

Long-term Stability Analysis of DGRs in Crystalline and Sedimentary Settings

B. Damjanac¹, Z. Radakovic-Guzina¹ and T. M. Lam²

¹ Itasca Consulting Group Inc., Minneapolis, Minnesota, United States

² Nuclear Waste Management Organization, Toronto, Ontario, Canada

branko@itascacg.com, zorica@itascacg.com, tlam@nwmco.ca

Abstract

A bounding numerical analysis was performed to illustrate the stability and integrity of the rock mass enclosing a used fuel Deep Geologic Repository (DGR) during a 1Ma period. The analysis included a sequence of simulations designed to illustrate sedimentary and crystalline rock mass response to expected repository evolution and extreme events. Among others, scenarios considered include: i) repository gas pressure generation; ii) long-term rock strength degradation; iii) used fuel canister heat generation; iv) continental ice-sheet advance and retreat; and v) rare, strong seismic ground motions. Results indicate that rock damage evolves with time but is primarily driven by thermally-induced stresses occurring within 1000 years of repository closure. Glacial and earthquake perturbations did not yield significant rock damage even when combined. It is evident that the engineered backfill system provides sufficient confinement to prevent spalling and/or fracture dilation, and likely contributes to slowing the rate of time-dependent strength degradation. The numerical simulations also provide insight on the transient loading of a used fuel canister in response to internal and external repository perturbations.

1. Introduction

The Nuclear Waste Management Organization (NWMO) is responsible for implementation of Adaptive Phased Management (APM), the federally approved approach for safe long-term management of Canada's used nuclear fuel. In the APM approach, Canada's used nuclear fuel will ultimately be placed within a Deep Geological Repository (DGR) in a suitable sedimentary or crystalline rock formation.

The repository and its surroundings comprise a system that is designed to protect people and the environment through multiple barriers. These barriers include a corrosion-resistant used fuel canister, engineered sealing systems and the enclosing geosphere. The repository would be situated at a nominal depth of 500 m with a placement room layout able to accommodate 4.6 million used fuel bundles. The conceptual repository design incorporates a hemispherical head, carbon steel, copper clad, self-supporting used fuel container (UFC) for 48 CANDU used fuel bundles. The UFC will be encapsulated at surface in a rectangular buffer box consisting of highly compacted bentonite (HCB). The individual placement rooms, excavated using drill and blast methods, have nominal cross-sectional dimensions 2.2 m high by 3.2 m wide. These dimensions allow buffer boxes to be stacked two high and offset by spacer blocks sized to maintain a container surface temperature below 100°C. A total of 341 container buffer boxes can be placed in each nominal 300 m long placement room. Once

placement of the waste packages and backfilling is complete, a seal which consists of HCB and a concrete bulkhead, will be constructed at the entrance of each placement room. Further details on the conceptual repository design are described in NWMO (2016).

The intent of this illustrative numerical case study is to examine the long-term geomechanical stability of a conceptual APM repository over a 1Ma period. During this period of time, the repository will be exposed to both repository-generated and external perturbations that will influence rock mass response and, potentially, the integrity and longevity of the enclosing geosphere barriers. These perturbations will also create transient loading on a UFC. The scenarios modelled incorporate a range of hypothetical boundary conditions on a DGR in both sedimentary and crystalline type environments, including: i) glacial ice-sheet advance and retreat; ii) strong ground motion associated with rare earthquake occurrence; iii) UFC heat generation; iv) stress re-distribution during repository excavation; and v) repository gas generation. Physical properties of the geologic settings are considered representative and have phenomena, such as long-term rock mass strength degradation, adopted in a manner to capture and provide bounding estimates of the time rate of change and magnitude of repository system response that could influence repository performance.

2. Geologic Settings

For the purpose of the illustrative simulations, representative geologic settings were created. The physical properties for the crystalline and sedimentary settings were based on reported conditions observed during geotechnical investigations at research areas during the Canadian Nuclear Fuel Waste Management Program and, more recently, investigation of a proposed radioactive waste management facility in a sedimentary setting (NWMO, 2011).

The hypothetical sedimentary setting consists of a near-horizontally layered sedimentary sequence, approximately 800 m in thickness, comprised of interbedded dolostone, shale and limestone formations. The repository is situated in a competent, low porosity, low permeability limestone formation at a depth of 480 to 526 m below ground surface (BGS). The mechanical and thermal properties of the intact rock are described in detail by Intera (2011) and Itasca (2015).

For the crystalline setting, the host rock is assumed to be fractured to intact granite, closely matching the characteristics and attributes of a typical Canadian Shield rock formation. The assumed intact rock properties are described in detail by Itasca (2015).

3. Scenario Selection

The major task of this study is to predict how the stability and isolation capability of the repository and environs will respond to external- and repository-induced disturbances over the next million years. Time scales ranging from 100 years to 1Ma are relevant to the evolution and safety of an APM repository. The operational life of the DGR is 100 years, and over this period of time, access (shafts) and below-ground facilities should remain stable to allow for safe facility operations and closure. Following closure, repository evolution over the next 1Ma is evaluated as part of the DGR post-closure safety assessment. Over this time scale, two broad categories of disturbances can influence long-term repository performance: first, long-term natural processes such as climate change, erosion, and seismicity; and second, repository-induced disturbances,

which include geomechanical response to repository construction, thermal loading from the UFC, as well as gas generation – occurring principally as a result of container corrosion. The perturbation scenarios considered to influence and dominate geomechanical repository evolution in this study are summarized in Table 1.

Table 1 Perturbation Scenarios

External (Geological) Perturbations	Internal (Repository-Induced) Perturbations
• Rock strength degradation • Glacial ice-sheet loading • Rare, strong earthquake ground motions	• Ground stress re-distribution during excavation • UFC thermal loading • Gas generation and pressure

4. Conceptual Models: Assumptions

A number of key conservative assumptions regarding geotechnical conditions were adopted in this case study to yield bounding estimates of repository response, including:

- Time-dependent rock strength degradation;
- Cohesionless strength properties for rock joints;
- A high thermal coefficient of expansion of $10^{-5} 1/^{\circ}\text{K}$ for granite;
- Effective stress approximation in the low porosity rock;
- Last Glacial Maximum ice-sheet thickness approximately 3km;
- A peak repository gas generation pressure of 8.5 MPa;
- Rare seismic ground motions with 10^{-6} per annum (p.a.) probability (0.5g PGA); and
- Critical perturbation combinations occur at times of greatest repository vulnerability.

5. Developing Methodology for the Analysis

The analysis undertaken consists of thermo-mechanical (TM) modelling of a single repository placement room using the continuum finite difference and discrete element codes, FLAC3D (Itasca 2012), 3DEC (Itasca 2013) and UDEC (Itasca 2014), respectively. A flow chart of the numerical modelling process is shown in Figure 1.

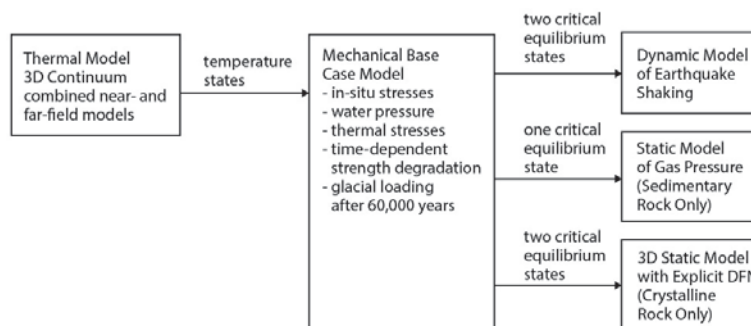


Figure 1 Numerical Model Simulation Methodology

6. Results: Sedimentary Setting

The deformation and damage around the placement rooms were analyzed in a two-dimensional discrete element model. Figure 2 shows the discretized model geometry of a placement room in the Cobourg (limestone) host formation. In this model, the bedding planes are explicitly represented as discontinuities with 0.75 m vertical separation. In a region (9.5 m wide and 10 m high) around the placement room, the rock mass is represented by Voronoi blocks, with an average size of 0.1 m, to facilitate the simulation of the mechanical behaviour of the limestone and development of fracturing, if any.

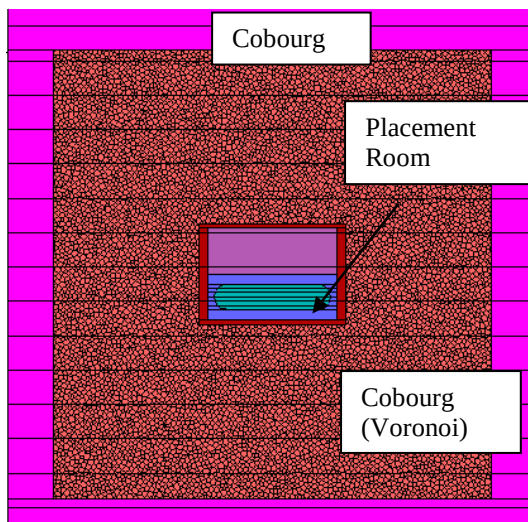


Figure 2 Details of Mechanical Model Discretization and Geometric Layout in Sedimentary Rock.

6.1 Impacts of Time-Dependent Strength Degradation and Thermal Decay

After excavation of the placement room, UFC buffer box positioning and placement room backfilling, the predicted rock mass damage is minimal. The heat released by the waste and induced thermal changes generally have observable impacts on the host rock to about 1000 years. The maximum rock mass temperature of 97°C is attained at 42 years (UFC surface temperature maintained <100°C as part of design criteria). Based on the computed temperature field, deformation and damage around the repository were analyzed using the aforementioned Voronoi block micro-mechanical model. The evolution of the Excavation Damage Zone (EDZ) around the room up to peak temperature is shown in Figure 3. The extent of damage is confined to less than 1 m in the roof and floor of the opening.

The predicted rock mass damage (indicated by black and red lines) at the time of maximum temperature is minimal, confined mainly to the bedding planes directly adjacent the placement room. Other than fracturing and rock mass damage created during the thermal loading cycle, there is no noticeable change in EDZ extent (Figure 3; 200, 2,000 and 50,000 years). Despite the assumption of a long-term rock strength of 40% unconfined compressive strength (UCS), this conservative strength assumption does not seem to have significant effect on room stability or rock mass yield.

The main reason for overall performance of the placement rooms is attributed to the clay-based engineered placement room backfill, which provides confining pressure to prevent spalling and fracture opening, and also acts to slow time-dependent strength degradation and stress corrosion processes. Sporadic, unconnected micro-fractures are present along bedding planes and throughout the vicinity of the room (<3 m). The density of the micro-fractures is greatest in the roof and floor of the placement room. Rock mass damage stabilizes around the placement room beyond 1,000 years approximately 1 m from the excavated surfaces.

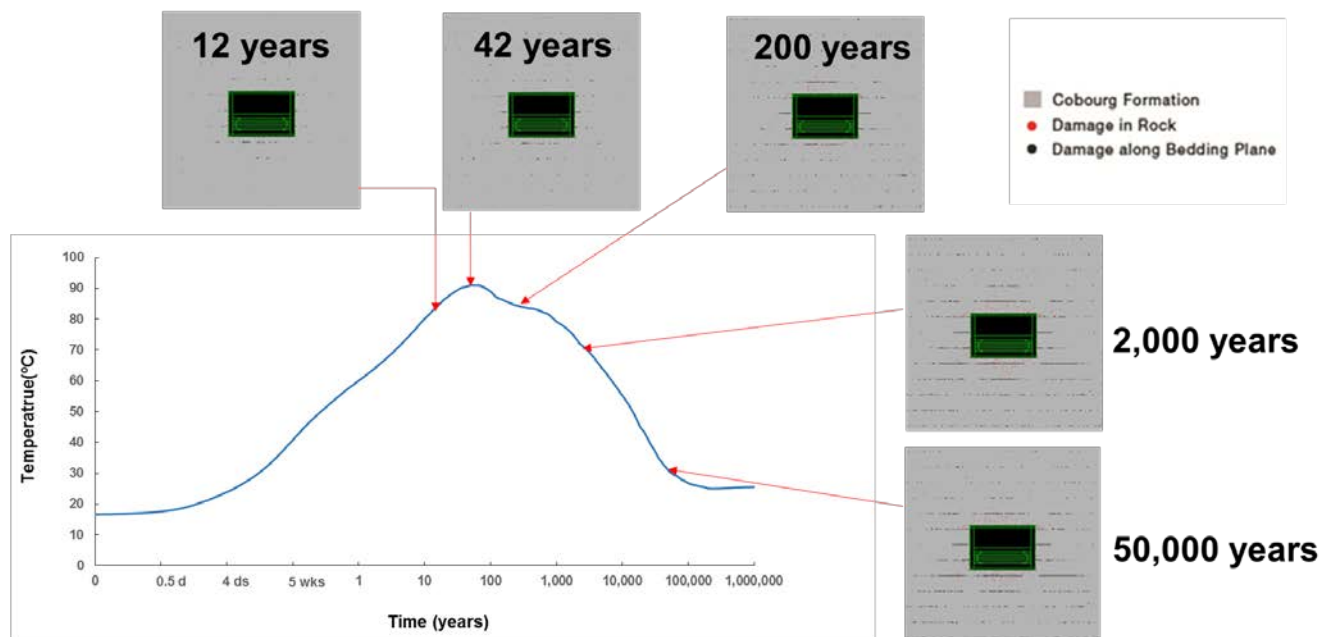


Figure 3 Evolution of Damage in Sedimentary Rock to 1Ma.

6.2 Impact of Glaciation

During the past 1Ma, the Canadian landscape has been glaciated multiple times (Peltier, 2011). Simulations were conducted for the sedimentary and crystalline sites assuming that the sequence of glacial events and corresponding histories of rebound stress (Figure 4) for a sedimentary rock site predicted Itasca (2015) will occur in the future starting at about 60,000 years from present. The numerical simulations, as illustrated in Figure 5, reveal that multiple glacial ice-sheet advances and retreats above a repository site does not materially affect the damage zones around the placement room (note: the results for the crystalline case are similar). The EDZ extends about 1 m into the roof and floor of the placement room. The lack of damage development around the opening is again attributed primarily to the confinement provided by the engineered placement room backfill and sealing systems. The placement rooms and pillars that separate the rooms remain elastic throughout the glacial cycles. The pillars maintain a 10 m wide elastic core with an average stress of about 18.7 MPa. The maximum relative displacement of room walls during a glacial event is about 5 mm, which is insufficient to induce fracture formation or reactivation within the rock mass enclosing the repository. Discontinuous micro-cracking along the horizontal bedding planes remains unchanged. Peak rock mass strength is not reached (i.e., $\approx 40\%$ UCS) at these locations, indicating that induced damage does not represent open connected fractures.

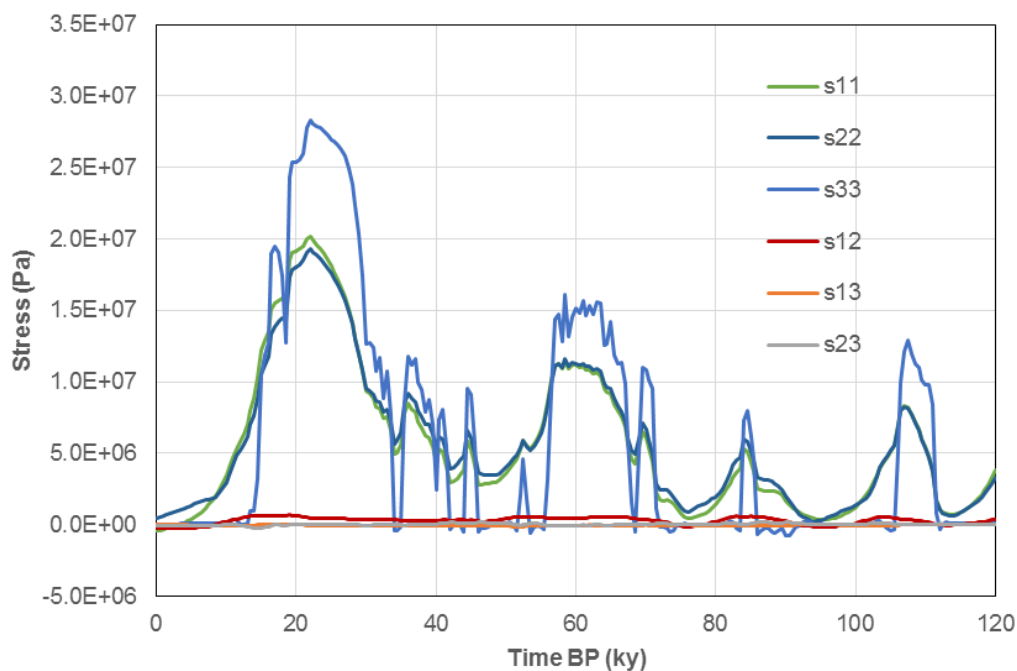


Figure 4 Calculated Glacially-induced Rebound Stress Histories in Sedimentary Rock Setting (BP = before present; 1=E-W, 2=N-s & 3=vertical).

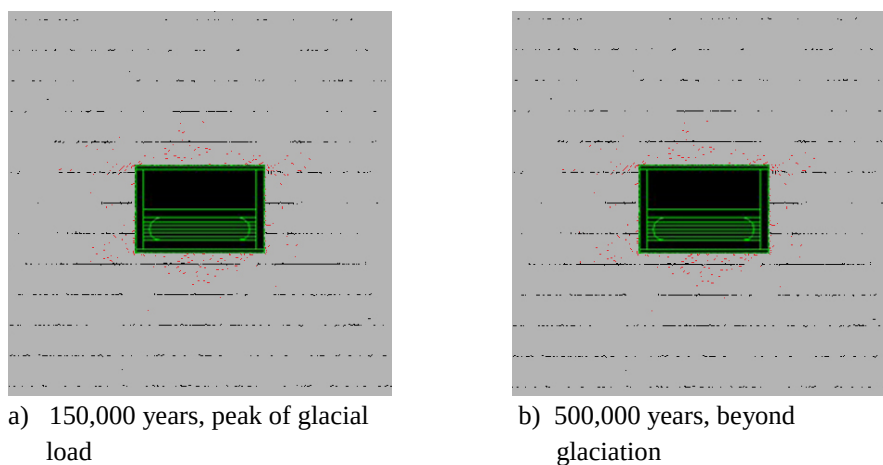


Figure 5 Micro-cracks in Rock During Glaciation Period and Beyond in Sedimentary Rock (damage in rock (red) and along bedding plane (black)).

6.3 Impact of Repository Induced Gas Pressure

Corrosion of the UFC inside the rooms will result in the generation of gas. In the sedimentary environment, this gas generation coupled with the low permeability of the enclosing host rock and the repository clay-based seals will result in the gradual build-up of gas pressure following repository closure. .

For the purpose of this case study, internally generated repository gas pressures were assumed to reach a maximum of 8.5 MPa at 29,000 years (Itasca 2015). The predicted rock mass damage is shown in Figures 6a and 6b, which contrast damage before and after gas loading. The effect of gas pressure on the room walls is minor. The increased gas pressure inside the placement room results in neither tension in the wall nor the initiation or propagation of gas-driven fractures. Thus, there is no change in EDZ geometry, which extends approximately 1 m into the rock mass, primarily in the roof and floor.

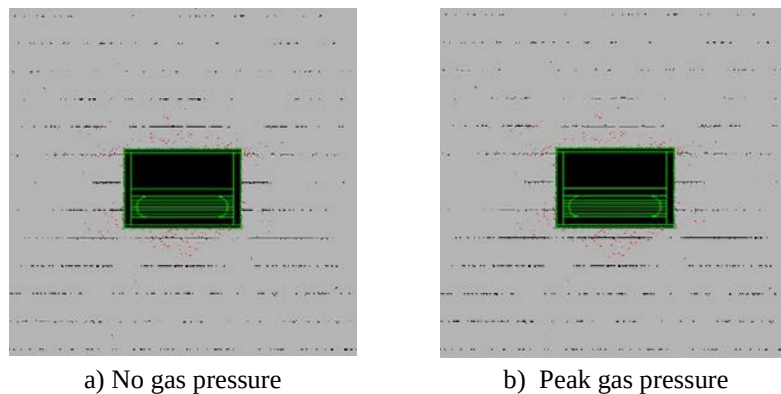
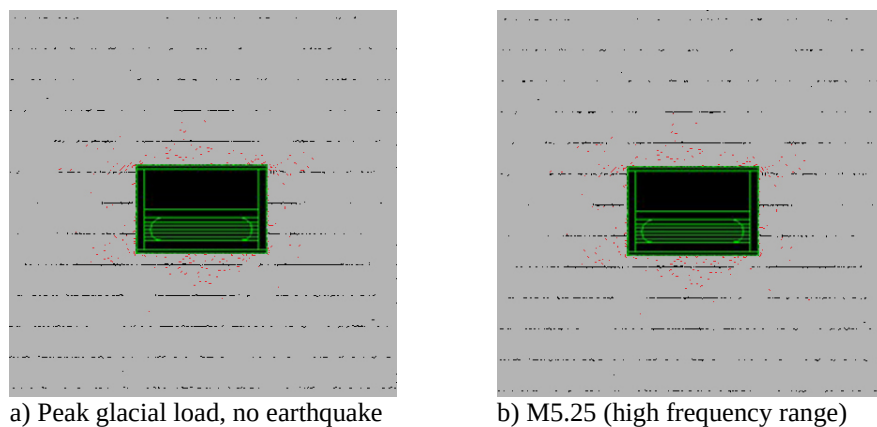


Figure 6 Effect of Gas loading on Damage in sedimentary rock (damage in rock (red) and along bedding plane (black)).

6.4 Impact of Seismic Ground Shaking

To evaluate the worst-case scenario, the 10^{-6} p.a. seismic loading (AMEC 2011) was applied to the model at two critical instances in time: when peak temperature is reached in the rock, and when maximum glacial load occurs (Figure 4). This provides a bounding load combination to ensure that the maximum stress increase in the surrounding rock mass is considered in the analysis. Figure 7 shows the damage level in the model for the three seismic time histories applied at the peak temperature state. Damage resulting from seismic loading is not observed. A similar outcome occurs at the time of maximum glacial load.



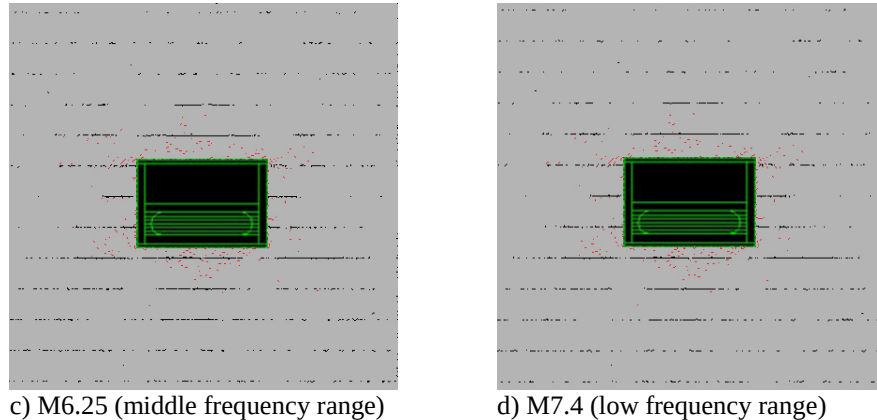


Figure 7 Micro-cracks in the Rock at Peak Glacial Load Subjected to Three 10^{-6} p.a. Earthquakes of Different Frequency.

7. Long-term Performance of Repository in Crystalline Rock

Similar to the sedimentary rock case described in Section 6, in order to demonstrate the long-term geomechanical stability of a conceptual APM repository design in a crystalline rock setting, a broad range of scenarios were considered in the analysis to provide a bounding prediction of rock mass damage evolution over 1Ma. From the results of these simulations, it is evident that except for the thermally-induced stresses, all other perturbations did not have a significant effect on placement room stability or EDZ development. The engineered backfill provides sufficient confinement to prevent spalling and fracture dilation, and appears to contribute to a decrease in the time dependent strength degradation of the host rock. Figure 8 reveals the evolution of damage in the rock around the placement room. The damage zone extends approximately 1 m into the placement room walls. Sparse and randomly distributed cracking extends 3 m from the excavated surfaces into the rock mass, forming a characteristic “butterfly” shape. The random cracks do not localize, forming macro fractures or shear zones. The rock mass within this zone of sparse and random fracturing remains in pre-peak stress state, between the crack initiation ($\sim 40\%$ UCS) and crack damage ($\sim 85\%$ UCS) stress states.

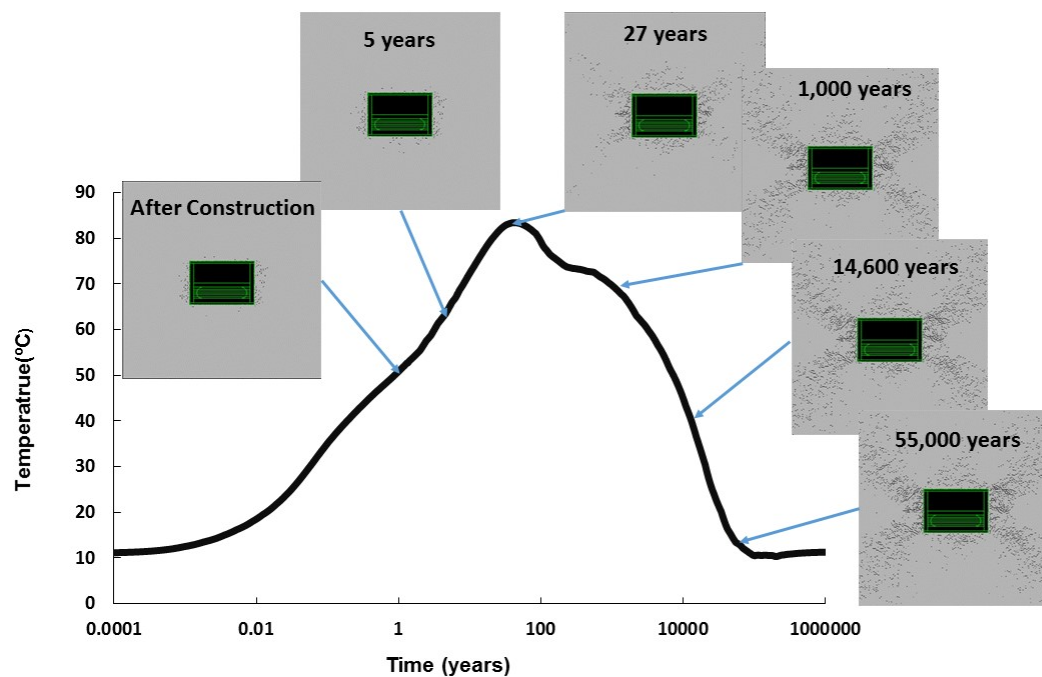


Figure 8 Evolution of Damage in Crystalline Rock.

7.1 Impact of Fracture Network

In order to investigate the effect of discrete fractures and to explore the validity of the equivalent rock mass approach used in model simulations, selected simulations were conducted considering an explicit representation of a pre-existing joint system. Because no joint data were available specifically for a Canadian crystalline setting, statistics of jointing based on mapping at the Forsmark site in Sweden were adopted for the hypothetical site (see Fox et al. 2007). Figure 9a shows a typical Discrete Fracture Network (DFN), one of several realizations considered.

For the purpose of the analyses, two states of repository evolution were considered: 1) peak rock temperature, and 2) maximum glacial load. Despite a relatively low friction angle of 30° for the fractures in the analyses, the simulations indicate that the induced shear displacements on pre-existing fractures are less than 2 mm for all scenarios. The contour plot in Figure 9b shows the shear displacements on joints. It also reveals that all slippage occurs along horizontal or sub-horizontal joints, with maximum shear displacements occurring 3 m from the excavated surface within the enclosing rock mass.

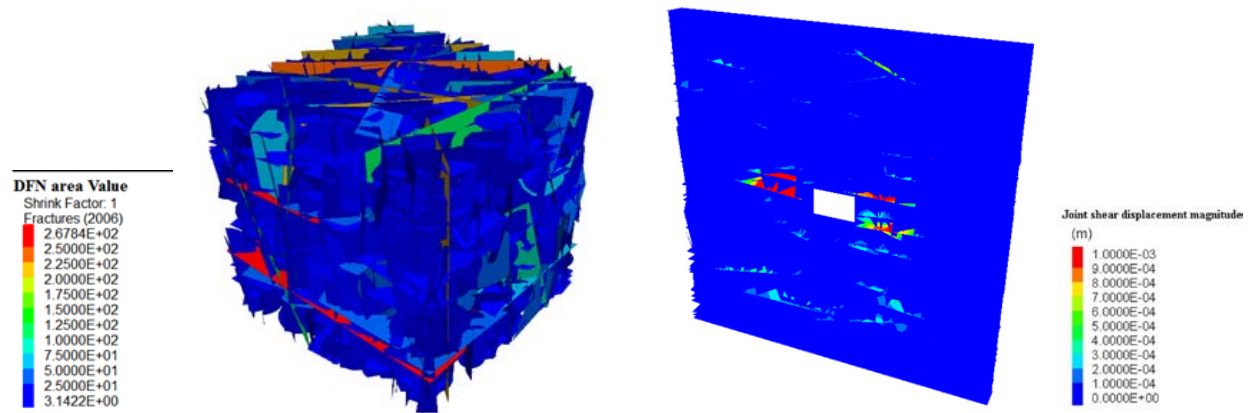


Figure 9 a) Typical Realizations Used in 3DEC Analyses: DFNs are Simplified with a Minimum Fracture Radius of 1m (colours correspond to the fracture size); b) Contours of Shear Displacements (m) on Joints at Peak Glacial Load.

8. Loading on UFCs

In addition to the prediction of rock mass responses, the pressure (load) acting on the UFC was evaluated at selected times throughout the post-closure repository period. The numerical model simulated loads on the UFC are those due to effective stresses and hydraulic pore pressure. In order to obtain total pressure, the swelling pressure of bentonite backfill needs to be added to these estimates. In both the sedimentary and crystalline settings, post-excavation rock stresses have insignificant effect on the UFC loading after deposition of waste packages. As thermal loading progresses, the pressure gradually increases, reaching a base value of about 6 MPa at about 1000 years. The most significant pressure increase occurs during glaciation. At the peak glacial load, the mean pressure exerted on a UFC could reach values tabulated in Table 2. Upon ice-sheet retreat at the end of the glacial cycle, the pressure on the container drops back to approximately 6 MPa. Figure 10 shows the time histories of the pressure on UFC surface for an entire glacial cycle for sedimentary and crystalline settings. The UFC loads provided in Table 2 contain values that include the pressure that would be induced due to swelling of the bentonite backfill.

Table 2 Summary of Maximum Pressure on UFC Surface

Host Rock	UFC Surface Load with Bentonite Swelling (MPa)	UFC Surface Load without Bentonite Swelling (MPa)
Cobourg Limestone	22.7	20.8
Granite	29.8	22.7

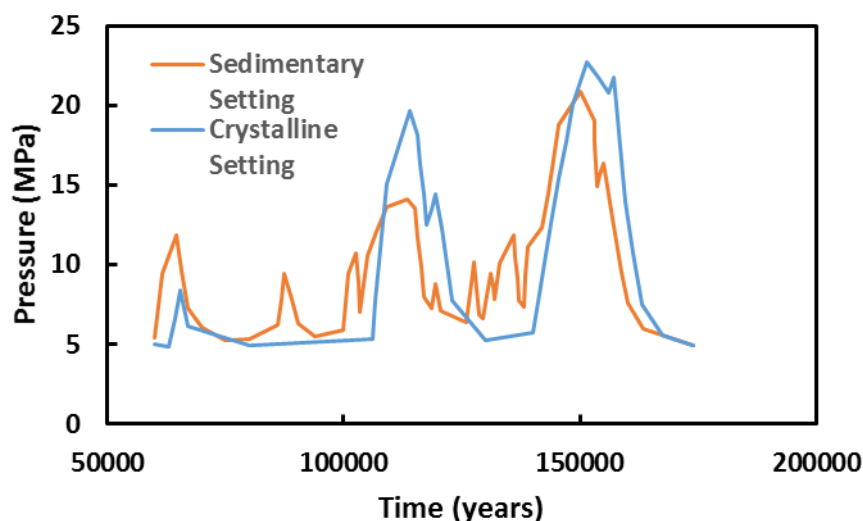


Figure 10 Evolution of Pressure (Excluding Swelling Pressure) on the UFC in Sedimentary and Crystalline Rocks.

9. Conclusions

Natural and repository induced perturbations that could influence the geomechanical evolution and performance of a Deep Geologic Repository were explored through a series of bounding numerical simulations. The assessment provides evidence that thermally-induced rock mass stresses are the main loading condition affecting the extent and intensity of rock mass damage around a conceptual used nuclear fuel repository situated in crystalline and sedimentary rock settings at 500 m depth. The evolution of the Excavation Damage Zone occurred within 1000 years of closure, extending approximately 1 m from the excavated surfaces. Heating will cause vertical displacement of the rock mass, but the displacements are relatively uniform such that only small differential displacements of less than 5 mm are predicted to occur. For the crystalline rock case, an explicitly represented discrete fracture network, as considered in a 3-dimensional simulation, did not result in significant deformation. The predicted maximum shear deformation of less than 2 mm along pre-existing fractures extending 3 m into the enclosing rock mass will not effect the stability or performance of the repository. It is apparent that the confinement afforded by the engineered barrier system provides sufficient confinement to prevent spalling and fracture dilation, and possibly decrease the rate of rock strength loss. Overall, the illustrative modelling case study reveals that repository placement rooms will remain stable and that the integrity of the enclosing geosphere barrier is not compromised.

10. References

- AMEC GEOMATRIX. 2011. Seismic Hazard Assessment. AMEC Geomatrix, Inc. report for the Nuclear Waste Management Organization NWMO DGR-TR-2011-20 R000. Toronto, Canada.
- Fox, A., P. La Pointe, J. Hermanson and J. Öhman, 2007. Statistical geological discrete fracture network model, Forsmark modelling stage 2.2., R-07-46, Svensk Kärnbränslehantering AB.
- Intera. 2011. OPG's Deep Geologic Repository for Low and Intermediate Level Waste. Descriptive Geosphere Site Model. Intera Engineering Ltd. report for the Nuclear Waste Management Organization NWMO DGR-TR-2011-24 R000. Toronto, Canada.
- Itasca. 2012. FLAC3D (Fast Lagrangian Analysis of Continua in 3 Dimensions) Version 5.2. Itasca Consulting Group Inc. Minneapolis, USA.
- Itasca. 2013. 3DEC (3-Dimensional Distinct Element Code) Version 5.2. Itasca Consulting Group Inc. Minneapolis, USA.
- Itasca. 2014. Universal Distinct Element Code (UDEC) Version 6.00. Itasca Consulting Group Inc. Minneapolis, USA.
- Itasca. 2015. Long-term Stability Analysis of APM Mark II Conceptual Design in Sedimentary and Crystalline Rock Settings. Itasca report to the Nuclear Waste Management Organization NWMO-TR-2015-27, Toronto, Canada.
- NWMO. 2011. OPG's Deep Geologic Repository for Low and Intermediate Level Waste. Geosynthesis. Nuclear Waste Management Organization Report NWMO-DGR-TR-2011-11 R000. Toronto, Canada.
- NWMO. 2016. Deep Geological Repository Conceptual Design Report Crystalline / Sedimentary Rock Environment. Nuclear Waste Management Organization Report APM-REP-00440-0015 R001. Toronto. Canada.
- Peltier, W.R. 2011. Long-Term Climate Change. Nuclear Waste Management Organization Report NWMO DGR-TR-2011-14 R000. Toronto, Canada.