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Numerical modeling of Rock Spalling in the Mine-by Experiment, using Zero-Thickness Interface Elements with a Fracture-based Visco-Plastic Constitutive Model

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Abstract

The precise extent and opening of cracks and fractures in the rock mass around waste disposal facilities is an important element of concern because of the potential detrimental effect on the effective long term sealing of the repository. This is the main motivation for this study, focused on the rock spalling observed in the Mine-by test tunnel of the AEC laboratory (Canada), located at a depth of 420 m in the massive brittle granite of Lac du Bonnet, where high horizontal initial stresses have led to significant spalling which has been widely documented in the literature. The present numerical study is based on the FEM with zero-thickness interface elements (FEM-z). These elements are equipped with an energy-based work-softening constitutive model incorporating Fracture Mechanics parameters. The model is implemented in two versions: elasto-plastic and visco-plastic. Visco-plasticity is used primarily as a numerical tool in the context of the visco-plastic relaxation strategy, although it also opens the door to considering the physical time evolution of fractures and spalling as observed in the field. The procedure developed includes one or more excavation stages, each of which consists of removal of elements and application of the corresponding contact forces, which leads to stress redistribution around the excavated area and potentially to opening/sliding of existing or new cracks. A first excavation involves the tunnel cross-section. Additional excavation stages may be necessary to remove continuum elements or blocks that become completely surrounded by open cracks as the result of previous excavation stages. The methodology is applied to the Mine-by case. The results obtained show that the procedure employed is capable of leading to the observed spalling using parameters and assumptions which are in agreement with the information available for the site.

Keywords

Spalling, Fracture Mechanics, Finite Element Method (FEM-z), Visco-plastic model

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1 Introduction and Background

Rock spalling around tunnels or underground excavations is characterized by the formation of rock slabs, typically occurring in brittle rock subject to high in situ stresses. A good understanding of the spalling phenomenon and the extent of cracking that is involved in the vicinity of the opening, is crucial for the safe design of nuclear waste repositories and the correct evaluation of the sealing conditions. However, the numerical modeling of rock spalling is not a straight-forward task. A variety of strategies have been proposed in the literature, which may be grouped into three categories: continuum-based models, discrete models and mixed models. In continuum-based models, also known as smeared crack models, the crack deformations (opening/sliding) are considered included as part of the deformations of the continuum constitutive model, typically based on frameworks such as elasto-plasticity or continuum damage mechanics. A variety of models of this type have been proposed using failure criteria such as Hoek-Brown or Mohr-Coulomb, or more complex schemes such as the Cohesion Weakening-Friction Strengthening (CWFS) model developed by Hajiabdolmajid et al. (2000), or the model proposed by Saceanu et al. (2022) based on continuum damage mechanics and the calculation of stress intensity factors (SIFs) at each Gauss point. However, these models generally fail to capture the actual extent and depth of brittle failure in rock masses, and do not provide a physical representation of the change of geometry and stress redistributions implied in the spalling phenomenon.

Although continuum-based models may provide results consistent with field observations, continuum kinematics is unable to explicitly represent the localized deformations associated to fractures. In contrast, discrete models are better suited for this purpose because they can more accurately represent fractures and their associated behavior. The most widely utilized method within the discrete approach is the Distinct Element Method (DEM), initially developed for granular materials by Cundall and Strack (1979). This method was later adapted for rock materials under the name Bounded Particle Model (BPM) by Potyondy and Cundall (2004). In BPM models, the continuum is discretized into small, rigid particles, each represented by a central point. These particles interact through deformable beams capable of transmitting both normal and shear forces. Building on these methods, the Finite Discrete Element Method (FDEM) was introduced as a hybrid approach, combining the strengths of continuum and discrete techniques. FDEM is more effective for modeling spalling. However, this approach is typically formulated as an explicitly dynamic scheme, with the advantage that it can do it as it can track individual fragments spalled (something in general not required), but the disadvantage that it typically requires a very large number of elements and (especially) of time steps to achieve accurate results.

In the context described, the proposed model is a discrete approach based on the Finite Element Method combined with zero-thickness interface or "cohesive" elements as introduced by Goodman, (1968). These elements may be inserted along the contact surfaces in between continuum finite elements and are used for the discrete representation of discontinuities or fractures. The constitutive laws for the interface elements follow a recent visco-plastic extension of an existing fracture-based elasto-plastic formulation (Jaqués and Carol, 2024). Another crucial feature of the model is the excavation strategy for the elements that detach during the spalling process, along with the subsequent redistribution of stresses following each excavation stage.

The proposed model has been validated using a well-documented case, the Mine-by Experiment, realized at the Underground Research Laboratory (URL) in Canada, which provides invaluable insights into spalling phenomena in deep rock excavations and has become a popular benchmark example for this type of problem in the literature.

2 Numerical model and excavation process

2.1 Zero-Thickness Interface Elements and Visco-plastic Constitutive model

Zero-thickness interface elements were introduced by Goodman (1968). These elements, later also known as "cohesive elements", are special elements which may be inserted in between two adjacent continuum elements in order to represent the possibility of relative displacements between them, such as opening or sliding. Zero-thickness elements share the nodes with the adjacent continuum elements, and therefore take the form of line elements (in 2D) or surface elements (in 3D) with the peculiarity of exhibiting double nodes. The constitutive laws for these elements are expressed in terms of the normal and shear component of the stress tractions ("stress") and the corresponding components of the relative displacements ("strain"). The detailed formulation of those elements, together with some elasto-plastic constitutive model, may be found elsewhere (e.g. Gens et al, 1988, 1995).

Zero-thickness interface elements were originally used to represent geomechanical discontinuities or contact surfaces between different materials (Gens et al, 1990), but with the appropriate constitutive laws they may be also used to represent developing cracks (López et al, 2008). For that purpose, it is crucial that the constitutive law incorporates softening and fracture energy parameters. One such model was proposed by Carol et al, (1997), and later improved by Caballero et al (2008). Recently, the same formulation was extended to Perzyna visco-plasticity by Jaqués and Carol (2024), which is the formulation used in this study.

In Perzyna visco-plasticity (Perzyna, 1966), total "strain" is decomposed into the elastic part $\boldsymbol{r}^{el}$ and the visco-plastic part $\boldsymbol{r}^{vp}$, and the elastic part is assumed related to stresses via linear elasticity

$$\boldsymbol{r} = \boldsymbol{r}^{el} + \boldsymbol{r}^{vp} \tag{1}$$

$$\boldsymbol{r}^{el} = \boldsymbol{D}_0^{-1}\colon \boldsymbol{\sigma}_J \tag{2}$$

where $\boldsymbol{D}_0^{-1}$ is the elastic compliance matrix and $\boldsymbol{\sigma}_J$ the vector of interface stress tractions. The visco-plastic strain is expressed in rate form as:

$$\dot{\boldsymbol{r}}^{vp} = \frac{1}{\eta}\psi(\langle F\rangle)\boldsymbol{m} \tag{3}$$

$$\psi(\langle F\rangle) = \left[\frac{\langle F\rangle}{\bar{F}}\right]^N \tag{4}$$

where η is the viscosity of the material, F is the cracking surface of the interface, $\bar{F}$ represents a normalizing factor, N is a the Perzyna's visco-plasticity parameter that should satisfy $N \geq 1$, and $\boldsymbol{m}$ is the flow rule. The McAuley brackets in equation (3) indicate that:

$$\langle F\rangle = \begin{cases} F, & if \;\; F > 0 \\ 0, & if \;\; F \leq 0 \end{cases} \tag{5}$$

Jaqués and Carol (2024) extend formulations to the case of Hardening/Softening (H/S). The cracking surface of the interface is defined as $F = 0$ with a hyperbolic cracking function F defined as:

$$F(\boldsymbol{\sigma}_{\mathrm{J}}, \boldsymbol{p}) = -(c - \sigma_N \tan\phi) + \sqrt{\sigma_T^2 + (c - \chi\tan\phi)^2} \tag{6}$$

where c is the cohesion, χ the uniaxial tensile strength and tan ϕ the tangent of the internal friction angle. In order to represent the softening, these parameters evolve in terms of a single history variable: the work spent in fracture process (W^{vcr}) which is defined in incremental form:

$$dW^{vcr} = \begin{cases} \bar{\boldsymbol{\sigma}}_{\mathrm{J}} : d\boldsymbol{r}^{cr} & if \quad \sigma_N \geq 0\ (tension) \\ (\overline{\sigma_T} + \overline{\sigma_N}\tan\phi)dr_T^{cr} & if \quad \sigma_N < 0\ (compression) \end{cases} \tag{7}$$

where it is important to note that $\bar{\boldsymbol{\sigma}}_{\mathrm{J}}$ is the stress projected on the cracking surface (since, in the visco-plastic model the interface stress $\boldsymbol{\sigma}_{\mathrm{J}}$ may be outside the surface). The evolution laws for c, χ and tanϕ, consist of decay functions with W^{vcr}, such that tensile strength χ vanishes when W^{vcr} reaches the value of G_f^I (fracture energy parameter in tensile mode *I*), and the apparent cohesion c vanishes and when W^{vcr} reaches G_f^{IIa} (fracture energy parameter in asymptotic shear-compression mode *IIa*). Further details of the model formulation and implementation as well as some examples of constitutive application may be found in Jaqués and Carol (2024).

2.2 Excavation strategy

Spalling is the formation of thin blocks or slabs around a tunnel as the result of cracking caused by stress redistribution. Physically, roof or wall blocks fall under the influence of gravity when the cohesive or frictional resistance is lost. In the calculation, once the blocks have been identified as detached from the surrounding rock, they are effectively removed from the system, allowing the stress equilibrium within the surrounding rock mass to be re-established.

Potts et al. (2001) describes the various approaches for geomechanical excavation. In this case, the methodology implemented is similar to the one described by Garolera et al. (2019), and consists of the following steps:

1. Identifying the interface elements that reach the established failure condition, and checking whether a continuous path of failed interfaces isolate a blocks from the rest of the rock mass. In this case, the failure criterion has been established as the fracture work reaching the value of the fracture energy mode $I\left(W^{vcr} = G_f^I\right)$.
2. Removing the isolated block and replacing it by the equivalent contact forces. This process consists of two sub-steps:
    a. Calculation of the equivalent forces as the integral of stress over the block to be removed or excavated, plus the external forces acting on the same block.

$$\boldsymbol{F}_{equiv} = \int_{\Omega_t} \boldsymbol{B}^T \boldsymbol{\sigma}' \mathrm{d}\Omega + \boldsymbol{F}_{block}^{ext} \tag{8}$$

    b. Assembling the equivalent forces into a global load vector and applying them to the excavation boundary as the block elements are removed from the mesh.
3. Applying excavation forces, defined as the negative of the equivalent forces.

$$\boldsymbol{F}_{excav} = -\boldsymbol{F}_{equiv} \tag{9}$$

The application of the excavation forces will in general be carried out in small increments to facilitate numerical convergence.

3 Numerical simulation of the Mine-by experiment

The "Mine-by Experiment" included the excavation of a 3.5m diameter tunnel at a depth of 420 meters. The tunnel longitudinal axis was aligned with the intermediate principal stress direction (σ_2), while the major and minor principal stresses (σ_1 and σ_3) were near horizontal and near vertical with magnitudes of 60 MPa and 11 MPa, respectively. The maximum principal stress is oriented 14 degrees counterclockwise from the horizontal, and the minimum principal stress is perpendicular to it. In the calculation, gravity forces have not been considered and the principal stresses have been assumed aligned with the horizontal and vertical axes to simplify the boundary conditions. However, the results depicted in Fig. 3 and 4 are rotated slightly to be displayed with the correct physical orientation.

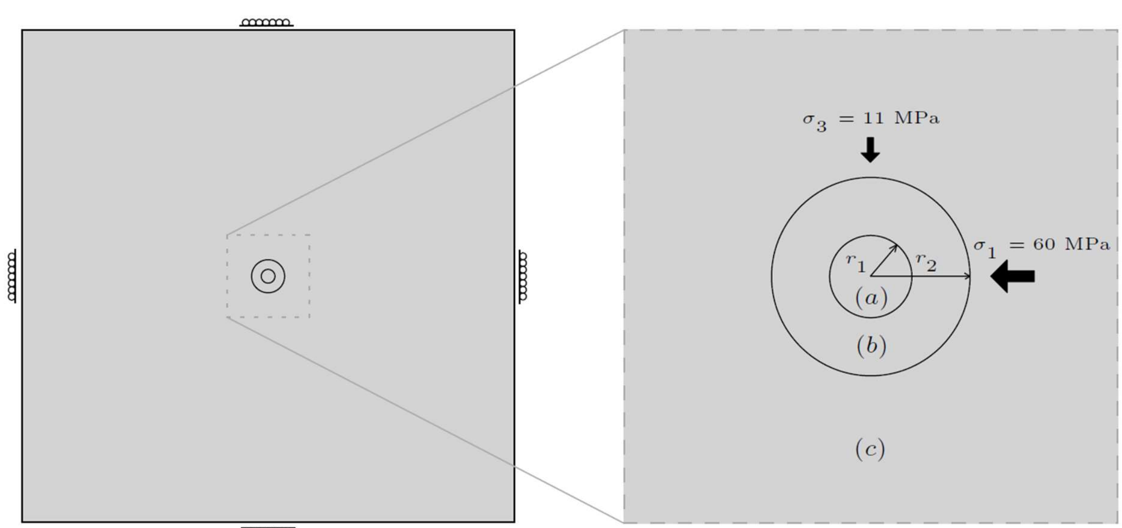

Fig. 1 Geometric domain of the Mine-by Experiment model, showing the detailed referenced zones and the initial stress conditions. Gravity effects are neglected, allowing the principal stresses to be aligned with the horizontal and vertical axes.

The experiment was conducted in the massive Lac du Bonnet granite, whose material properties were measured in the laboratory for the intact rock. Using the data reported (Martin, 1993; Martin and Kaiser, 1996; Ohta and Chandler, 1997; Hajiabdolmajid et al., 2000), the parameters of the constitutive fracture law (Eq. 6) were calibrated leading to the values presented in Table 1.

Table 1 The rock mass material properties utilized for the modeling

Mechanical properties	**Value**
Rock mass Young's modulus	$E = 60\ 000$ MPa
Poison's ratio	$\nu = 0.2$
Tensile strength	$\chi_0 = 7$ MPa
Cohesion	$c_0 = 20$ MPa
Friction angle	$\phi_0 = 48°$
Residual friction angle	$\phi_0^{res} = 43°$
Fracture energy (mode I)	$G_f^I = 5.0 \cdot 10^{-4}$ MN/m
Fracture energy (mode IIa)	$G_f^I = 5.0 \cdot 10^{-2}$ MN/m

For the analysis, a two-dimensional domain of 120x120 meters has been considered with the tunnel at the center and sufficient distance to the domain limits to avoid boundary effects. As represented in Figure 1, the domain is divided into three zones: (a) the tunnel zone to be excavated, (b) the spalling or fracture zone, and (c) the external zone. The main focus of interest is on region (b), where spalling may occur. A finer mesh is used in this zone, and interface elements are introduced along all mesh lines in order to provide sufficient freedom for the cracks to develop. In contrast, zones (a) and (c) only include continuum elements, as they are only necessary to obtain the elastic stresses and replicate realistic boundary conditions.

As shown in Figure 2, the procedure for tunnel excavation and spalling consists of multiple stages, reflecting the evolving geometry of the problem with each successive excavation. The initial stage, or Stage 1, considers a complete cross-section before the tunnel excavation. External forces are applied and initial stresses are generated. In Stage 2, the tunnel is excavated; the corresponding elements are removed and replaced with the equivalent forces, and then the excavation forces are applied progressively in a number of small steps in combination with the time steps of the visco-plastic model. Once the visco-plastic procedure has been completed and a new equilibrated stress state has been reached, the state of cracking is inspected to determine whether any blocks have become detached according to the criterion described in Section 2.2. If this is the case, these blocks are excavated, and Steps 1-2-3 in Stage 2 are repeated as many times as necessary. The process is concluded when no further detached blocks or layers can be identified.

The simulation of the Mine-by experiment using the workflow described in Figure 2, leads to nine sequential excavation stages which are illustrated in Figure 3.

According to the results obtained, spalling occurs in the upper (roof) and the lower (floor) parts of the tunnel cross-section, which are subject to shear-compression cracking of the interfaces. The final average spalling depth is 2.35 m (calculated based on the average length from floor to roof at the lowest point.). This spalling depth is consistent with observations from the AECL experimental laboratory (Martin, 1997; Ohta and Chandler, 1997) and is in line with results reported by other authors (Hajiabdolmajid et al. 2000; Zhao et al. 2010).

The results also show that the above mentioned spalling is accompanied by the formation of a network of fractures in the rock mass extending over two meters left and right of the tunnel (Fig. 4). In the case of a nuclear waste repository, the information about this kind of "hidden" cracking (not visible from the tunnel interior), may be crucial for guaranteeing the structural integrity of the repository and for determining the optimal spacing between nuclear waste tunnels to prevent interconnection and potential leakage.

A more detailed description of the analyses performed and the results obtained using the proposed methodology may be found in Crusat et al (2025).

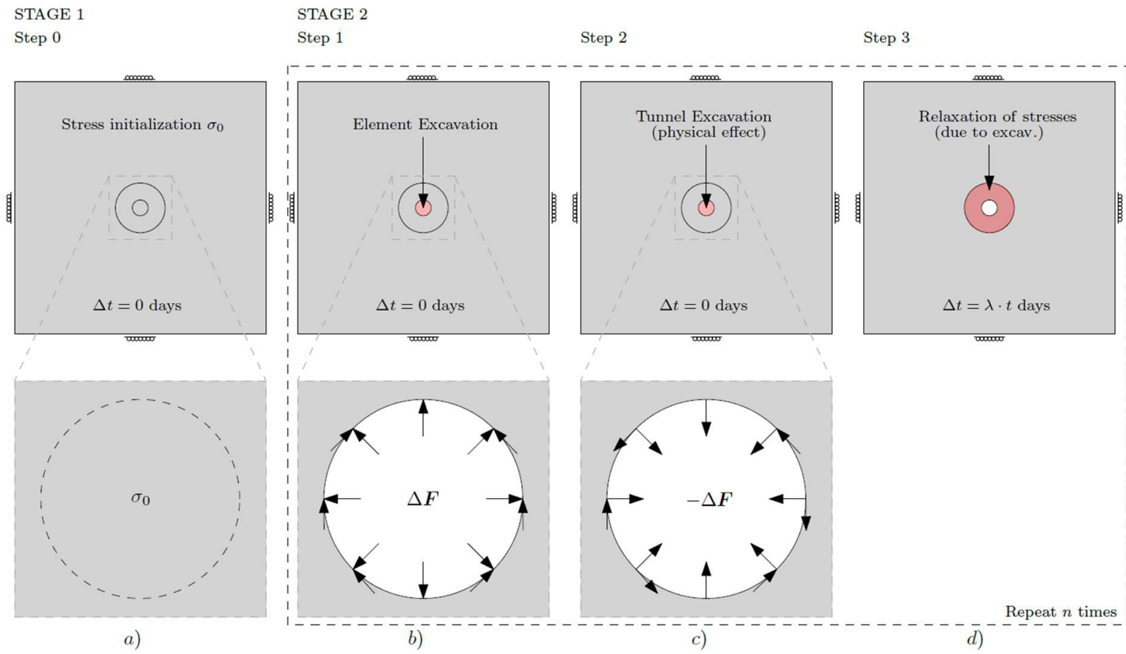

Fig. 2 Boundary conditions applied at each step of the simulation to model the spalling phenomenon. Additionally, a detailed representation of the excavation process employing the strategy of applying equivalent forces.

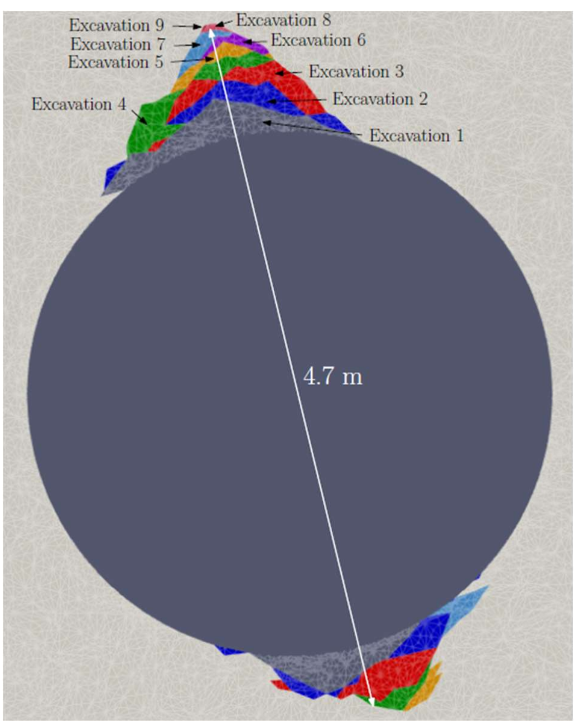

Fig. 3 Excavation process evolution and spalling depth for 2.35m.

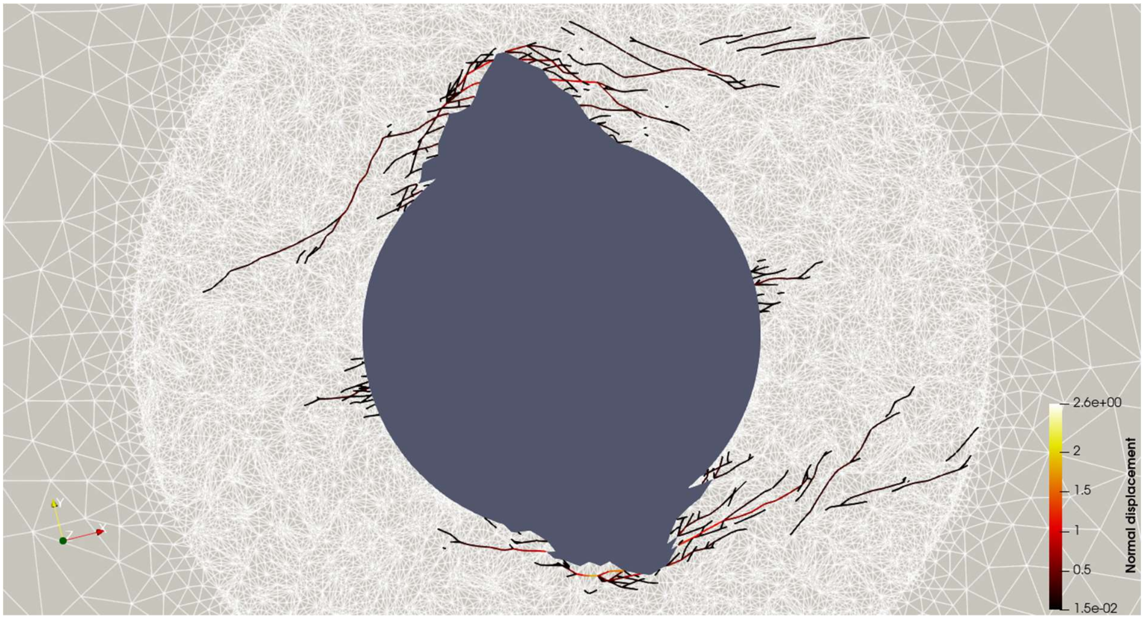

Fig. 4 Open cracks with normal relative displacements that exceed the established threshold value of 0.01 mm after the final excavation stage, are represented coloured.

4 Concluding remarks

A novel approach to the analysis of brittle failure and spalling in deep tunnels has been presented. It is based on a FEM analysis with zero-thickness interface elements equipped with a visco-plastic fracture law, and an excavation workflow. The methodology incorporates two key aspects: the visco-plastic strategy, which ensures convergence of the model and facilitates stress redistribution; and the excavation process, which promotes crack initiation after previous excavations and enables the growth of the spalled region. When applied to the Mine-by experiment in Lac du Bonnet granite, this approach effectively reproduces the observed spalling and provides useful data regarding rock mass behavior, spalling depth and the development of hidden, hydraulically connected fractures.

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