnected by Goodman joint elements (Goodman et al. 1968) to represent the rock mass.

The ability of the CVBM to produce numerical results compatible with the hard-rock behavior is demonstrated through numerical laboratory tests (Creighton granite) and field-scale simulation (Mine-By tunnel and Creighton pillar). The model proved to be robust on the laboratory-scale and described the rock's relevant macro-properties in conventional tests: crack initiation stress (CI), crack damage stress (CD), simple and triaxial compression strength, tensile strength, Young's modulus and Poisson's ratio. On a field-scale, the model represented the mass deterioration process explicitly, captured the rupture geometry, and the excavations' convergence displacements.

Of note, this paper presents a brief view of the works made with CVBM. For more de-tails about this numerical approach and the study of cases shown, the reader is referred to the work of Rógenes (2021) and Rógenes et al. (2021, 2022, 2023)

2 CONTINUUM VORONOI BLOCK MODEL

The Continuum Voronoi Block Model was built using the Rocsciense software RS2, a two-dimensional numerical program based on the FEM. In this model, the rock mass is represented as a set of elastoplastic particles (also called cells or blocks) joined at their interfaces by joint elements. The particles are established from a Voronoi mosaic, and a finite element mesh internally discretizes each block. Goodman joint elements (Goodman et al. 1968) are inserted at the edges of the particles, which allow the simulation of blocks interaction.

The term Continuum Voronoi Block Model was first used by Rógenes et al. (2021) to define this pseudo-discontinuum modeling technique based on FEM method. Figure 1 shows the CVBM discretization process, the juxtaposed Voronoi blocks, and the FEM mesh inside each block.

This tool was developed based on the minerals' geometric heterogeneity role in the fracture process, stated by Lan et al. (2010) as the primary component for promoting a heterogeneous stress flow within the rock. The Voronoi mosaic promotes this geometric heterogeneity, inducing tensile stress in the joints and inside the particles, the same mechanism that occurs inside the rock when compressed. Thus, the behavior of hard rocks emerges in the numerical model.

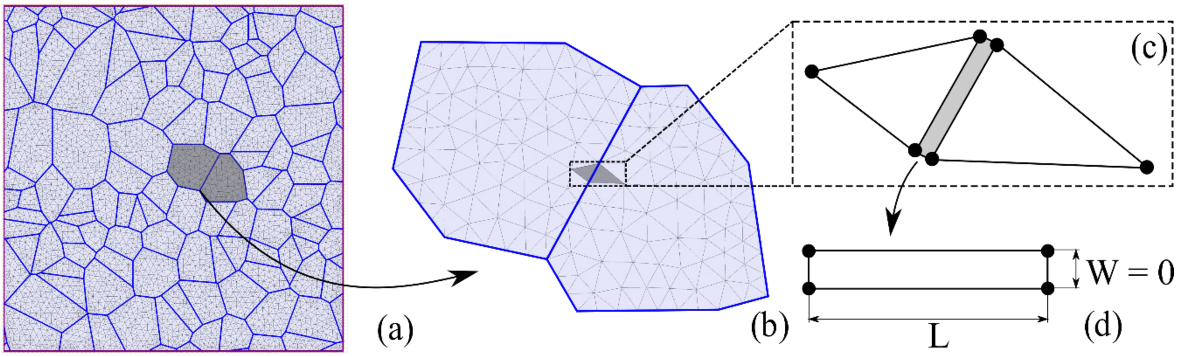

Figure 2. (a) Discretization process used by Continuum Voronoi Block Model (CVBM), (b) Voronoi blocks, (c) FEM mesh, and (d) Goodman's joint element in the interface between two blocks (Rógenes et al. 2021).

RS2 allows different failure criteria to be adopted for Voronoi blocks and joint elements. The Mohr-Coulomb criterion was used coupled to the Rankine criterion. An advantage in adopting the Mohr-Coulomb criterion is that its parameters have simple physical meaning, thus providing a better phenomenological interpretation of the model's results.

Similar modeling concepts have been used to simulate different field scale phenomena such as the effects of rock mass heterogeneity on in-situ stresses, rock plateau toppling, and intrablock structures (Kaiser 2016, Day et al. 2019). These results encourage the use of CVBM to represent the brittle failure process in hard-rock pillars.

3 LABORATORY-SCALE STUDIES

To show the CVBM's ability to represent hard rocks' behavior, a granite located at the Creighton Mine, in Sudbury, Canada, was chosen. Creighton Mine is one the deepest in the world, and the material studied was collected at a depth of 2.4 km. Creighton granite was subjected to several unconfined compression tests, triaxial compression tests, and Brazilian tests. The laboratory results were published by Walton (2014).

3.1 Model setup

Numerical models were developed for the same tests to which the Creighton Granite was subjected in the laboratory. The sample used in these simulations is 55 mm in diameter and 120 mm in length (Figure 2). All simulations were conducted with controlled deformation to facilitate the convergence of the implicit solution scheme after failure.

In defining the Voronoi blocks' size, an average joint length of 2 mm was applied (Sinha & Walton 2020). It should be pointed that this value is intended to respect the mean grain size, not to mimic precisely the grain size distribution. The discretization inside the blocks was done with six-noded triangular elements.

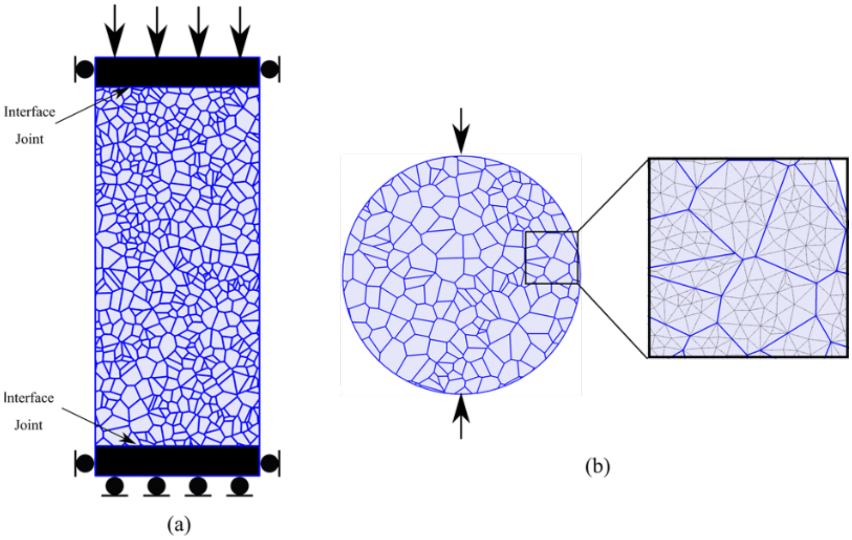

Figure 2. (a) Model setup for unconfined and triaxial compression tests, and (b) Brazilian test

The parameters reported by Sinha & Walton (2020) to match the laboratory test results for Creighton granite in a homogeneous inelastic DEM model were adopted as a starting point for the CVBM's calibration. Through a trial and error process, each numerical micro-property was individually modified. From this method, a set of values was found to represent Creighton granite's behavior in the CVBM model. These results are presented in Table 1 (superscript a).

3.2 Model setup

The models developed to simulate the field-scale cases are presented in Figure 4. The excavation sequencing was performed in different stages using the stress relaxation method. To reduce the numerical cost, the CVBM was applied at a specific location, the excavation boundary, where the spalling and bulking are expected to occur.

When attempting to model field scale problems using Voronoi tessellation, a key issue is selecting an appropriate block size. Since using the same block size as in the laboratory scale Voronoi models would be computationally restrictive, an average joint length of 7.5 cm was used. This value is compatible with the size commonly used for filed scale simulation (Rasmussen & Farias 2019). The discretization inside the Voronoi blocks was done with six-node triangular finite element mesh.

The CVBM parameters were first estimated by laboratory tests simulation and posteriorly adjusted to match the field behavior in terms of monitoring displacement and depth of failure. The parameters applied in the simulations were resumed in Table 1 (superscripts b and c).

Table 1. CVBM parameters.

Type	Voronoi Block		Joint	
Elastic Parameters	Young's Modulus (GPa)	75^{a}; 90^{b}; 85^{c}	Normal Stiffness (TPa/m)	$45{,}0^{a}$; $1{,}2^{b}$; $2{,}2^{c}$
	Poisson's Ratio	0.25^{a}; $0.19^{b;}$ 0.20^{c}	Shear Stiffness (TPa/m)	$28{,}0^{a}$; $0{,}8^{b}$; $0{,}4^{c}$
Peak Strength	Peak Cohesion (MPa)	$100^{a,b}$; 45^{c}	Peak Cohesion (MPa)	60^{a}; 65^{b}; 20^{c}
	Peak Friction Angle (°)	$55^{a,b,c}$	Peak Friction Angle (°)	45^{a}; 42^{b}; 55^{c}
	Peak Tensile Strength (MPa)	38^{a}; 14^{b}; 19^{c}	Peak Tensile Strength (MPa)	15^{a}; 6^{b}; 47^{c}
Residual Strength	Residual Cohesion (MPa)	$0^{a,b,c}$	Residual Cohesion (MPa)	$0^{a,b,c}$
	Residual Friction Angle (°)	$30^{a,b}$; 10^{c}	Residual Friction Angle (°)	20^{a}; $10^{b,c}$
	Residual Tensile Strength (MPa)	$0^{a,b,c}$	Residual Tensile Strength (MPa)	$0^{a,b,c}$
	Dilation Angle (°)	$30^{a,b}$; 10^{c}	-	-

[a] For Creighton Granite in laboratory scale; [b] For Mine-By tunnel; [c] For Creighton mine pillar.

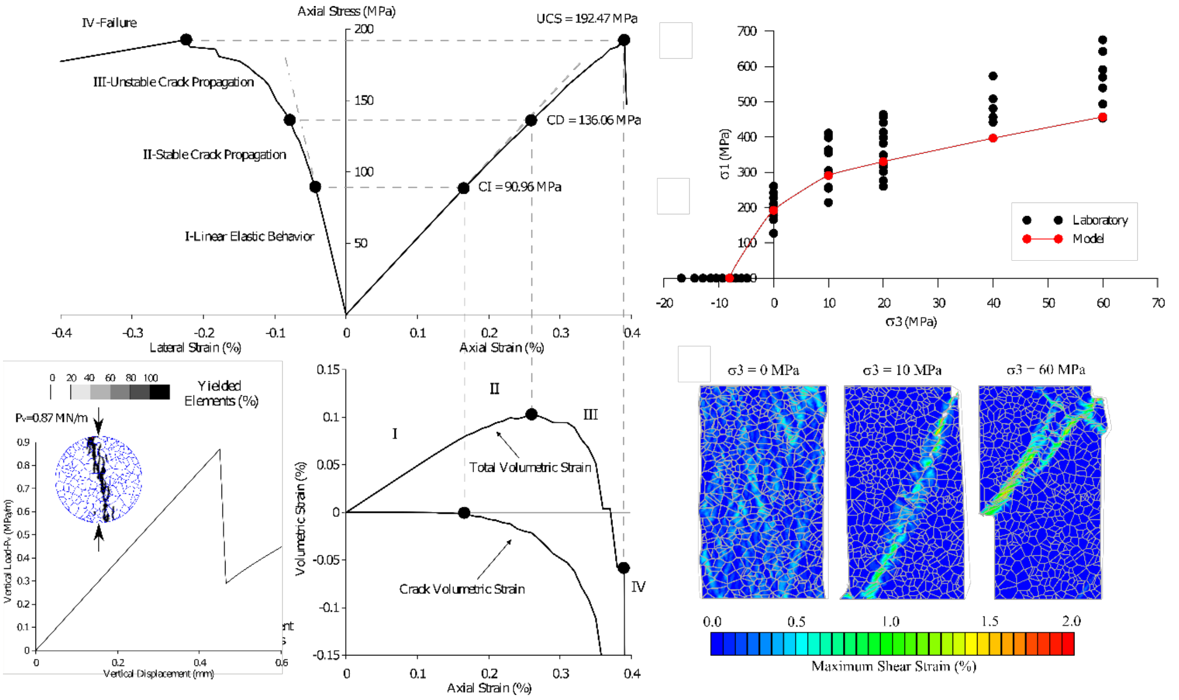

Figure 3. Numerical results from laboratory test simulations of Creighton granite.

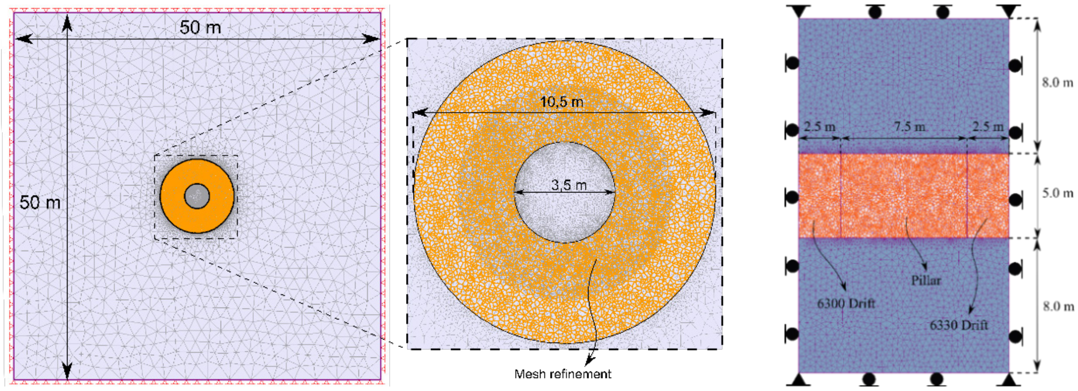

Figure 4. Model setups for field-scale simulations.

3.3 *Results and Discussions*

The failure regions in the simulations are presented in Figure 5 by the yielded elements and joints. The CVBM model captured the formation of wing cracks, which interconnect and give rise to fractures parallel to the excavation face. These fractures occur at different depths and generate intact rock slabs. It is possible to verify that the model captured the failure mechanism expected for a rock in highly stressed ground: a V-shaped notch, as reported by Diederichs (2003).

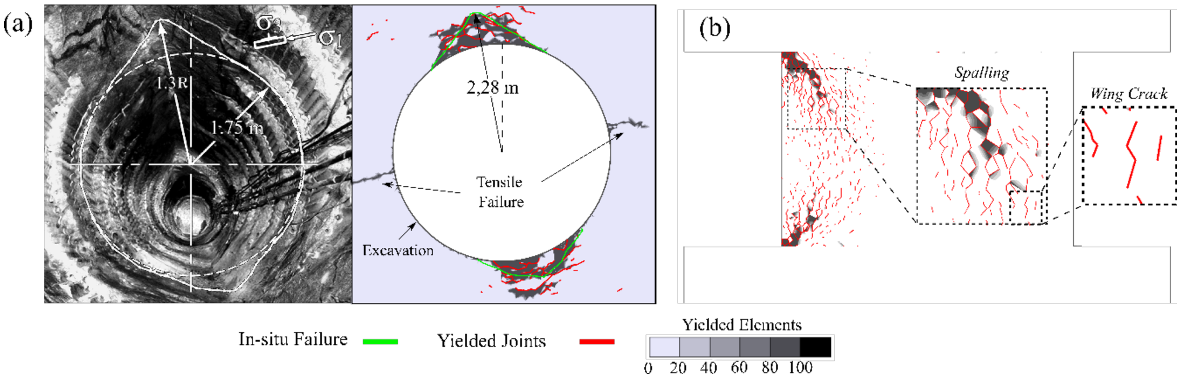

Figure 5. The spalling process demonstrated through yielded elements and joints: (a) tunnel and (b) pillar.

The CVBM also captured the displacements promoted by bulking, as shown in Figure 6. The displacement distribution assumes an irregular and heterogeneous shape due to the role of the Voronoi blocks, which incorporate geometric incompatibility in the model, one of the main causes of the bulking phenomenon, according to Kaiser (2016).

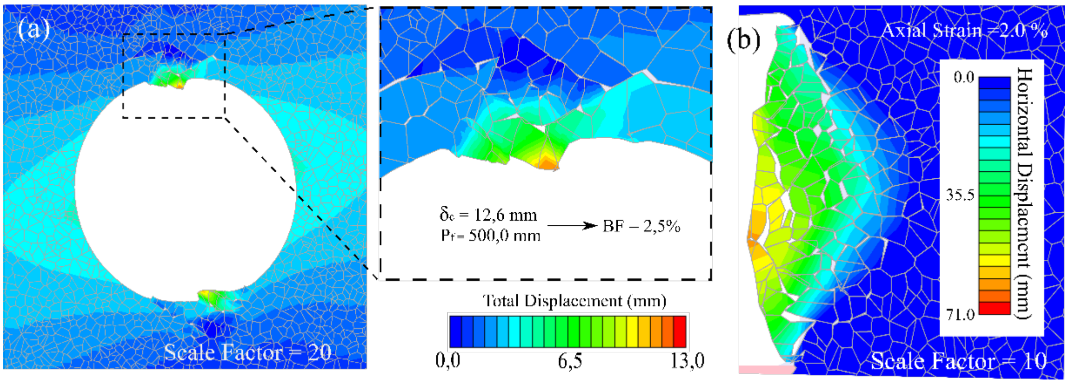

Figure 6. Total displacement due to bulking at field-scale simulation: (a) tunnel and (b) pillar.

4 CONCLUSIONS

In this work, a numerical model was presented to represent the fracture process in hard rocks based on the pseudo-discontinuum method called Continuum Voronoi Block Model-CVBM. To validate this tool, numerical models for the Brazilian test, unconfined compression test, and triaxial compression tests were calibrated to match laboratory test results for Creighton granite. The behavior of hard-rock mine excavation subjected to high field stresses was also simulated. Numerical analyses of the Mine-By tunnel and the Creighton mine pillar were performed to verify the potential of this numerical tool.

CVBM made it possible to simulate some of the rock's behavior in the laboratory, such as: the elastic properties (Young's modulus, Poisson's ratio); the tensile strength; the crack initiation and crack damage in the unconfined and confined conditions; and the changing of failure mechanism from axial splitting (unconfined test) to shear in a plane (confined test).

In field-scale studs, the CVBM explicitly showed the formation of wing cracks, macro-fractures parallel to the excavation wall, intact rock slabs, and V-shaped notches. All components are related to brittle failure.

The studies presented in this work confirm the CVBM as a potential tool for numerical modeling of underground works subjected to high stresses. Previous works did not simultaneously represent the laboratory-scale properties (peak strength, crack initiation, and crack damage) and field-scale behavior (spalling and bulking) through a pseudo-discontinuum method, as was done with CVBM. Moreover, the numerical model proposed in this research can promote the expansion of bonded block models to represent hard rocks beyond the academic scope, considering that programs based on the Finite Element Method, such as RS2, have relative accessibility and enjoy widespread recognition within the geotechnical community.

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