Evolution of spalling-inducing fractures around a deep geological repository for nuclear waste during glaciations and their effect on the long-term repository stability

M. Cristina Saceanu
Imperial College London, London, United Kingdom

Adriana Paluszny
Imperial College London, London, United Kingdom

Robert W. Zimmerman
Imperial College London, London, United Kingdom

Diego Mas Ivars
Swedish Nuclear Fuel and Waste Management Company (SKB), Solna, Sweden
Royal Institute of Technology (KTH), Stockholm, Sweden

ABSTRACT: This paper studies the potential impact of glaciations on the deposition boreholes of the future deep geological repository for nuclear waste at Forsmark, Sweden. A multiple-borehole numerical model is considered, in which fracture growth leading to spalling is simulated in three-dimensions, using the Imperial College Geomechanics Toolkit, a finite element-based discrete fracture growth simulator. Fractures initiate in tension due to *in situ* stress redistribution after drilling, and grow based on stress intensity factors computed at fracture tips. Glaciation is modelled through its effect on the horizontal stresses determined by ice-crust-mantle simulations, and the vertical stress is determined by the weight of the overlying ice sheet. Numerical results indicate that changes in the *in situ* stresses influence nucleation and growth patterns, increasing the extent of the damaged rock around the deposition boreholes during the glacial cycle.

Keywords: deep geological disposal, nuclear waste, spalling, numerical modelling, glaciations.

1 INTRODUCTION

Spalling is a common failure mechanism in brittle rock under high compressive *in situ* stresses, and it is expected to occur around the deposition boreholes of deep-drilled geological disposal facilities for nuclear waste (Martin 2005). Spalling-inducing fractures initiate in tension and propagate as a response to the mechanical and, if present, thermal loading of the borehole. The fractures interact and coalesce in the vicinity of the borehole, forming excavation damage zones (EDZs), which can be classified based on the intensity of the damage (Tsang 2005). The damaged zone closest to the borehole wall contains interconnected fractures and is generally referred to as highly damaged zone (HDZ). The fractures within the HDZ may cause slabs of rock to spall from the borehole wall, resulting in a distinctive V-shaped notch, *i.e.* the “spalled” zone, in the direction of the minimum compressive stress (Figure 1a). Beyond the spalled zone, the host rock becomes progressively less damaged, but the fractures in the outer excavation damage zones still alter host rock properties such as permeability (Siren *et al.* 2015).

Observations from field studies indicate that mechanical spalling is a common occurrence during the excavation stage of deep-drilled boreholes and tunnels in hard, brittle rock (Read 2004, Martin 1999), and that it may be aggravated during the thermal stage of a deep geological repository (DGR) for nuclear waste disposal (Anderson 2007). DGRs in high latitude regions also have the additional long-term risk of being influenced by glaciations (SKB TR-10-23), which may cause new fractures to nucleate in the EDZs, or cause pre-existing fractures to reactivate.

During glaciations, the cyclical expansion and contraction of the ice sheet exerts increased mechanical load on the repository, through both the added weight of the ice as overburden, and the flexural response of the Earth's lithosphere. In Sweden, the lithospheric flexure will induce additional horizontal stresses, that are roughly equal in magnitude to the vertical stress resulting from the weight of the ice (SKB TR-09-15). This will cause fluctuations of the same order of magnitude in the all three far-field stresses at repository depth, as shown in Figure 1b. The changes in the *in situ* stresses during glaciations can cause increased fracturing, leading to heightened permeability and additional fault slip, as observed in several endglacial faults from northern Sweden (SKB TR-09-15).

The aim of this paper is to present a preliminary assessment of the potential impact of glaciations on fracture growth around the future deposition boreholes at the Swedish repository site at Forsmark.

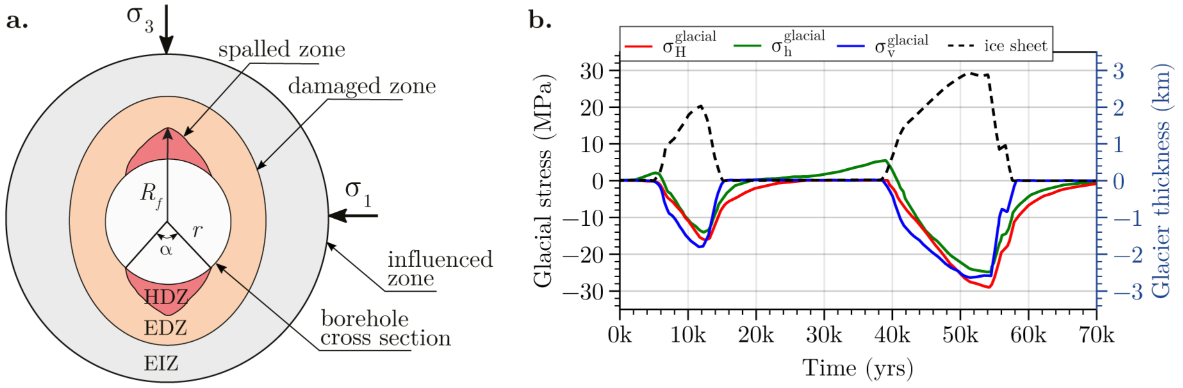

Figure 1. (a) Schematic representation of the three main damage zones around a circular excavation [modified from Read (2004)]. The parameters r, α, and R_f denote the borehole radius, spalling width, and spalling depth, respectively. (b) Temporal evolution of the ice sheet thickness and the glacially induced stress components at repository depth, *i.e.*, 500 m depth, at Forsmark (from SKB TR-10-23).

2 METHODOLOGY

2.1 Mechanical deformation

Mechanical deformation is computed as elastic deformation (Cook *et al.* 2007) in an initially homogeneous and isotropic numerical domain. The force balance of the system is solved numerically using the finite element method (FEM) to determine the displacement, stress, and strain fields. Two main simplifying assumptions are made in this study:

1. The thermal transient phase of the repository has completed before the start of the glaciation and the repository temperature has returned to its initial value prior to the emplacement of the spent fuel canisters, *i.e.* 11.2 °C (SKB TR-10-23).
2. The host rock is initially unfractured and has zero porosity. In reality, the ice sheet is expected to elevate the water pressure in the pre-existing fractures within the host rock (SKB TR-10-23). The coupled THM response of the rock to the changes in the *in situ* stresses will be part of a future study.

2.2 *Fracture nucleation*

A damage mechanics approach is used to describe the fracture initiation process (Mazars 2015). The nucleation loci of initial fracture disks are found from the equivalent strain, $\tilde{\varepsilon}$, which is the vector norm of the positive part of the strain tensor, and a measure of extensile strain. Fractures nucleate in the elements where $\tilde{\varepsilon}$ exceeds the critical nucleation strain ε_c, defined as the ratio of uniaxial tensile strength to elastic modulus:

$$\tilde{\varepsilon} = \|\langle \boldsymbol{\varepsilon} \rangle\|_2^2 \geq \varepsilon_c. \tag{1}$$

2.3 *Fracture growth*

Fractures are grown quasi-statically, and their growth is driven by stress intensity factors (SIFs), corresponding to the three principal deformation modes (opening, in-plane shear, and out-of-plane shear). The SIFs are computed using the interaction integral method (Nejati *et al.* 2015), and incorporated in growth criteria to determine if, and by how much, fracture tips will extend at each growth step. Richard *et al.*'s (2014) mixed-mode propagation criterion, utilising the vales of all three SIFs, is evaluated at each fracture tip to determine the critical SIF at which the tip will extend:

$$\frac{K_I}{2} + \frac{1}{2}\sqrt{K_I^2 + 4(\alpha_1 K_{II})^2 + 4(\alpha_2 K_{III})^2} \geq K_{IC}, \tag{2}$$

where K_{IC} is the critical fracture toughness, and α_1 and α_2 are the ratios of mode I fracture toughness to modes II and III, respectively (Table 1). If the above failure criterion is satisfied at a fracture tip, growth criteria for the propagation angle (Richard *et al.* 2004) and propagation length (Thomas *et al.* 2020) are applied to determine the propagation vector at that tip.

The methodology is described in detail by Paluszny & Zimmerman (2013) and Thomas *et al.* (2020), and by Saceanu *et al.* (2022) in the context of spalling. These studies also provide the full equations for the deformation, damage, and the fracture nucleation and growth criteria.

3 NUMERICAL MODEL SET-UP

A multiple-borehole model is considered, consisting of a 40×20×20 m block of granodiorite. The numerical domain contains three 1.75 m diameter circular boreholes, with an access ramp at the top, spaced 6 m apart. The model is subjected to a far-field anisotropic triaxial stress, as shown in Figure 2a. The domain boundaries are placed sufficiently far from the boreholes, so as not to influence fracture growth in the near borehole region. The rock mechanical properties (Table 1) are representative of granodiorite, the most common lithology at the Swedish site.

Figure 2b illustrates the *in situ* stresses that existed during the previous glaciation and their deviation from present-day base values. The horizontal stresses evolution is based on SKB's reconstruction of the Weichselian glaciation through ice-crust-mantle simulations (SKB TR-09-15), and the vertical stress is equivalent to the ice load throughout the glaciation.

Six cases are investigated, corresponding to six snapshots in time during the glacial cycle (labeled as stages A-F in Figure 2b). Each case comprises different combinations of the principal *in situ* stresses (σ_{H}, σ_{h}, σ_{v}) as listed in Table 1. Fracture nucleation and growth are simulated at the six different glaciation stages, corresponding to six snapshots in time during the glacial cycle (stages A-F). The influence of the *in situ* stresses on fracture nucleation and growth is assessed by simulating each scenario independently from the others, *i.e.,* pre-existing damage is not taken into account.

Table 1. Rock properties and *in situ* stresses used in the spalling simulations.

Rock properties (SKB TR-08-05)		Glaciation stages and far field stresses (SKB TR-09-15)			
Property	Value	Stage	σ_H	σ_h	σ_v
Density	2730 kg/m^3	A: 1st forebulge	41.0 MPa	20.5 MPa	13.2 MPa
Young's modulus	76 GPa	B: 1st glacial maximum	56.7 MPa	36.8 MPa	31.3 MPa
Poisson's ratio	0.23	C: 1st edge retreating	48.5 MPa	28.0 MPa	13.2 MPa
UCS	226 MPa	D: 2nd forebulge	41.0 MPa	17.5 MPa	13.2 MPa
Tensile strength	13 MPa	E: 2nd glacial maximum	70.0 MPa	47.8 MPa	39.2 MPa
K_{IC}	3.8 MPa/m$^{1/2}$ *	F: 2nd edge retreating	51.9 MPa	30.9 MPa	13.2 MPa

* Mode I fracture toughness of the Äspö diorite (Andersson, 2007); other properties are for the Forsmark site.

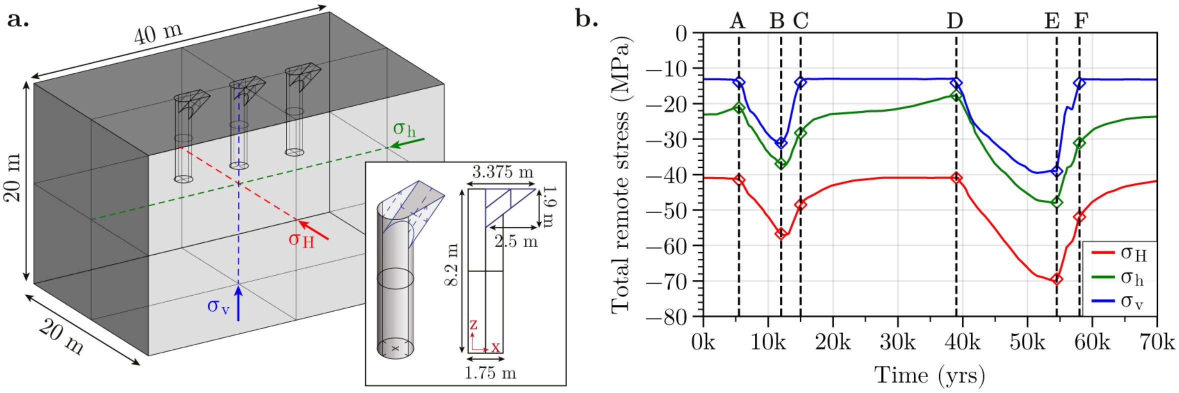

Figure 2. (a) Model geometry and boundary conditions. (b) Predicted temporal evolution of the total remote stress at Forsmark throughout the next glaciation (from SKB TR-10-23).

4 RESULTS

Figure 3a shows top views (stacked *x-y* planes along the borehole length) of the fracture patterns that develop during the six glacial stages. Fractures are represented as lofted surfaces and the surface isocurves are coloured according to the growth step for each glaciation stage. The spalling depths and widths are summarised in Figure 3b as cumulative distributions for each simulation case, showing the proportion of fracture tips located below given values of radial and azimuthal distance with respect to the borehole wall. The CDF curves encompass fracture tip locations from across all growth steps and from all growing fractures, per glaciation stage.

For each fracture tip, θ is defined as the azimuth angle of the tip relative to σ_H direction, and R_f is defined as the distance from the tip to the borehole wall. The presence of a fracture tip at a certain distance (R_f, θ) from the borehole wall does not imply that spalling occurs at that location, but rather that the host rock is fractured. In this work, "spalled zones" refer to the diametrically opposite fractured regions that develop around the borehole in the σ_h direction, assuming material buckling and collapse into the borehole have not occurred yet.

The simulation results show that, despite fractures extending as far as 2.5 m away from the borehole wall, most of the growth is heavily concentrated in the first 30 cm away from the boreholes, for both the central and flanking boreholes. In all simulation cases, except case E, the fractures extending beyond 30 cm from the borehole wall are those developing around the ramps of the deposition boreholes. During the 2nd glacial maximum (case E), higher stress concentrations cause fractures to nucleate and extend further from the borehole walls, but there is less overall interaction with the boreholes, as only a small proportion of fracture tips intersect the borehole. This is because the fracturing from prior glaciation stages has not been considered.

The decrease in σ_h due to forebulging (cases A and D) leads to an increase in the spalled zones depths, but the extent of spalling fractures is greatest during the early stages of ice sheet retreat (cases C and F). This can be attributed to the fact that variations in σ_h have a greater impact on the horizontal stress ratio ($\sigma_\mathrm{H}/\sigma_\mathrm{h}$), causing higher tangential stresses around the boreholes. Therefore, numerical results indicate that spalling depth is influenced primarily by the relative magnitudes of the *in situ* stresses, rather than the absolute mean stress magnitude. For every stress state, no through-going fractures develop in the rock pillars separating the deposition boreholes, suggesting that the repository configuration with borehole spacing of 6 m is stable, and the damaged zones where spalling occurs are confined to the close vicinity of their respective borehole.

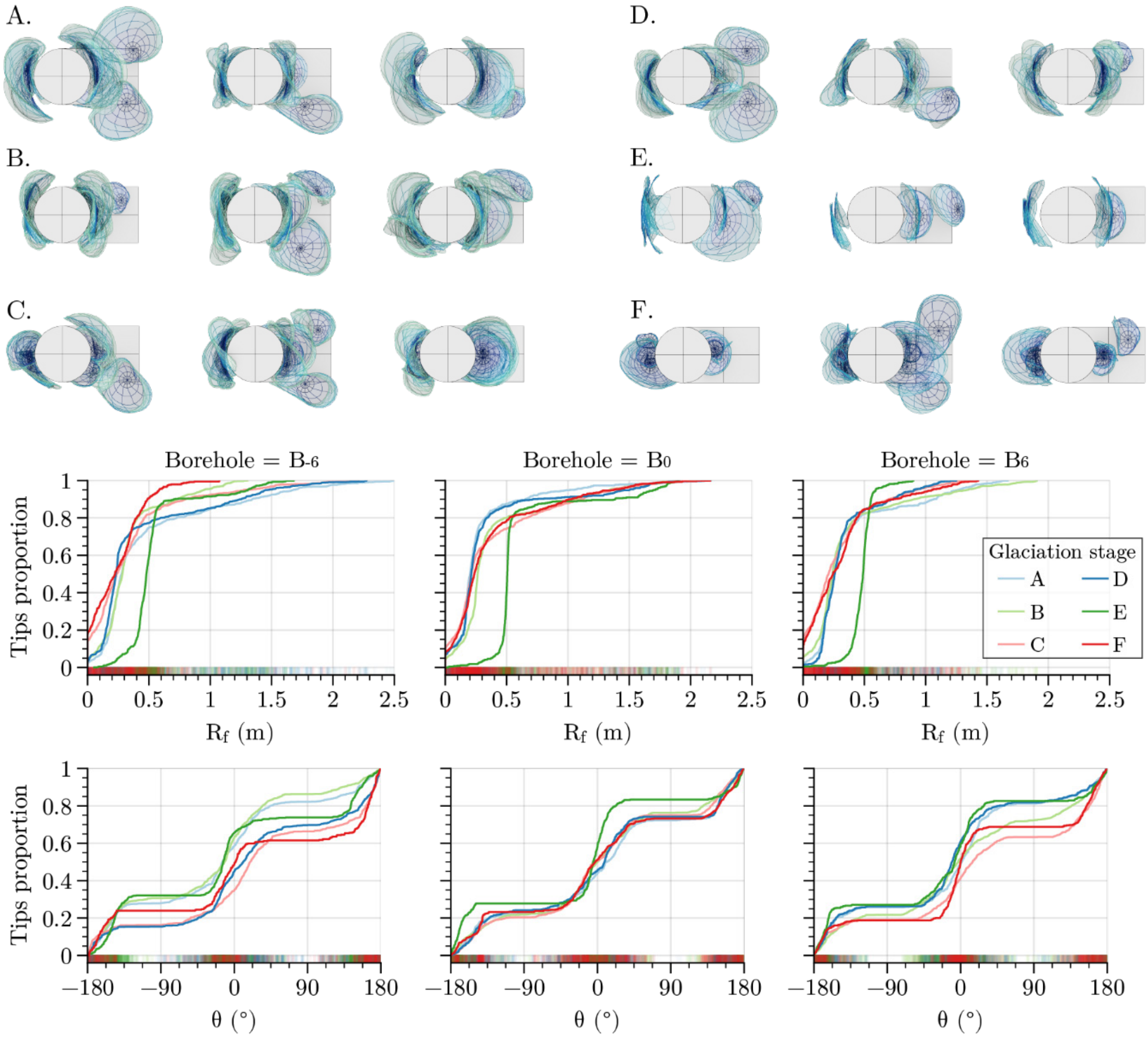

Figure 3. (a) Top views of the fracture patterns that develop during the selected glacial stages A-F. (b) Cumulative distributions showing the proportion of fracture tips located below given values of radial and azimuthal distance with respect to the borehole wall.

5 CONCLUSIONS

Fracture nucleation and growth around the deposition boreholes of a future deep geological repository was simulated in three dimensions using a fracture mechanics approach. Six *in situ* stress scenarios corresponding to glaciation stages were investigated, showing their influence on nucleation and growth patterns. In all simulated cases, fracturing was localised to the close vicinity of the boreholes, and there are no inter-borehole interactions. The simulations presented in this paper consider fracture nucleation and growth response due to changes in the *in situ* stress magnitude independently, assuming that damage does not get carried forward from previous glaciation stages. Further work is planned to take into account pre-existing damage and determine if the stabilised fractures reactivate during subsequent glaciation stages.

ACKNOWLEDGMENTS

The authors thank the Swedish Nuclear Fuel and Waste Management Company (SKB), Sweden for funding this work, through contract EAPER_PA5969 with Imperial College. The authors also thank the Royal Society UK for funding this research, through fellowship UF160443, awarded to Adriana Paluszny.

REFERENCES

Andersson, J.C. (2007). *Äspö Pillar Stability Experiment: Rock Mass Response to Coupled Mechanical Thermal Loading* (Ph.D. thesis). Royal Institute of Technology (KTH), Stockholm.

Cook, R.D., Malkus D.S., Plesha M.E. and Witt R.J. (2007). *Concepts and Applications of Finite Element Analysis*. John Wiley & Sons, Hoboken, NJ.

Martin, C.D. (2005). Preliminary assessment of potential underground stability (wedge and spalling) at Forsmark, Simpevarp and Laxemar sites. Technical report R-05-71, Svensk Kärnbränslehantering AB.

Martin, C.D. and Christiansson, R. (2009). Estimating the potential for spalling around a deep nuclear waste repository in crystalline rock. *International Journal of Rock Mechanics and Mining Sciences* 46(2), 219–228.

Mazars, J., Hamon, F. and Grange, S. (2015). A new 3D damage model for concrete under monotonic, cyclic and dynamic loadings. *Materials and Structures* 48(11), 3779–3793.

Nejati, M., Paluszny, A., and Zimmerman R.W. (2015). A disk-shaped domain integral method for the computation of stress intensity factors using tetrahedral meshes. *International Journal Solids and Structures* 69-70, 230–251.

Paluszny, A. and Zimmerman, R.W. (2013). Numerical fracture growth modeling using smooth surface geometric deformation. *Engineering Fracture Mechanics*, 108, 19–36.

Read, R. (2004). Twenty years of excavation response studies at AECL's Underground Research Laboratory. *International Journal of Rock Mechanics and Mining Sciences* 41(8), 1251–1275.

Richard, H., Fulland, M. and Sander, M. (2004). Theoretical crack path prediction. *Fatigue and Fracture of Engineering Materials and Structures* 28(1-2), 3–12.

Richard, H., Schramm, B. and Schirmeisen, N. (2014). Cracks on Mixed Mode loading – Theories, experiments, simulations. *International Journal of Fatigue* 62, 93–103.

Saceanu, M.C., Paluszny, A., Zimmerman, R.W. and Mas Ivars, D. (2022). Fracture growth leading to mechanical spalling around deposition boreholes of an underground nuclear waste repository. *International Journal of Rock Mechanics and Mining Sciences* 152, 105038.

Siren, T., Kantia, P. and Rinne, M. (2015). Considerations and observations of stress induced and construction induced excavation damage zone in crystalline rock. *International Journal of Rock Mechanics and Mining Sciences* 73, 165–174.

SKB TR-08-05 (2007). Site description of Forsmark at completion of the site investigation phase. SDM-Site Forsmark. Technical report TR-08-05, Svensk Kärnbränslehantering AB.

SKB TR-09-15 (2009). Stress evolution and fault stability during the Weichselian glacial cycle. Technical report TR-09-15, Svensk Kärnbränslehantering AB.

SKB TR-10-23 (2010). Thermal, mechanical, thermo-mechanical and hydro-mechanical evolution of the rock at the Forsmark and Laxemar sites. Technical report TR-10-23, Svensk Kärnbränslehantering AB.

Thomas, R.N, Paluszny, A., and Zimmerman, R.W. (2020). Growth of three-dimensional fractures, arrays, and networks in brittle rocks under tension and compression. *Computers and Geotechnics* 121, 103447.

Tsang, C.F., Bernier, F. & Davies, C. (2005). Geohydromechanical processes in the excavation damaged zone in crystalline rock, rock salt, and indurated and plastic clays – in the context of radioactive waste disposal. *International Journal of Rock Mechanics and Mining Sciences* 42(1), 109–125.